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Technical Report
NREL/TP-5500-65667
January 2017

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List of Acronyms

AC	air conditioner
ACH_{50}	air changes per hour at 50 pascals pressure difference between indoors and outdoors
AFUE	annual fuel utilization efficiency
ASHP	air-source heat pump
BTO	DOE Building Technologies Office
CCHP	cold climate heat pump
DHP	ductless heat pump
DOE	U.S. Department of Energy
DHP	ductless heat pump
DHW	domestic hot water
EER	energy efficiency ratio (efficiency rating for room ACs)
EF	energy factor (efficiency rating for water heaters and some appliances)
HPWH	heat pump water heater
HSP	Building America House Simulation Protocols
HSPF	heating seasonal performance factor (efficiency rating for heat pumps)
HVAC	heating, ventilating, and air conditioning
LED	light-emitting diode
LHS	Latin hypercube sampling
NCCE	net cost of conserved electricity
MEL	miscellaneous electric load
NEEA	Northwest Energy Efficiency Alliance
NEEP	Northeast Energy Efficiency Partnerships
NPV	net present value
NPV>0	positive net present value (greater than 0)
NREL	National Renewable Energy Laboratory
NSRDB	National Solar Radiation Data Base
RECS	Residential Energy Consumption Survey
SEER	seasonal energy efficiency ratio (rating for residential central ACs)
SFD	single-family detached
SPP	simple payback period (years)
SPP<5	simple payback period less than five years
TMY3	typical meteorological year (version 3)
VSHP	variable-speed heat pump

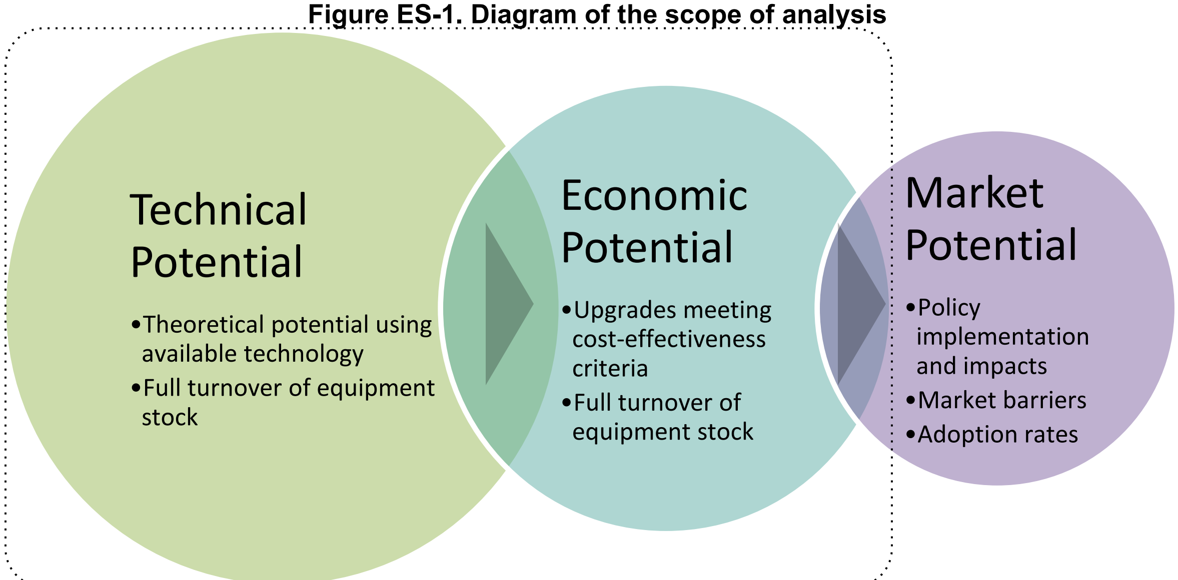
Executive Summary

Introduction

This report documents the methodology and results of an analysis of the electric end-use energy efficiency potential in the U.S. single-family detached housing stock. Technical and economic potential estimates inform the role that residential energy efficiency plays in addressing the objectives of reliable, affordable, and clean electricity for residential end uses. The analysis results identify priorities for residential electric energy efficiency initiatives at national, regional, state, and local levels.

Technical potential is the theoretical potential savings resulting from energy efficiency upgrades using available technology (Figure ES-1). *Economic potential* can be defined in different ways; this report defines it as the subset of technical potential for upgrades that meet cost-effectiveness criteria. *Market potential* (not covered in this report) includes adoption/diffusion rates, as influenced by policy implementation, market barriers (e.g., access to capital), technical/economic barriers not otherwise accounted for (e.g., asbestos or other conditions making upgrades difficult), and market drivers such as comfort, aesthetics, and other non-financial motivation for energy efficiency improvements.

Figure ES-1. Diagram of the scope of analysis



This analysis focuses on technical and economic potential; market potential is not part of the scope.

Typical approaches for assessing energy efficiency potential in buildings use a limited number of prototypes, and therefore suffer from all-or-nothing sensitivities regarding cost-effectiveness which can significantly underestimate or overestimate the economic potential of energy efficiency technologies in particular situations. This analysis applies a new approach to large-scale residential energy analysis, combining the use of large public and private data sources, statistical sampling, detailed building simulations, and high-performance computing to achieve unprecedented granularity—and therefore accuracy—in modeling the diversity of the single-family housing stock.

Methodology Summary

The ResStock[a] methodology used for this analysis involved the following steps:

Step 1. Housing Stock Characterization

We developed a data model to represent the energy-related characteristics of the U.S. single-family detached housing stock. The model uses a hierarchical structure of conditional probability tables that define more than 100 components of a building. The conditional probability distributions for each building component were synthesized from data queried, translated, aggregated, and extrapolated from 11 sources, including U.S. census data, the U.S. Energy Information Administration Residential Energy Consumption Survey, builder surveys, and other data from field studies. They were supplemented by estimates where data are lacking.

Step 2. Statistical Sampling

We used a modified Latin hypercube sampling approach to select representative homes from the parameter space defined by the housing stock data model. Convergence testing of simulation results sliced various ways led us to select 350,000 as the number of *building/location models* (combinations of building characteristics and climate locations) to represent the current U.S. housing stock. Weighting factors were used to scale results up from 350,000 to the 80 million single-family detached homes included in the analysis.

Step 3. Baseline Building Simulations

Detailed subhourly annual EnergyPlus building energy simulations for each of the 350,000 building/location models were run on the National Renewable Energy Laboratory's *Peregrine* high-performance computer to evaluate energy consumption of the baseline housing stock.

Step 4. Validation

The housing stock model was validated by comparing modeled consumption against the U.S. Energy Information Administration's Residential Energy Consumption Survey 2009 consumption values for slices of the housing stock, such as region, vintage, and space heating fuel type. Iterative changes to model inputs were made to bring modeled consumption into better agreement with the reference consumption.

[a] ResStock was developed starting in 2013 for the U.S. Department of Energy's Residential Buildings Integration program, which is part of the Building Technologies Office within the Office of Energy Efficiency and Renewable Energy, with additional funding from Bonneville Power Administration and the National Renewable Energy Laboratory laboratory-directed research and development program. The ResStock framework leverages long-term investment in EnergyPlus, the U.S. Department of Energy's flagship building energy simulation engine, and residential simulation capabilities developed to support the Building America program.

Step 5. Efficiency Upgrade Simulations

More than 50 efficiency upgrades were defined for application to the baseline housing stock. Each upgrade involves rules that apply the upgrade to an appropriate subset of the 350,000 building/location models, with development of EnergyPlus input files, corresponding reference models (with automatic equipment upgrades to federal minimum standards), and definition of incremental costs for the upgrade and reference scenarios in each modeled home.

Step 6. Technical and Economic Potential Calculations

Technical potential was calculated as the aggregated annual savings in all homes in which the upgrade applies. Economic potential was calculated as the aggregated annual savings for upgrades in the subset of homes in which the upgrade passes a cost-effectiveness threshold of net present value greater than zero (NPV>0) or simple payback period less than five years (SPP<5). This involves applying utility rates for electricity and other fuels to the modeled consumption.

Step 7. Package Simulations

To account for interactions between upgrades, packages of the most cost-effective upgrades in each home were simulated. For each building/location model, the upgrade with the highest NPV>0 in each category was chosen for inclusion in the package.

The economic calculations from Step 6 were conducted for the package results as well. The analysis scope did not include packages designed to maximize simple payback period (SPP); however, SPP was calculated for the net present value (NPV)-optimized packages.

Assumptions and Limitations

Key assumptions for this analysis are listed below.

- Technical and economic potential are presented as <u>annual energy savings</u> rather than cumulative energy savings over a number of years.
- The annual energy savings presented assumes <u>full turnover</u> of the stock of equipment and appliances, which could take 15–30 years to wear out and be replaced, depending on the type of equipment. This provides more consistency when comparing against non-equipment upgrades, because these would also take multiple years to reach full adoption.
- Cost-effectiveness is evaluated using costs and benefits from the <u>building owner's perspective</u> rather than a utility or societal perspective.
- <u>Two versions of economic potential</u> were calculated: <u>*NPV>0*</u> uses positive net present value (NPV) as the cost-effectiveness criterion and <u>*SPP<5*</u> uses simple payback period less than five years as the criterion.

- For NPV calculations, 30 years of future cash flows (utility bill savings, equipment replacement at end of life, and residual value) are brought to the present using a 3% real discount rate.
- The packages used to estimate overall economic potential were constructed using NPV as the cost-effectiveness metric.
- The same economic calculations are used for both owner-occupied and tenant-occupied homes. For tenant-occupied housing, it is assumed that either the building owner pays the utility bills or rent can be increased by an amount equal to utility bill savings.
- State, utility, and local incentives (e.g., rebates) were not included in the economic analysis, due to the large number of unique incentives that exist. The federal income tax credit for residential energy efficiency was included and assumed to be available in future years (capped at $500 per household).

The scope of this analysis is limited in the following ways:

- The analysis covers single-family detached housing only. The housing stock characteristics tool developed for ResStock currently is limited to single-family detached housing and excludes all multifamily buildings (including duplexes and townhomes) as well as mobile homes.
- House counts and housing characteristics are a snapshot based on circa-2012 data; projections of future construction and changes in housing characteristics were not included in this analysis.
- Geographic scope is limited to the 48 contiguous U.S. states and Washington, D.C. Sources of housing characteristics and consumption data (particularly the Residential Energy Consumption Survey) for Alaska, Hawaii, and U.S. territories tend to have low sample sizes, resulting in high uncertainty in the data.

Differences in assumptions or format of results may make comparisons to other efficiency potential analyses invalid.

Results and Discussion Summary

The results of the steps outlined above can be used to inform priorities for national, regional, state, or local residential electric energy efficiency initiatives. **Federal and regional policymakers** will find the national maps and tables in the Results and Discussion section of the report most useful, while **state, utility, and city decision makers** will find the state-specific supply curves in Appendix C most useful.

National Potential

From a national perspective, this analysis has estimated economic potential (using the NPV>0 threshold) electricity savings of upgrade packages to be 245 terawatt-hours (TWh) per year, or 22% of electricity used by the single-family detached housing stock in 2012 (Table ES-1). This represents about 6.3% of the total annual U.S. electricity consumption in 2014 and would represent 5.7% of consumption in 2030, based on the U.S. Energy Information Administration's Annual Energy Outlook projections.

Many of the upgrades also save natural gas, propane, and fuel oil. The packages save an estimated 4.2 quads (quadrillion Btu/yr) of source energy, which is 24% of consumption by the SFD housing stock. Similarly, the packages reduce carbon emissions of the stock by 24% (291 million metric tons CO_2e per year).

Table ES-1. Economic Potential (positive net present value) **Electricity Savings Relative to Consumption**

Economic Potential (NPV>0) Electricity Savings in U.S. SFD[i] Homes	**245 TWh/yr**
As a percentage of	
Electricity consumption in U.S., SFD homes (1,118 TWh/yr[ii]; modeled)	21.9%
Electricity consumption in U.S., residential sector (1,407 TWh/yr)	17.4%
Electricity consumption in U.S., total (3,903 TWh/yr)	6.3%
Electricity consumption in U.S., 2030 AEO[iii] reference case (4,326 TWh/yr)	5.7%

[i]SFD: single-family detached
[ii]TWh/yr: terawatt-hours per year
[iii]AEO: U.S. Energy Information Administration's Annual Energy Outlook

This table contextualizes the 245 TWh/yr of economic potential in single-family homes by comparing it to the electricity consumption of the single-family sector and the residential sector at large, as well as the total U.S. electricity consumption, both today and in 2030.

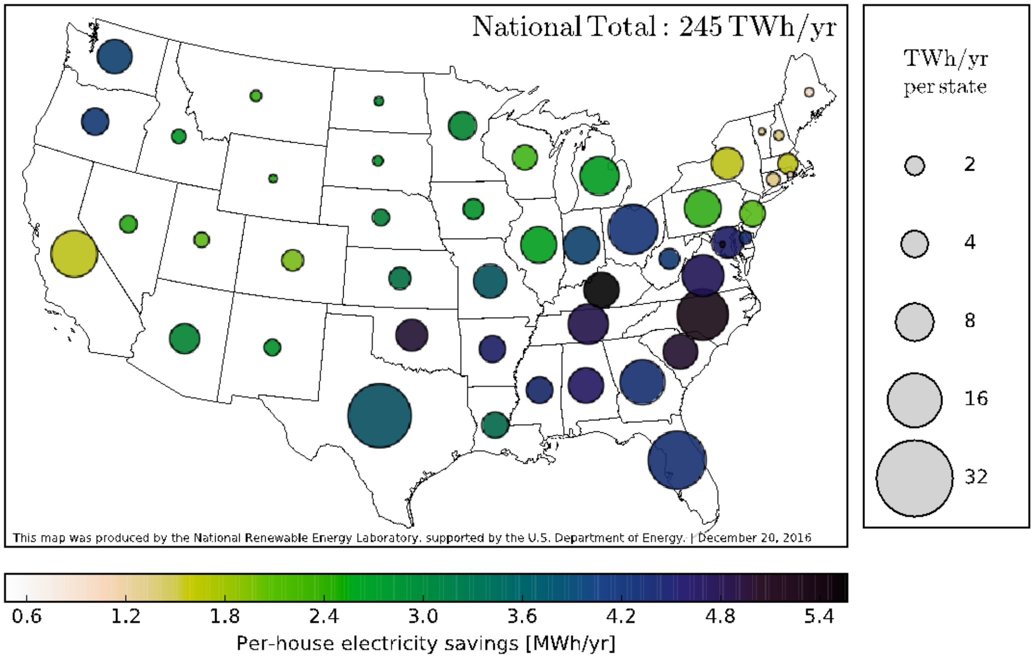
Though the packages were defined to maximize NPV, individual upgrades were also evaluated using the SPP<5 cost-effectiveness threshold. In most market adoption models, market penetration drops off steeply for payback periods around five years or more, so this version of economic potential begins to incorporate some aspects of *market potential* or *achievable potential*. It is estimated that a set of packages designed to maximize SPP<5 economic potential would result in 116 TWh/yr of savings, which is less than half of the total savings offered by packages with NPV>0.[b]

Potential by State

Figure ES-2 shows how the 245 TWh per year of economic potential electricity savings are distributed across the states and D.C. (area of bubbles). The bubble colors indicate the average savings per house. Figure ES-3 shows the savings as a percentage of each state's single-family detached electricity consumption.

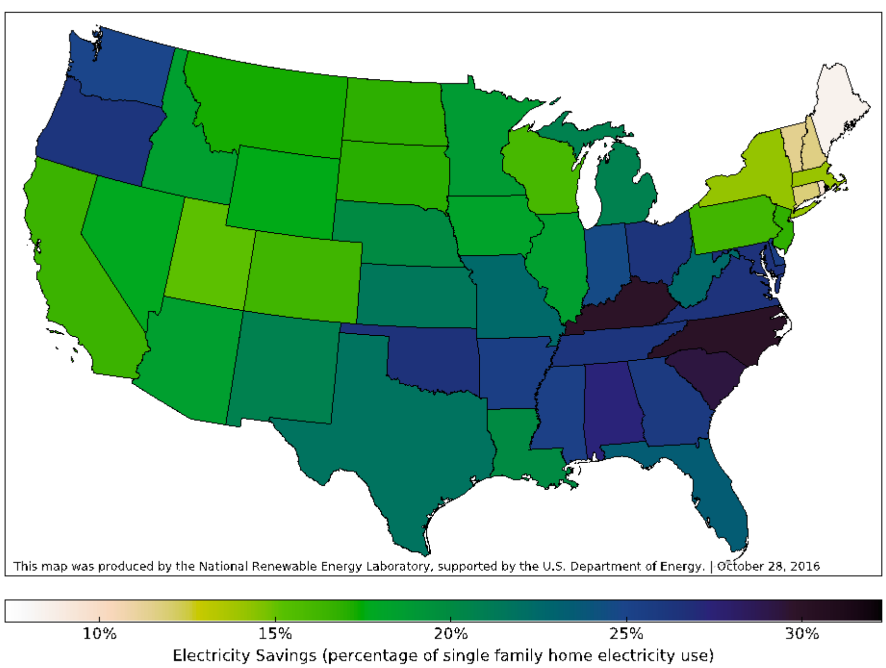
[b] This estimate is simply the sum of economic potential (SPP<5) for the electric heating, lighting, and appliance upgrades. These upgrades have relatively few interactions, so the simple sum of their potential is a reasonable approximation of the economic potential that would result from this SPP-based package.

Figure ES-2. Aggregate and average electricity savings (NPV>0 economic potential) – Packages of the most cost-effective upgrades in each home across all categories



This figure shows the economic potential (NPV>0) electricity savings by state in aggregate (bubble area) and on average, per house (bubble color).

Figure ES-3. Percentage electricity savings (NPV>0 economic potential) – Packages of the most cost-effective upgrades in each home across all categories



Most states can save 15–30% of single-family home electricity use cost-effectively. Electricity savings are lower in New England, where oil-to-electric fuel switching for home heating is often NPV-optimal.

Top Priority Upgrades

Table ES-2 lists the top 11 efficiency upgrades contributing to national economic potential (NPV>0) electricity savings. This list is based on electricity savings; when upgrades are ranked by source energy savings to include other fuels, the rank order changes, and notably, basement and crawlspace wall insulation upgrades become significant contributors.

Table ES-2. Efficiency Upgrades with the Largest Contributions to Economic Potential (NPV>0) Electricity Savings

Efficiency Upgrade	Electricity Savings [TWh/yr[i]]
Upgrade electric furnace/AC[ii] to high-efficiency heat pump at wear out	83
Install LED[iii] lighting in 95% of fixtures	39
Drill-and-fill wall cavity insulation	30
Install high-efficiency ductless heat pumps in homes with electric baseboard heating	26
Install smart thermostats in homes not currently using programmed thermostats	21
Install attic insulation (to R-49 or R-60)	18
Seal and insulate ducts	18
Upgrade central air conditioner to SEER[iv] 18 at wear out	17
Upgrade electric water heater to heat pump water heater	17
Install low-e storm windows	12
Seal air leaks (25% reduction in whole-home leakage)	9

[i]terawatt-hours per year
[ii]air conditioner
[iii]light-emitting diode
[iv]seasonal energy efficiency ratio

Replacing electric furnaces (and air conditioners) with high-efficiency heat pumps provides the most economic potential electricity savings, with more than twice the potential of the second largest contributing upgrade.

Market Adoption Barriers

While this analysis did not evaluate market potential, the technical and economic potential results can help identify barriers to market adoption. Using the NPV>0 threshold, many of the efficiency upgrades have economic potential that is at least 90% of technical potential, meaning the upgrades are cost-effective in most homes. After combining individual upgrades into packages, 94% of the savings from the packages retained cost-effectiveness (NPV>0) after accounting for interactions.[c] This suggests that there are a significant number of homes in which the upgrades and packages are attractive investments for rational consumers with sufficient upfront cash or financing.

In contrast, the SPP<5 filter removes a large fraction of the potential savings for a majority of the upgrades. Market penetration drops off steeply for payback periods longer than around five

[c] The national average simple payback period for the NPV-optimized packages is 12.5 years.

years. Therefore, consumers' demand for short paybacks is likely a barrier to adoption of these upgrades. If investments in efficiency upgrades could be wholly or partially recouped when the home is sold, payback period would be less of a concern for building owners.

Four upgrades stand out as having excellent economic potential after applying the SPP<5 years threshold, retaining at least 90% of their technical potential:

- Upgrade electric furnace/air conditioner to high-efficiency heat pump at wear out (94%)
- Install smart thermostat (occupants not home during the day) (94%)
- Install ENERGY STAR® clothes washer at wear out (100%)
- Install ENERGY STAR refrigerators at wear out (97%).

ENERGY STAR clothes washers and refrigerators already have significant market penetration (66% and 74%, respectively, based on 2013 ENERGY STAR unit shipment data archives). Reasons why the other upgrades are not more widespread could include lack of homeowner/contractor awareness (electric furnace), new technology (smart thermostat), split incentives in rentals, or access to capital or financing.

Incentives and marketing campaigns are traditional ways of promoting energy efficiency adoption. The ResStock approach can be used to more optimally target such incentives or marketing, e.g., by vintage or heating fuel type of homes in a particular state or region. Emerging models for energy efficiency implementation and financing—such as residential energy service companies, property-assessed clean energy (PACE) financing, and on-bill financing—may help address these and other market barriers. These financing mechanisms enable longer-term perspectives regarding energy efficiency improvements, so they may play a role in unlocking economic potential that fails the SPP<5 years threshold yet can provide a positive return on investment under the NPV>0 paradigm. These mechanisms can use ResStock results to help prioritize and target upgrades in particular locations or types of homes.

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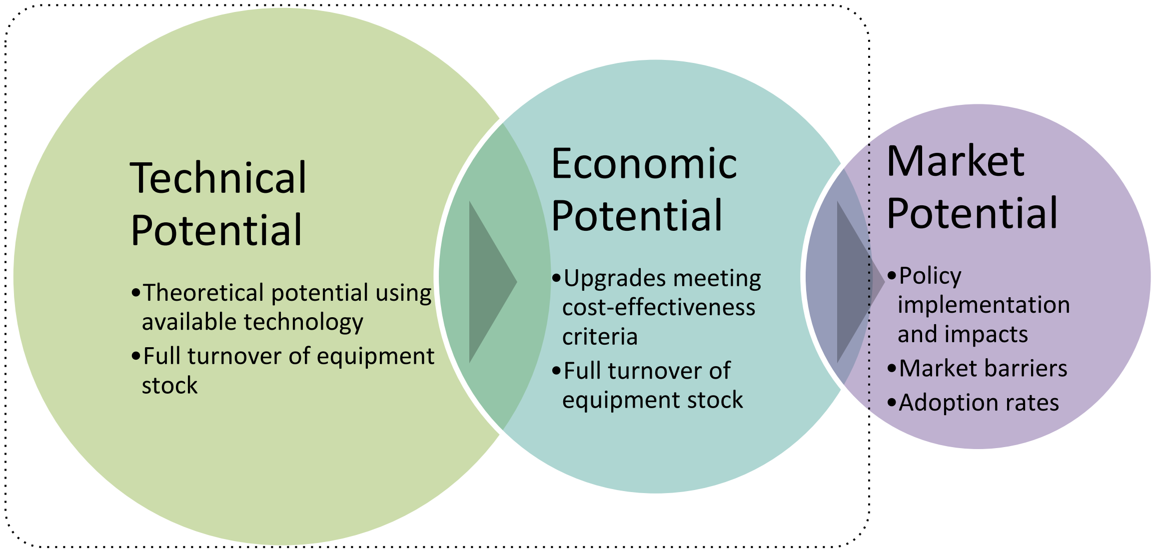
1 Introduction

This report documents the methodology and results of an analysis of the technical and economic potential of end-use energy efficiency in U.S. single-family detached (SFD) housing stock. This analysis used the ResStock analysis framework, which was developed starting in 2013 for the DOE Building Technologies Office Residential Buildings Integration program, with additional funding from the Bonneville Power Administration and the National Renewable Energy Laboratory (NREL) laboratory-directed research and development program. The ResStock framework leverages long-term investment in EnergyPlus, DOE's flagship energy simulation engine, and residential simulation capabilities developed to support the Building America program.[1] [2]

Renewable energy potential has been analyzed with high geospatial resolution[3]; however, analysis of EE potential has typically been coarse in comparison, relying on average savings values from literature, field studies, or simulations of a small number of prototypical buildings.[4] [5] [6] [7] [8] ResStock is unique in the high level of granularity used to represent the diversity of housing stock characteristics and climates across the contiguous United States. ResStock brings together the use of large public and private data sets, statistical sampling, detailed subhourly building energy simulations, and high-performance computing resources.

As illustrated in Figure 1 the analysis documented in this report is focused on technical and economic potential, but not market potential (also called achievable potential). *Technical potential* is the theoretical potential savings resulting from energy efficiency upgrades using available technology. *Economic potential* is the potential savings of upgrades meeting cost-effectiveness criteria. For this analysis, both technical and economic potential include full turnover of equipment stock (heating, ventilating, and air conditioning [HVAC]; water heating; and appliances). Factors falling under market potential, which accounts for adoption/diffusion rates, include policy implementation, market barriers (e.g., access to capital), technical/economic barriers not otherwise accounted for (e.g., asbestos or other conditions making upgrades difficult), and market drivers such as comfort, aesthetics, and other non-financial motivations for energy efficiency improvements.

Figure 1. Diagram of the scope of analysis



This analysis focuses on technical and economic potential; market potential is not part of the scope.

This report provides detailed documentation of the ResStock analysis methodology, including a section describing the motivation for using a high-granularity approach to analyzing energy efficiency potential. We include a description of the economic analysis used to evaluate economic potential, with key assumptions. The methodology section contains a detailed description of the upgrades being evaluated, along with costs and other assumptions.

In the remainder of the report, we present the results in various formats, discuss insights gained from the results, and conclude with a summary of high-level findings and opportunities to leverage the ResStock capabilities for other applications.

2 Methodology

In this section, we describe the ResStock methodology used to analyze the technical and economic potential of energy efficiency upgrades for the U.S. SFD building stock. First, background information and the motivation for a high-granularity analysis are presented to provide context for the ResStock methodology. We then describe how multiple data sources for building characteristics are combined into a highly granular database that preserves the important interdependencies of the characteristics. Then we describe the statistical sampling technique used to generate a representative set of hundreds of thousands of building models. Next we describe how simulation input files are generated for the representative buildings for simulation on an NREL supercomputer. This is followed by a description of the detailed validation/calibration against building stock consumption data.

The remainder of the methodology section includes a description of the economic analysis performed on simulation output, including key assumptions and details of the cost-effectiveness calculations. We then provide a detailed description of each efficiency upgrade and relevant assumptions, followed by a description of how packages of upgrades are constructed. Finally, the limitations of the analysis are discussed.

2.1 Background

Building simulation is increasingly used in various applications related to energy-efficient buildings. For individual buildings, applications include design of new buildings, prediction of retrofit savings, ratings, performance path code compliance, and qualification for incentives. Beyond individual building applications, larger-scale applications (across the stock of buildings at various scales: national, regional, and state) include codes and standards development, utility program design, regional/state planning, and technology assessments. For these sorts of applications, a set of representative buildings is typically simulated to predict performance of the entire population of buildings.

Historically, a relatively small number of "typical" or "average" buildings have been used to represent building stocks. With today's computing resources, software platforms to facilitate batch processing, big data, and statistical approaches, it is useful to ask what an appropriate number of representative buildings is and how those buildings should be defined.

A surprisingly large number of representative buildings may be appropriate, considering real-world combinations of general building characteristics (e.g., location, vintage, size, number of stories, foundation type, and heating fuel type) and detailed building component characteristics (e.g., insulation levels, equipment efficiencies). The degree of *granularity*[d] required for accurate results depends on the analysis questions to be answered. For example, granularity is especially important when modeling economic potential because efficiency upgrade applicability, energy savings, and cost-effectiveness are likely non-linear and situation-dependent.

[d] In this report, the term "granularity" is used to describe the level of detail used to represent a building stock.

2.2 Motivation for High Granularity

The degree of granularity required for accurate results depends on the analysis questions to be answered. Savings analysis is more demanding than consumption analysis. Increased granularity is also useful for analysis targeted at specific incentive programs, technologies, vintages, or geographic areas.

2.2.1 *Energy Savings Calculations*

In general, estimating savings for a particular retrofit requires more granularity in building characteristics than estimating consumption—first, for the building characteristic to be changed by the retrofit, and second, for other building characteristics that may affect the retrofit savings.

Upgrade Component Characteristics

For estimates of savings resulting from a particular upgrade, more granularity is needed to accurately quantify the pre-retrofit efficiency of the component across the housing stock, so that savings can be calculated for the upgrade efficiency versus different levels of pre-retrofit efficiency.

Whole Building Characteristics

The energy savings resulting from a particular upgrade can vary depending on the characteristics of the rest of the building. In the case of a particular envelope component upgrade (e.g., wall cavity insulation) the savings are only weakly influenced by the level of insulation of the rest of the envelope (attic insulation, windows, etc.). This is because a more inefficient envelope has a higher balance temperature and more heating degree days, leading to increased savings for a particular efficiency improvement, and a more efficient building envelope leads to somewhat reduced savings for a particular envelope efficiency upgrade. However, these indirect (balance point) interactions are generally weak unless there is a very large difference in the overall building loss coefficient.

More significant direct interactions occur between savings for a particular envelope efficiency upgrade and the level of HVAC equipment efficiency, and vice versa. For example, savings for an envelope improvement are directly (inversely) proportional to the equipment efficiency and savings for an equipment improvement are directly (inversely) proportional to the overall building envelope efficiency level.

The interactions described above also apply when analyzing multiple upgrades to the same building. To account for the interactions between upgrades, we simulated packages of energy efficiency upgrades as described in section 2.9.

2.2.2 *Economic Potential Calculations*

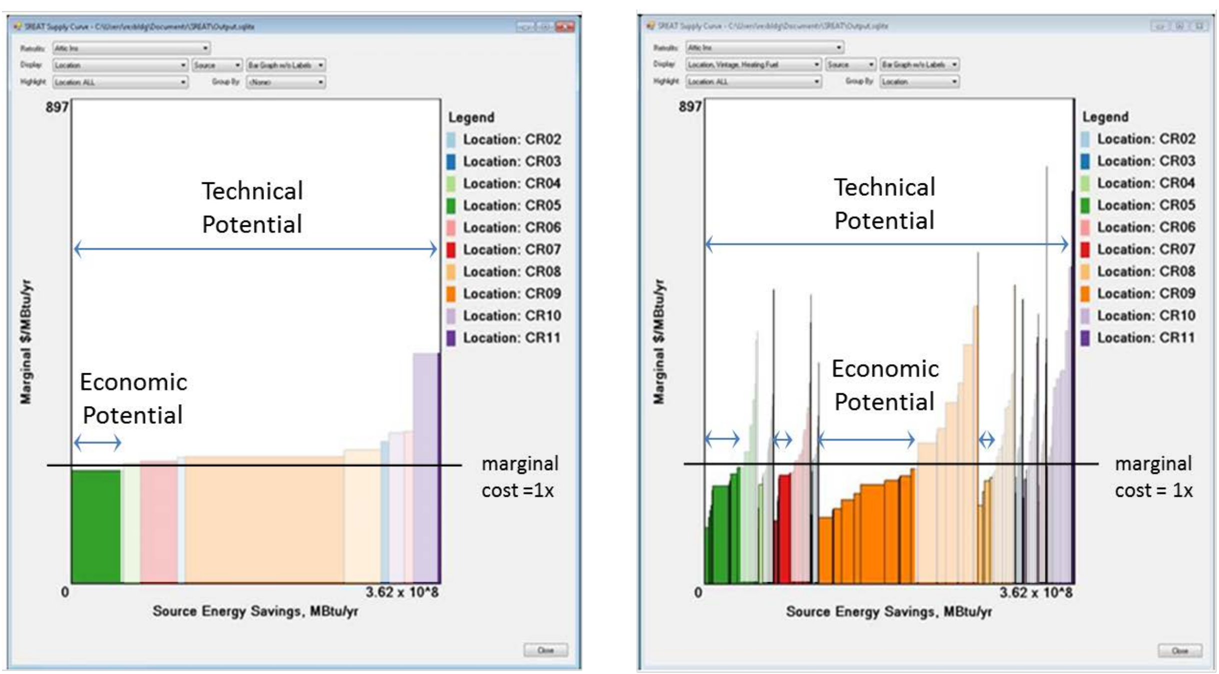
Beyond energy savings, economic calculations impose additional granularity requirements. Economic potential calculations are often based on a cost-effectiveness threshold. This pass/fail situation is highly non-linear, so granularity is crucial for accurate results. A non-granular model could produce results for a particular efficiency upgrade barely on either side of the threshold, indicating either significant economic potential or zero economic potential depending on assumptions.

The example supply curves in Figure 2 and Figure 3 illustrate the issue. For an attic insulation upgrade evaluated in 10 regions of the U.S. (see Figure 15), the marginal cost of saved energy for each region (height of the bar) is compared with the cost-effectiveness threshold (height of the horizontal line). *Technical potential is indicated by the width of all bars; economic potential is indicated by the width of the bars with marginal costs below the threshold.*

In Figure 2 (left), the non-granular model (averaged across vintages) shows cost-effective results only for the region labeled "Location: CR05" (green bar); in all the other locations, marginal costs of saved energy exceed the cost-effectiveness threshold. On the other hand, the granular model (disaggregated by vintage) results, in Figure 2 (right), show cost-effective savings for some vintages in all locations. Summing all locations, the predicted ratio of economic potential to technical potential from the non-granular model and the granular model are approximately 15% and 50%, respectively. The non-granular model results differ significantly from the more precise results of the granular model.

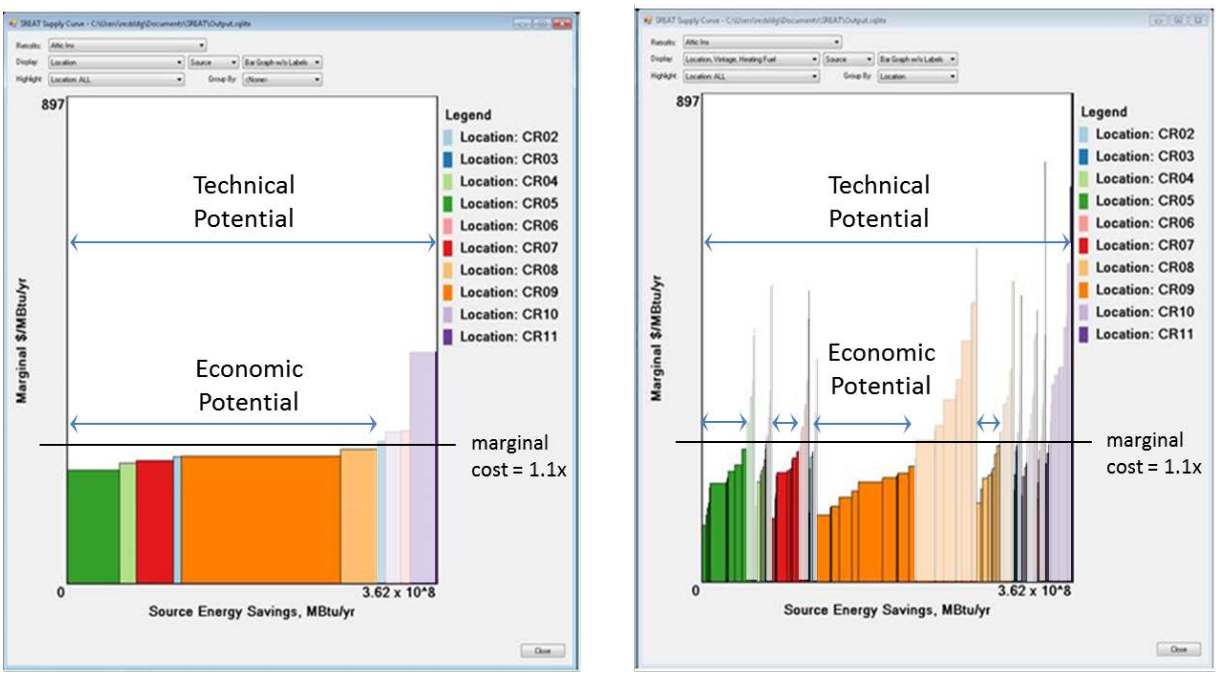
Figure 3 (incorporating a slightly higher cost-effectiveness threshold or equivalently lower marginal costs), shows a dramatic change in the results. The predicted ratio of economic potential to technical potential from the non-granular model and the granular model are approximately 85% and 55%, respectively. The non-granular model is inordinately sensitive to a modest change in assumptions (dramatically underpredicting or overpredicting economic potential); the granular model shows more appropriate sensitivity.

Figure 2. Example supply curves (for cost-effectiveness threshold = x) with marginal cost of saved energy (left) averaged across vintages and (right) disaggregated by vintage



The non-granular model (left) shows cost-effective results only for the region labeled "Location: CR05" (green bar); in all the other locations, marginal costs of saved energy exceed the cost-effectiveness threshold. On the other hand, the granular model (disaggregated by vintage and heating fuel type) results (right) show cost-effective savings for some vintage and fuel type combinations in all locations.

Figure 3. Example supply curves (for cost-effectiveness threshold = 1.1 x) with marginal cost of saved energy (left) averaged across vintages and (right) disaggregated by vintage



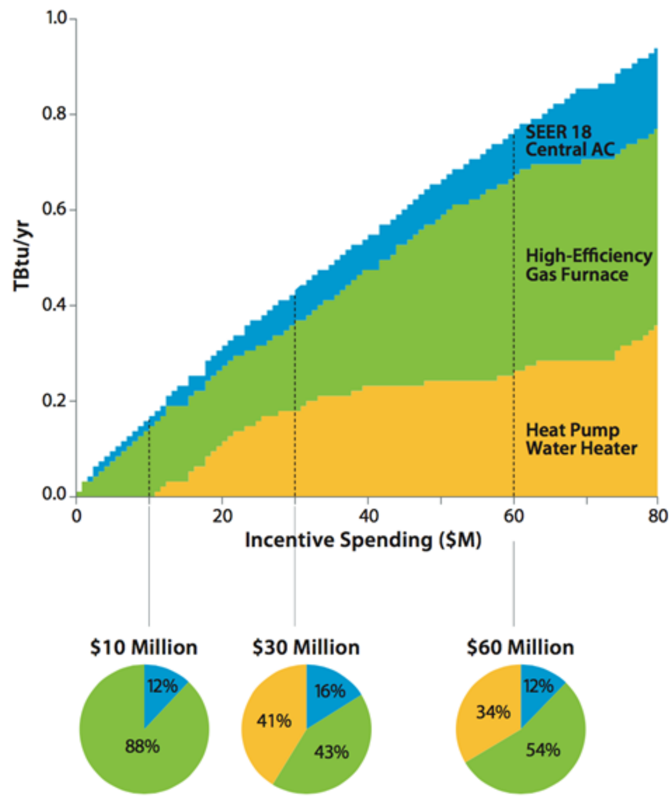
With a slightly higher cost-effectiveness threshold, there is a dramatic change in the results. The non-granular model is inordinately sensitive to a modest change in assumptions (dramatically underpredicting or overpredicting economic potential); the granular model shows more appropriate sensitivity

2.2.3 *Efficiency Program Planning*

Utility energy efficiency program planning is often based on supply curves with the Total Resource Cost Test used as the economic threshold in planning and evaluating utility efficiency programs. High-granularity supply curves can have significant impacts in these cases by allowing programs to target upgrades to particular sets of homes (location, vintage, etc.).

Another potential advantage of high-granularity supply curves is the possibility of optimizing programs for different budget levels (or for different phases of implementation). Programs can be designed to acquire savings with the cost-optimal mix, as shown in Figure 4. These results are derived from a corresponding supply curve (using a granular version, as in Figure 2 [right]) by extracting the economic potential as a function of different economic threshold values.

Figure 4. Example of cost-optimal allocation of incentive expenditures (e.g., rebates) depending on program budget

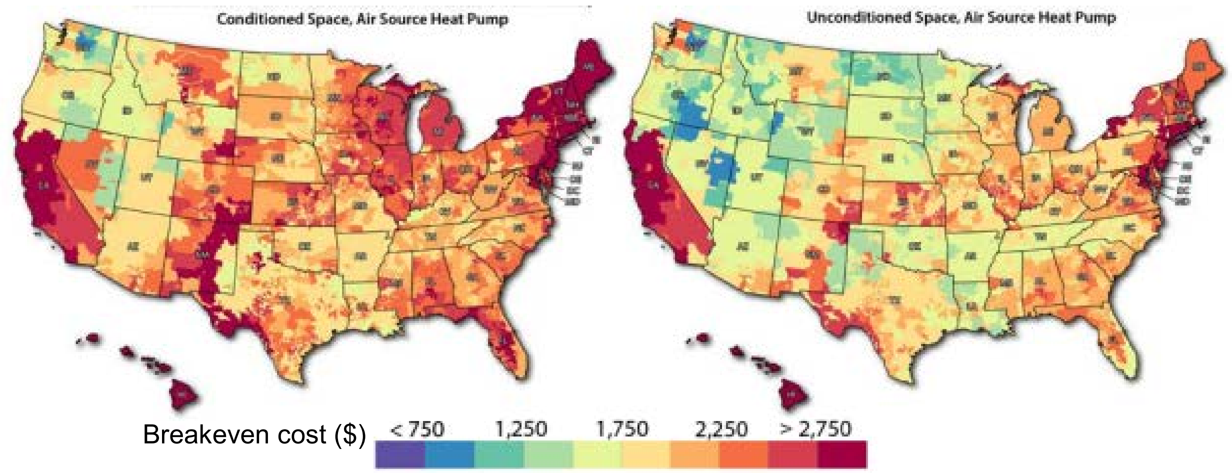


The optimal allocation of program incentive expenditures can vary greatly depending on program budget.

2.2.4 *Assessment of Emerging Technologies*

Figure 5 shows breakeven costs (from the homeowner's perspective) for an 80-gallon heat pump water heater (HPWH) compared with an electric resistance water heater when a new water heater is required (either in new construction or after a water heater has failed). Breakeven cost is the net installed cost of the HPWH that achieves cost neutrality with a typical electric water heater over its lifetime. It is calculated as the point at which all net present benefits of the HPWH (utility bill savings over the unit's lifetime) equal the incremental net present costs (net installed cost and any maintenance costs).

Figure 5. Breakeven costs for a heat pump water heater versus an electric resistance water heater (with air-source heat pump space conditioning) in conditioned space and unconditioned space



Source: Maguire et al. 2013[9]

These figures illustrate how technology breakeven cost can be calculated with high resolution.

Such maps are based on the granular data for utility electricity costs and cold water mains temperatures, as well as building characteristics used in building simulations to predict HPWH impacts on air conditioner (AC) energy consumption. Combined with additional granular data on the presence of electric water heaters (generally correlated with electric space heating, see Table 1) and space conditioning types, these results can be used to estimate economic potential and market size. Potential use cases include:

- Policy analysts and program managers—emerging technologies' economic potential
- Manufacturers—new product pricing and market potential.

2.3 Housing Stock Characterization

For residential building stock analysis, energy simulations of representative buildings require inputs based on characteristics of actual buildings. Table 1 shows building characteristics, dependencies, and data sources for the high-granularity approach used in this analysis.

2.3.1 *Archetypes*

In the building characteristics data, there are certain aspects of buildings (e.g., location, vintage, heating fuel type) upon which other building characteristics (e.g., insulation levels, window type) depend.

We refer to building aspects upon which other building characteristics depend as *archetype parameters* (e.g., location, vintage, heating fuel type).

Archetype buildings are defined by a particular combination of archetype parameter values (e.g., Mid-Atlantic, 1980s, gas).

Table 1. Building Characteristics, Dependencies, and Data Sources

	Characteristics	Dependencies: *Location*	*Vintage*	*Heating Fuel*	*Usage Level*	*Daytime Use*	*Floor Area*	*Number of Stories*	*Found. Type*	Data Sources: 2009 RECS (EIA 2012) [10]	NAHB[11 12 13 14]	IECC 2009 [15]	RBSA (NEEA 2012)[16]	Ritschard et al. 1992[17]	American Community Survey[18]	Labs et al. 1988[19]	Chan et al. 2012[20]	Wenzel et al. 1997[21]	Lucas and Cole 2009[22]	Eng. Exp. & Calibration	Geographic Resolution	# of Options
Meta	*Location*																				TMY	216
	Vintage	✓													•						C	7
	Heating fuel	✓	✓							•											C	6
	Usage level																			•	U.S.	3
	Daytime use																				U.S.	2
Geometry	*Floor area*	✓	✓							•											R	6
	Number of stories	(✓)	✓				✓		✓	•											R	3
	Foundation type	✓									•					•					48	5
	Attached garage	(✓)	✓				✓			•											R	2
	Orientation																				U.S.	4
Envelope	Window type	✓	✓							•		•								•	R	5
	Wall insulation	✓	✓								•			•							R	8
	Attic insulation	✓	✓								•		•								R	7
	Foundation insulation	✓	✓								•									•	R	5
	Air leakage	✓	✓				✓	✓	(✓)								•			•	R	12
Equipment	Heating system type	✓	✓	✓						•	•										R	6
	Heating system efficiency	✓	✓								•							•		•	R	10
	Cooling system type	✓	✓							•											R	7
	Cooling system efficiency	✓	✓								•							•		•	R	7
	Duct insulation, tightness	✓	✓						✓			•							•	•	U.S.	5
	DHW system type	✓	(✓)	✓						•											R	5
	DHW system efficiency																	•		•	U.S.	3
	Cooking type	✓	(✓)	✓						•											R	10
	Clothes dryer type	✓	(✓)	✓						•											R	10
Occupancy	Heating, cooling set points	✓				✓				•											TMY	3
	Cooking usage				✓	✓														•	U.S.	3
	Clothes dryer usage				✓	✓														•	U.S.	3
	Lighting, appliances, MELs				✓	✓				•										•	U.S.	3

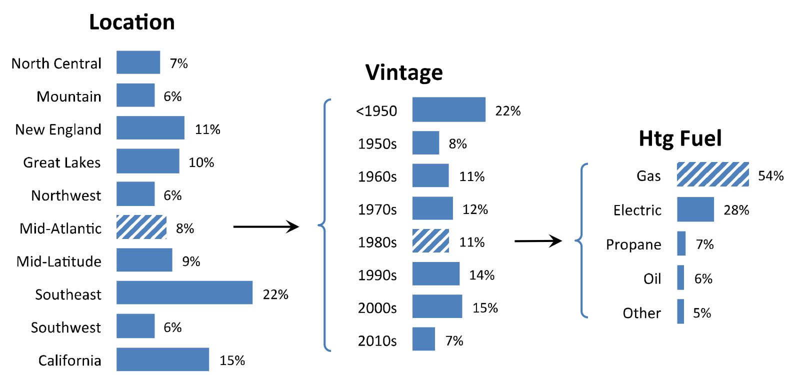
✓ = direct dependency (✓) = indirect dependency *italics* = archetype parameters MELs = miscellaneous electric loads

C = Census Tract R = Regional (custom) TMY3 = 216 typical meteorological year subregions

ResStock statistically represents housing stock characteristics with 6,000 conditional probability distributions derived from a dozen data sources. This table provides information on how each parameter's probability distributions depend on other *archetype parameters*, as well as the data sources, geographic resolution, and number of options (bins) for each parameter.

Dependencies can also exist between archetype parameters, and the data can be organized hierarchically to define these dependencies. For example, as shown in Figure 6, the vintage probability distribution depends on location, and the heating fuel type distribution depends on vintage and location.[e]

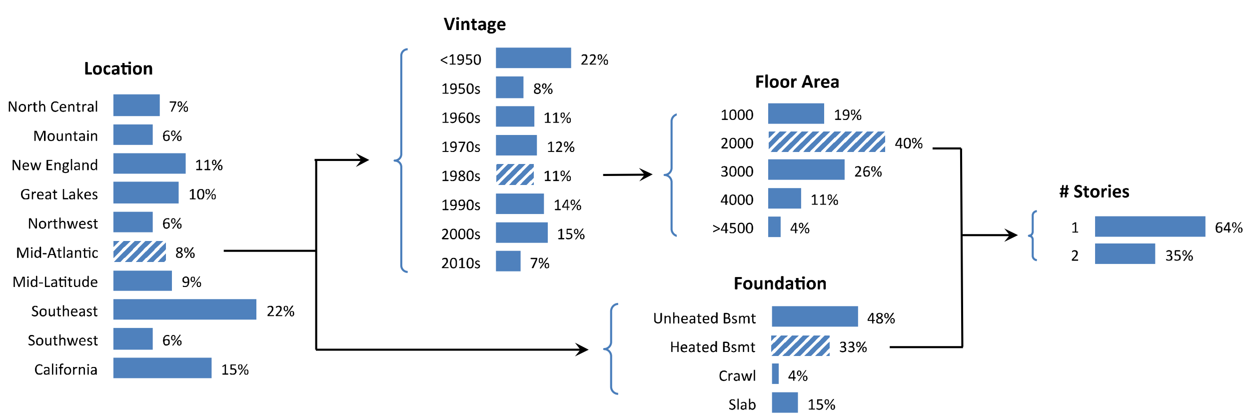
Figure 6. Archetype parameter probability distributions



The probability distribution for vintages depends on the location. The probability distribution for heating fuel types depends on location and vintage. The distribution for heating fuel types for 1980s homes in the Mid-Atlantic region is shown.

Certain building geometry characteristics (floor area, foundation type, and number of stories) are also included as archetype parameters, with the following interdependency (Figure 7):

Figure 7. Geometry probability distributions



The probability distribution for number of stories depends directly on vintage, floor area, and foundation type, and indirectly on location (because the vintage, floor area, and foundation distributions depend on location).

Use level (low, medium, or high) and daytime use (yes or no) also serve as archetype parameters, to account for occupant differences in the use of appliances, lighting, etc.

[e] The order of the hierarchical structure is somewhat arbitrary; for example, the same data set could be queried to develop location weighting factors as a function of vintage. Once weighting factors have been developed based on a particular hierarchical order, then that order is used for dependency-based calculations.

2.3.2 *Archetype Variants*

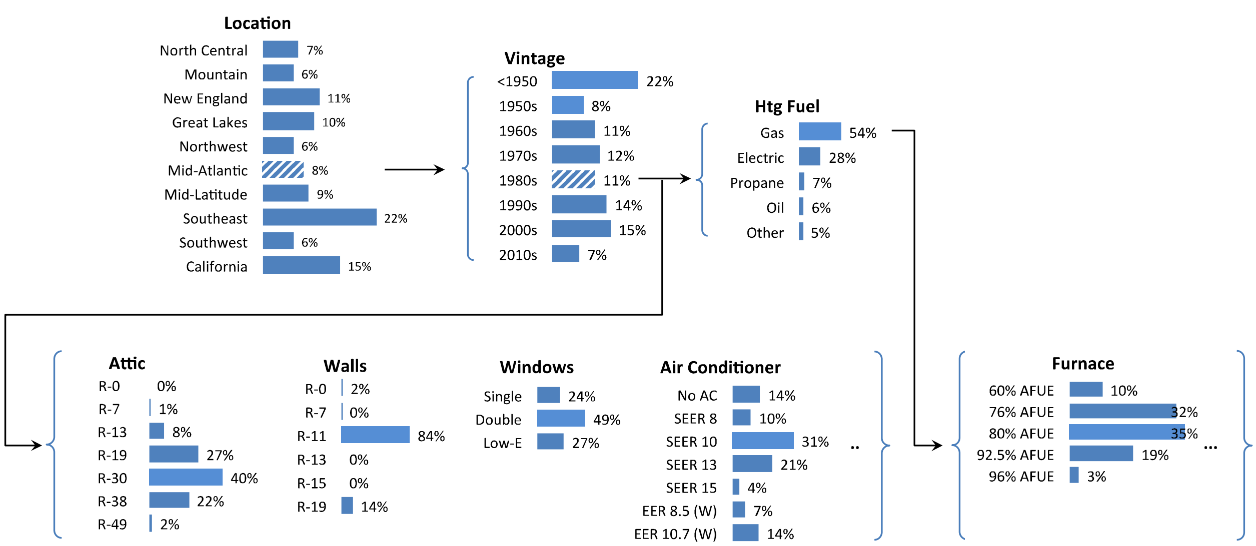
For specified archetype parameters, typical or predominant values may come to mind for building component characteristics (e.g., insulation levels, window type). However, in actual buildings, probability distributions exist for these characteristics.

For example, many homes built in the 1950s have uninsulated walls, with a few built to higher standards or retrofitted. Attic R-values, on the other hand, are more likely to have a broader range of values, as a result of retrofitting at different times (often motivated by different utility rates and/or incentives). Current equipment efficiencies for a particular archetype are also likely to vary based on replacement times and consumer choices. In general, each characteristic category has its own probability distribution over a range of efficiency options (Figure 8).

We refer to building characteristics that depend on archetype parameters as *variant characteristics*.

For each archetype building, various *archetype variant buildings* can be defined based on combinations of different variant characteristics, selected from a set of probability distributions appropriate to the particular archetype building.

Figure 8. Variant characteristics probability distributions based on archetype parameter values



Probability distributions for attic insulation, wall insulation, window glazing type, and air conditioner type/efficiency (among other parameters) depend on location and vintage. The distribution for Furnace efficiency depends on heating fuel type in addition to location and vintage.

Current Characteristics

For any given archetype, current buildings (as they exist today) include variant characteristics that depend on building components that are: 1) as-built, 2) retrofitted, or 3) replaced.

Envelope component characteristics are predominantly as-built—characterized with data based on new construction builder surveys, building codes, standard construction practices, and assessments of the majority of existing buildings. For retrofits, estimates are needed for the fraction of building components that have been retrofitted and the retrofit efficiency level. The fraction of retrofits observed in the data is influenced by cost-effectiveness (cost of retrofit and energy savings, depending on pre- and post-retrofit characteristics, climate, cost of utility power, and availability of incentives), but also by other factors such as ease/convenience of retrofit and non-energy benefits. For example, attic insulation is a relatively attractive retrofit that has occurred in significant numbers for older building vintages.

Equipment characteristics for older vintage buildings are predominantly based on replacements at wear out (early replacement upgrades are relatively rare); data can be generated based on component lifetimes and equipment sales data. For new building vintages, as-built characteristics are more likely to be still current; data can be derived from equipment energy standards. In all cases, efficiency levels may vary across the choice of upgrades available to consumers. Diversity in probability distributions, however, primarily reflects the mix of as-built, replacement, and retrofits.

2.3.3 *Data Sources*

No single data source exists for the range of characteristics needed for residential building stock modeling. NREL developed a *Housing Stock Characterization Tool* for the purpose of generating a representative set of building simulation models. The Housing Stock Characterization Tool is a data-based statistical model that synthesizes data queried, translated, aggregated, and extrapolated from multiple sources.[f]

The tool uses a hierarchical structure of conditional probability tables that define more than 100 components of a building, which can depend on any of the archetype parameters described previously. This internal structure of relationships was developed through correlation analysis and engineering experience.

The conditional probability distributions for each building component were derived from 11 data sources, supplemented by estimates where data are lacking. The process of deriving each distribution generally involved the following steps:

1. Determine how the probability distribution should depend on other parameters (Figure 9), based on correlation analysis and engineering experience. These dependencies must balance the ability to capture detailed correlations against noise caused by low sample size in thinly sliced source data.

Figure 9. Create probability distribution based on dependencies

Wall insulation R-value = f (vintage, location)

[f] The statistical model is being open-sourced. Contact the eric.wilson@nrel.gov for more information.

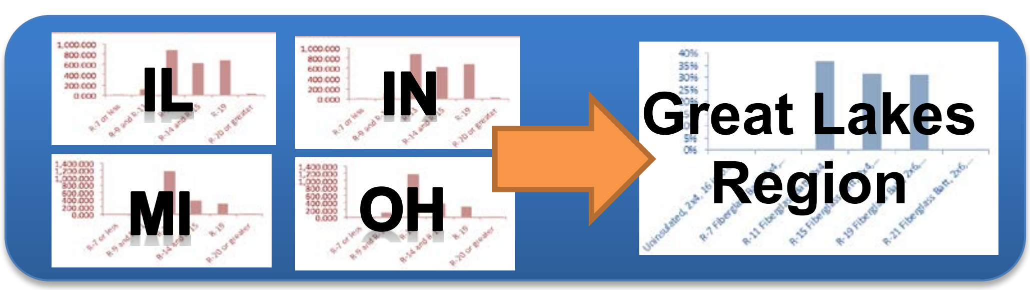
2. Query the dataset using custom query scripts to parse data sources in order to develop probability distributions based on dependencies (Figure 10).

Figure 10. Querying the dataset to develop probability distributions

3. Aggregate, translate, extrapolate, bin, and/or combine the queried data as necessary (Figure 11). Examples include:

    a. Aggregate across multiple states to get a distribution for a region
    b. Translate units of data from *ft^2 of material* to *percentage of homes*
    c. Extrapolate from two years of data to a decade using housing start weighting
    d. Aggregate data to reduce statistical model sampling noise[g] (e.g., furnace efficiencies of 94%, 95%, and 96% annual fuel utilization efficiency [AFUE] are clustered as 95% AFUE)
    e. Combine multiple data sources:
        i. Source 1: Age of AC as a function of vintage of home
        ii. Source 2: Efficiency of AC as a function of age.

Figure 11. Aggregate, combine, interpolate, smooth, and bin the queried data as necessary



The data sources used to develop the statistical model are listed in Table 2.

[g] In cases where there are relatively few simulations available to cover a probability distribution of characteristics (i.e., less common combinations of archetype parameters), a proliferation of similar values in the distribution can cause a misrepresentation of the associated energy use. For example, if there are only a few simulations available for a distribution that has five furnace efficiency values: 80%, 90%, 94%, 95%, and 96%, and the corresponding probability values are 0.33, 0.25, 0.14, 0.14, 0.14, the sampling algorithm will be inaccurately biased toward the 80% and 90% efficiencies over the 94%–96% efficiencies, and therefore overpredict energy use and savings potential. Clustering the 94%, 95%, and 96% efficiencies into a single bin with probability of 0.42 mitigates the bias.

Table 2. List of Data Sources Used to Develop the Statistical Model

Full Reference	# of probability distributions
"Residential Energy Consumption Survey (RECS), 2009 RECS Survey Data," U.S. Energy Information Administration, accessed in 2012, https://www.eia.gov/consumption/residential/data/2009/.	2792
Using engineering experience or calibration due to lack of data	1235
Wanyu R. Chan, Jeffrey Joh, and Max H. Sherman, *Air Leakage of US Homes: Regression Analysis and Improvements from Retrofit* (Technical Report LBNL-5966E) (Berkeley, CA: Lawrence Berkeley National Laboratory, 2012, Eqn. 2 and Table 1).	1050
Thomas P. Wenzel, Jonathan G. Koomey, Gregory J. Rosenquist, Maria C. Sanchez, and James W. Hanford, *Energy Data Sourcebook for the U.S. Residential Sector* (Technical Report LBNL-40297) (Berkeley, CA: Lawrence Berkeley National Laboratory, 1997).	760
American Community Survey: Five-Year Summary File," U.S. Census Bureau, 2012 (from National Historical Geographic Information System, Minnesota Population Center, 2015).	432
"New Construction Builder Practice Survey Data," National Association of Home Builders, 1982, 1987	152
Using default values from Eric Wilson, Cheryn Engebrecht Metzger, Scott Horowitz, and Robert Hendron, *2014 Building America House Simulation Protocols* (Technical Report NREL/TP-5500-60988) (Golden, CO: National Renewable Energy Laboratory, 2014), http://energy.gov/eere/buildings/downloads/building-america-2014-house-simulation-protocols.	96
"New Construction Overview," Home Innovation Research Labs 1999, 2007 (New Housing Characteristics; Insulation; Sheathing—Wall), http://www.homeinnovation.com/trends_and_reports/data/new_construction.	56
"Residential Building Stock Assessment: Single-Family Characteristics and Energy Use," Northwest Energy Efficiency Alliance, 2012.	52
Kenneth Labs, John Carmody, Raymond Sterling, Lester Shen, Yu Joe Huang, and Danny Parker, *Buildings Foundation Design Handbook* (Technical Report ORNL/Sub/86-72143/I) (Oak Ridge, TN: 1988).	48
International Code Council, *2009 International Energy Conservation Code* (Washington, D.C.: 2009).	40
Ronald L. Ritschard, James W. Hanford, and A. Osman Sezgen, *Single Family Heating and Cooling Requirements: Assumptions, Methods, and Summary Results* (Technical Report LBL-30377) (Berkeley, CA: Lawrence Berkeley National Laboratory, 1992.	36
"Building America Field Data Repository," National Renewable Energy Laboratory, 2015.	7

This table lists the data sources used to develop the statistical model of housing stock characteristics used for this analysis.

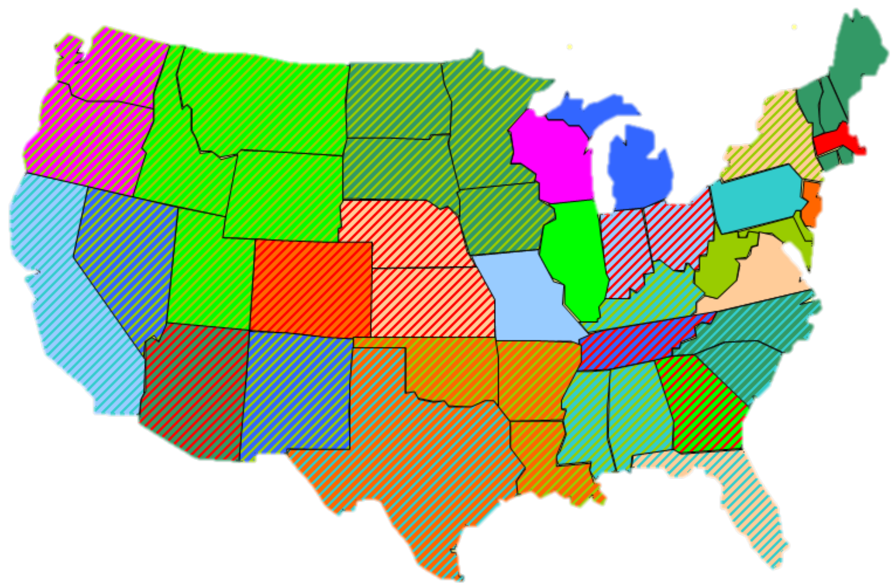
2.3.4 *Geographic Resolution*

Residential building stock analysis has various geographic dimensions including the location dependencies of archetype parameters and variant characteristics, climate data, and utility service territories. As illustrated below, data are available at widely varying geographic resolutions, and one of the technical challenges is merging the data from various sources for analysis.

Building Characteristics

Residential Energy Consumption Survey (RECS) microdata are available by reportable domains, which are 16 individual large states and 11 aggregations of multiple states (Figure 12).[23]

Figure 12. Residential Energy Consumption Survey reportable domains

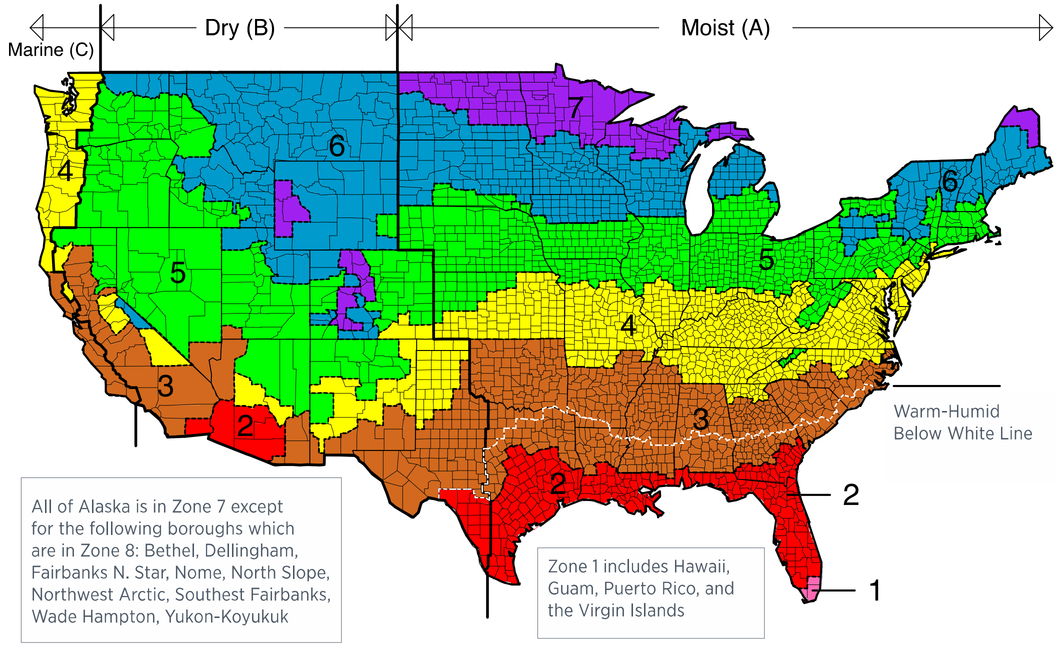


Each sample in the 2009 RECS microdata is associated with one of 27 reportable domains, which are 16 individual large states and 11 aggregations of multiple states. Alaska and Hawaii (not shown here and not part of this analysis) share a reportable domain with Washington and Oregon.

For recent home vintages, as-built (new construction) building characteristics are influenced by building codes. The timing of code adoption varies across the country sometimes by state or municipality, but the International Energy Conservation Code provides code levels prescribed for envelope characteristics by climate zones (Figure 13).[24]

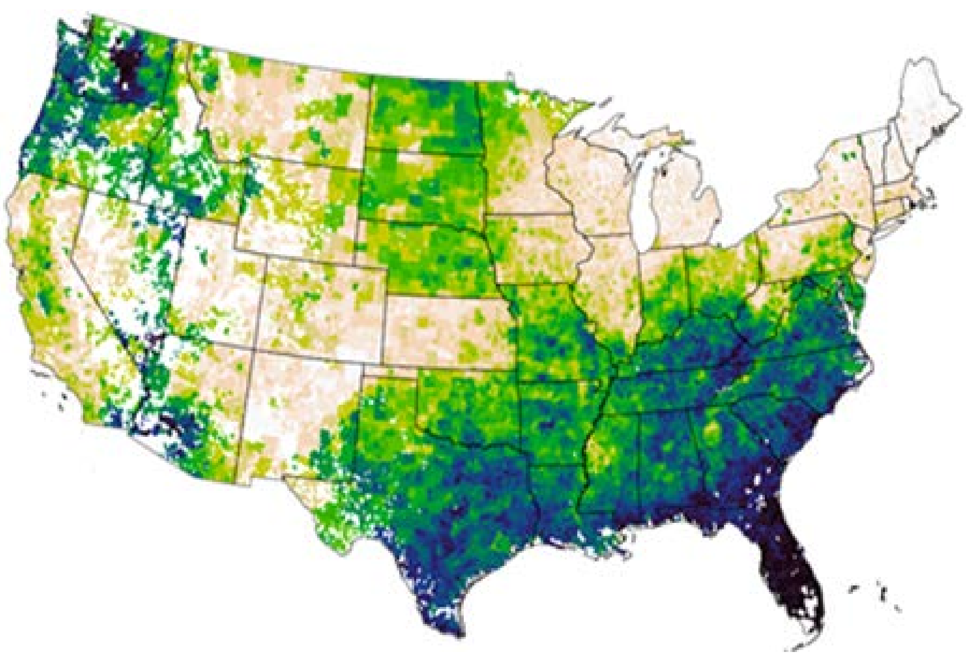
The America Community Survey (by the U.S. Census) provides high geographic resolution data (by census tract) for building characteristics for U.S. housing stock such as year built and heating fuel type (Figure 14). Census tract data was mapped into 10-kilometer gridcells and the gridcells were mapped to typical meteorological year (TMY3) subregions. The details of this process are included in Appendix B.

Figure 13. International Energy Conservation Code climate regions



Building energy codes are specified using these climate zone regions.[25]

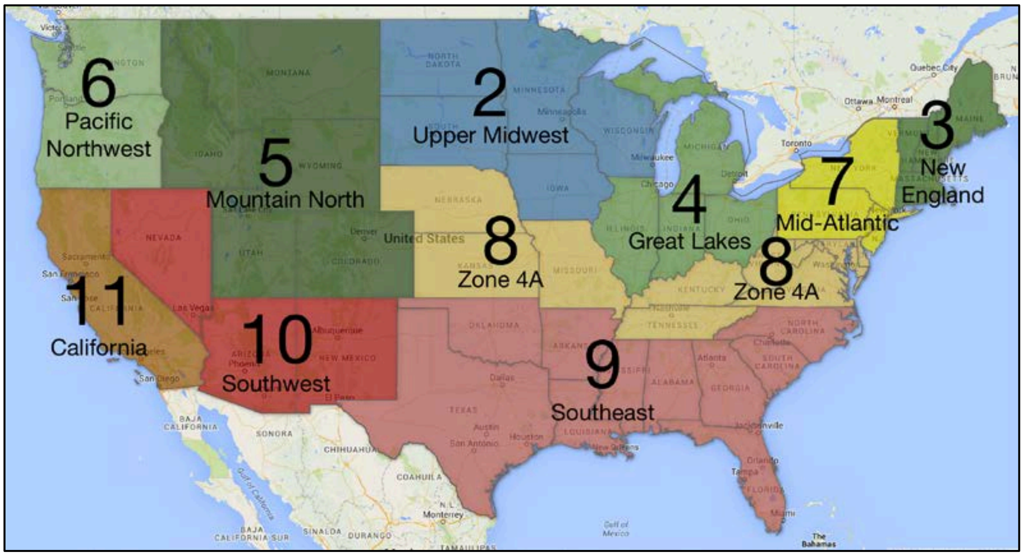
Figure 14. American Community Survey—percentage of houses with electric heating



This map shows an example of data from the American Community Survey (percentage of homes using electricity as the primary space heating fuel), which provides data with high geographic resolution. For this map, census tract data was mapped to 10-kilometer gridcells.

For the purposes of a) developing location-based dependencies and b) reporting energy-related results, NREL developed 10 custom regions[h] (Figure 15) consisting of climate-based aggregations of RECS reportable domains. Higher resolution data (e.g., census-based data, weather data, utility data) can still be used as appropriate within these custom regions.

Figure 15. ResStock custom regions



Base Map Data Source: Google 2016

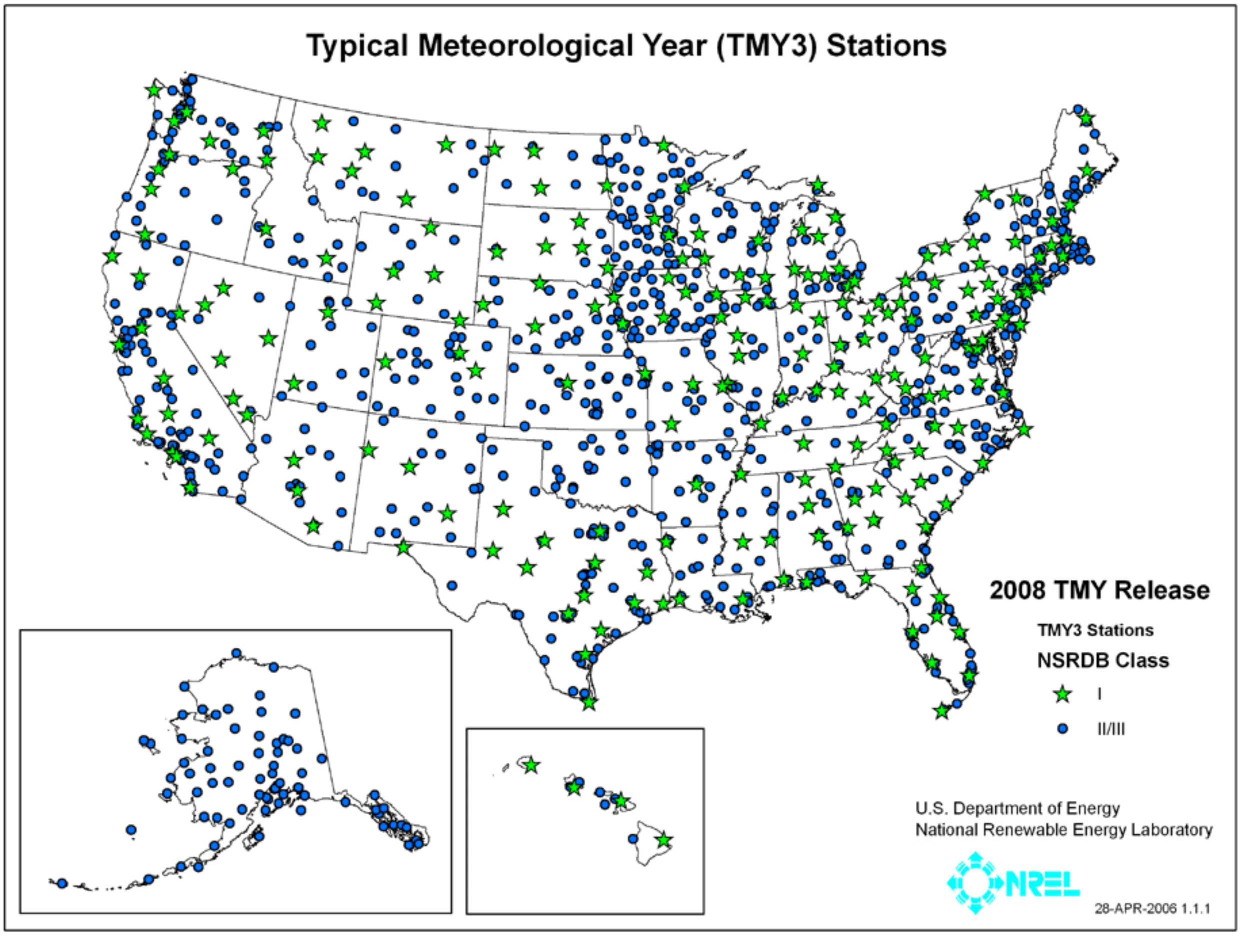
The *custom regions* shown are based on the 27 RECS reportable domains, aggregated into similar climates. Heating and cooling degree day values were used to remove samples from Alaska and Hawaii from the Pacific Northwest region and separate Kentucky from Mississippi and Alabama.

Climate Data

Simulations for individual buildings are often based on one of the 936 TMY3 data files for the continental United States (Figure 16).

[h] Custom regions 1 and 12 refer to Alaska and Hawaii, but to date NREL's analysis has focused on the continental United States because of small sample sizes for those states in RECS and other data sources.

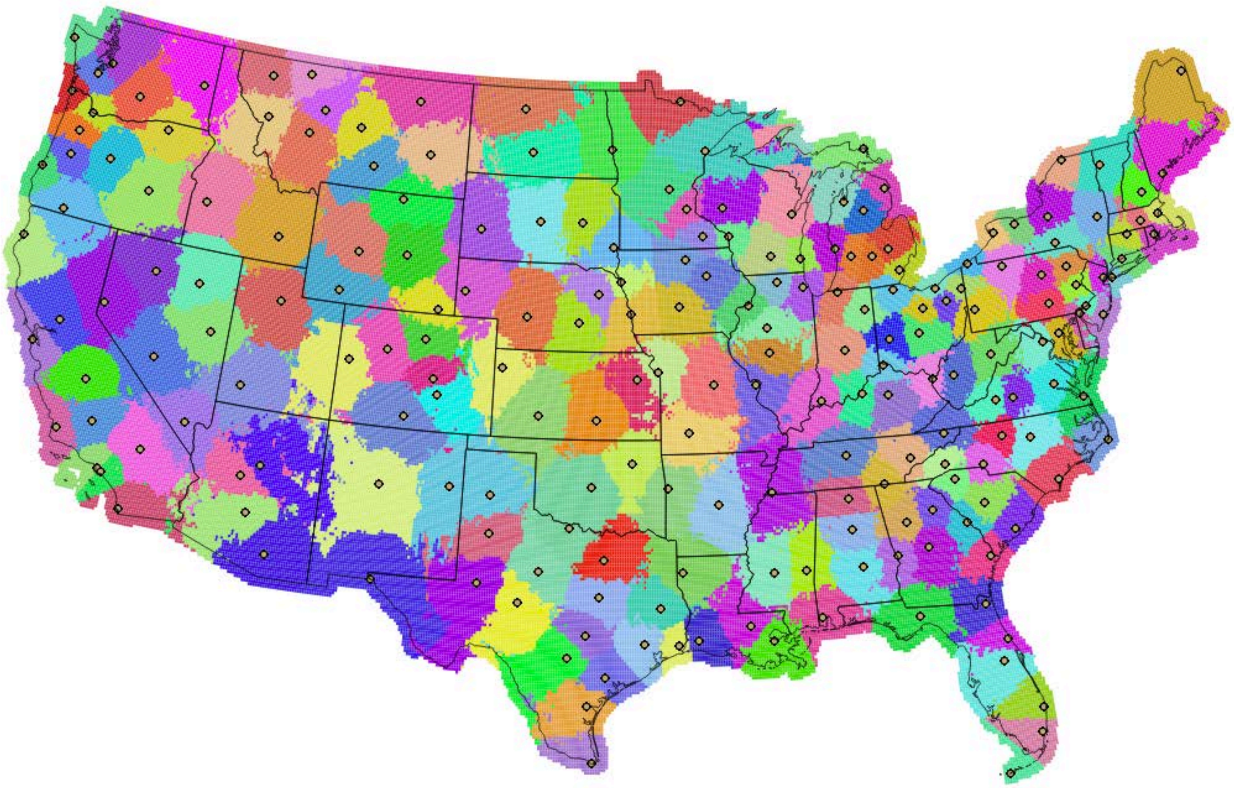
Figure 16. Locations of the typical meteorological year (version 3) stations in the United States



There are 936 TMY3 station locations in the continental U.S., but it was determined that a subset of 216 locations provides adequate resolution for ResStock simulations.

Building stock analysis requires climate data with sufficient granularity to cover the range of climatic conditions within the area of interest. For this national-scale analysis, we found that 936 locations would be superfluous and that using a subset of 216 locations provided sufficient granularity. Subregions for the 216 TMY3 locations have been developed based on data quality, proximity, and elevation (Figure 17). These subregions are aggregations of National Solar Radiation Data Base (NSRDB) gridcells (see Appendix B for methodology).

Figure 17. Subregions for 216 TMY3 locations

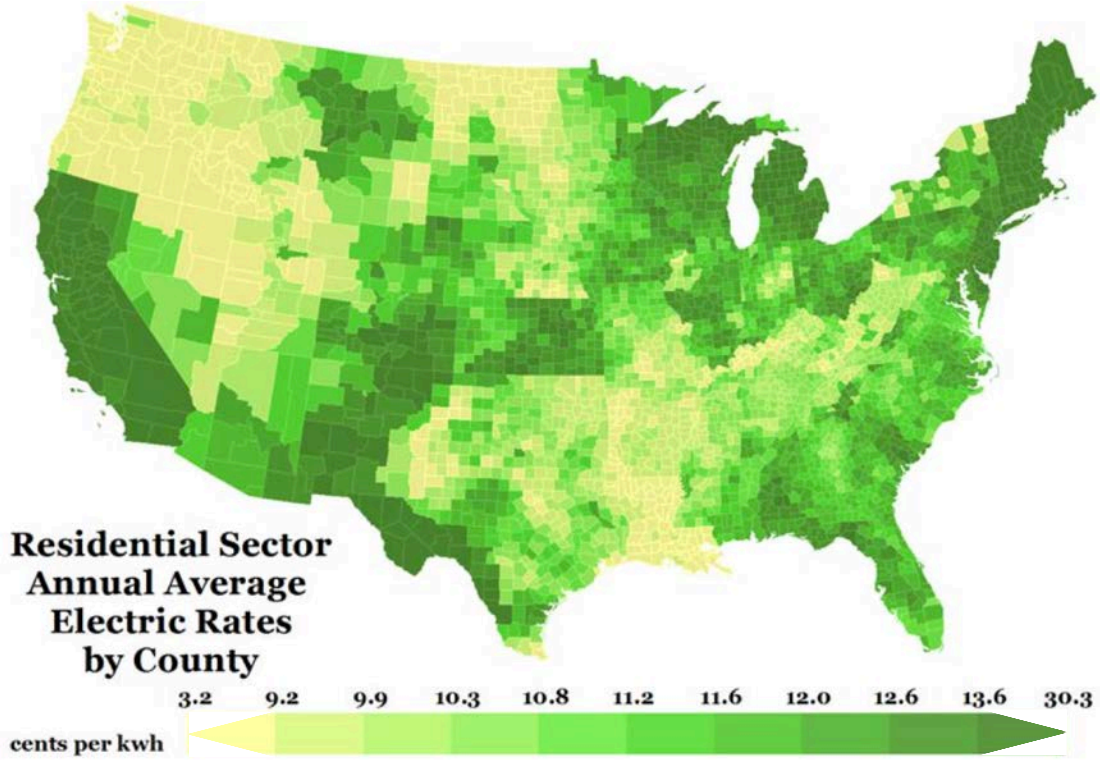


Subregions for the 216 TMY3 locations were developed based on data quality, proximity, and elevation. These subregions are aggregations of National Solar Radiation Data Base 10-kilometer gridcells.

Utility Rates

For this analysis, we used state average prices for natural gas, propane, and fuel oil, as provided in BEopt.[26] While average state electricity rates might sometimes be used for cost-effectiveness and economic potential calculations, we used utility-specific rates in this residential building stock analysis for higher geographic resolution. Utility-specific electricity prices were derived from residential sector revenue and sales for each utility in 2013, as reported on U.S. Energy Information Administration forms (shown by county in Figure 18). Future analysis could include additional utility-specific factors including rate structures, demand and/or time-of-use rates, and utility avoided costs (for Total Resource Cost calculations).

Figure 18. Residential annual average electricity rates by county (derived from revenue divided by sales)



Source: Sigrin et al. 2016

Average electricity rates by county (flat $/kWh estimates derived from revenue divided by sales) were used for the current analysis. Note that the first and last color scale bins are larger that the rest.

For this analysis, national site-to-source and carbon factors were used (Table 3).[27] Future analyses could incorporate regional site-to-source factors as well as carbon and other emission rates, using the U.S. Environmental Protection Agency's eGRID subregions.

Table 3. Site-to-Source Energy Multipliers and Carbon Factors[28]

Fuel	Site-to-Source Energy Multiplier	Carbon Emissions Factor (kg CO_2e/kWh)
Electricity	3.15	0.692
Natural Gas	1.09	0.219
Fuel Oil	1.19	0.307
Propane Gas	1.15	0.267

This table lists the national average site-to-source and carbon emissions factors used for this analysis.

2.3.5 *Occupant Behavior*

The Building America House Simulation Protocols (HSP) provide a set of standard operating conditions defining average occupant use levels and operating schedules to facilitate consistent analysis of residential buildings, similar to the miles per gallon rating for automobiles.[29] The protocols have been developed over the course of years, leveraging Building America research and input from many research organizations and industry partners.

For this analysis, it would not be appropriate to assume the same set of average or typical occupants defined by the HSP across all homes. To account for occupant diversity, ResStock uses a "usage level" archetype parameter. This usage level parameter is used to scale usage up and down from the HSP operating conditions, which in turn scale with conditioned floor area and number of bedrooms.[30] The scaling multiplier for each end use is shown in Table 4.

Table 4. Usage Level Scaling Multipliers

End Use	Low Usage	Medium Usage	High Usage
Cooking Range	80%	100%	120%
Dishwasher	80%	100%	120%
Clothes Washer	80%	100%	120%
Clothes Dryer	80%	100%	120%
Miscellaneous Electric Loads	50%	100%	200%
Hot Water Usage (sinks, showers, and baths)	50%	100%	200%

The usage level archetype parameter allows multiple end uses to be scaled at the same time, representing occupant behavior of different households.

Table 5 shows the distribution of low, medium, and high usage homes for this analysis. This distribution was found to provide a reasonable representation of the range in occupant usage seen in the validation against RECS energy consumption data.

Table 5. Distribution of Values for the Occupant Usage Level Archetype Parameter

Low Usage	Medium Usage	High Usage
25%	50%	25%

This distribution of low, medium, and high usage households was used to incorporate diversity in occupant behavior.

Thermostat Settings

Heating and cooling set points for this analysis were derived from RECS microdata.[31] We used heating and cooling set points that vary based on climate (regressions on heating and cooling degree days); this approach was found to provide a better validation against RECS consumption data than set points that do not vary based on climate. We considered a set point algorithm that included other variables, such as vintage of home (as a proxy for how quality of thermal enclosure affects comfort and therefore set point) or household energy costs, but these were not found to be significant drivers of set point in the RECS data.

The regressions were made on a weighted average of RECS variables for temperature when someone is home during the day, temperature when no one is home during the day, and temperature at night. The range of set points resulting from the regressions is shown in Table 6. The set points used for this analysis used a constant schedule.

Table 6. Range of Heating and Cooling Set Points Resulting from the Regressions

	Minimum: Florida 627 HDD_{65}[i]	**Median:** Washington 5467 HDD_{65}	**Maximum:** North Dakota 9148 HDD_{65}
Heating Set Point (constant)	69.5ºF	67.8ºF	66.4ºF
	Minimum: Washington 157 CDD_{65}[i]	**Median**: New Jersey 850 CDD_{65}	**Maximum**: Florida 3351 CDD_{65}
Cooling Set Point (constant)	71.9ºF	72.7ºF	75.6ºF

[i] HDD_{65} and CDD_{65} are the population-weighted heating and cooling degree days (base 65ºF) for the listed states. For the analysis, set points were determined for the 216 TMY weather file locations rather than the state averages presented here.

This analysis used heating and cooling set points based on regressions of RECS-reported set points against heating and cooling degree days.

2.4 Statistical Sampling

2.4.1 *Parameter Space*

Theoretically, a very large number of archetype variants exist, based on all possible combinations of characteristics. However, within this parameter space, archetype variants represent differing numbers of actual homes, depending on the product of the archetype probability and the component characteristic probabilities.

In fact, many cells in the parameter space will be essentially empty (i.e., many theoretical variants will represent no or a statistically insignificant number of actual homes). For example, the combination of "built in the 2000s in the Southwest, with a basement and oil heat" will represent few, if any, actual homes. Obviously, modeling such variants is unnecessary.

Even after eliminating zero house-count variants, the parameter space is potentially very large. Therefore, approaches to limiting the number of archetype variants to be simulated are considered.

2.4.2 *Selecting Archetype Variants*

We use a modified Latin hypercube sampling (LHS) approach to select archetype variants to be simulated. The approach is described and compared to alternatives below. Table 7 lists the alternatives.

Table 7. Alternative Sampling Approaches

Sampling Approach	Coverage of Archetype Variant Combinations
Entire Parameter Space	All theoretical combinations
Typical Prototype Houses	Typical combinations developed manually
Maximum House Count	Combinations with highest probability
Latin Hypercube Sampling	Combinations proportional to probability distributions

This table describes the sampling approach alternatives that were considered.

The first and second approaches bound the range of possibilities from using a great many simulations to using only a limited number. The third and fourth approaches use an intermediate (but perhaps, large by historical standards) number of simulations.

1. Entire parameter space—all theoretical archetype variants

    a. Define archetype variants (all possible combinations of characteristics)
    b. Simulate all archetype variants with non-zero house-count
    c. Multiply results by archetype variant house-count weighting factors.

2. Typical prototype houses—developed with expert knowledge

    a. Develop high house-count archetypes, paired with:
        i. Average house size
        ii. Typical foundation type
        iii. Typical component characteristics.
    b. Simulate prototype houses
    c. Multiply results by prototype house-count weighting factors.

3. Maximum house count—selected archetype variants based on weighting factors

    a. Define archetype variants (all possible combinations of characteristics)
    b. Calculate house-count weighting factors based on product of probabilities
    c. Simulate archetype variants with largest house-count weighting factors
    d. Multiply results by archetype variant house-count weighting factors
    e. Multiply results by factor to adjust for square footage of houses not simulated.

4. Latin Hypercube Sampling—selected archetype variants based on modified[i] LHS, with probability distributions and dependencies

[i] The described LHS approach differs from classical LHS in two ways:
a) the simplest form of LHS specifies that a variable value appears in only one sample, but here the mapping of probability distributions purposely leads to characteristic options appearing in multiple archetype variants; however, the described approach does preserve the LHS principle of sampling in ranges of equal probability
b) classical LHS does not include dependencies, and its elegant solution based on simply selecting each sample based on a row from a matrix of columns of randomized sample number depends on having non-correlated

a. Choose number of simulations, e.g., m = 350,000
b. Construct a matrix with m rows (samples) and n columns (archetype parameters and variant characteristics—ordered by dependencies):
    i. Populate each column with m sample #'s in random order
    ii. For each row
        1. For each column (from left to right), map current sample # to the corresponding building characteristic option according to the probability distribution from dependencies based on archetype characteristics in previous columns
        2. Repeat for next column *(when all columns for the row have been processed, the result is an archetype variant to be simulated).*
    iii. Repeat for the next row *(when all rows have been processed, the result is a complete set of archetype variants to be simulated).*
c. Simulate the LHS-selected archetype variants
d. Multiply by the single LHS house-count weighting factor (= total # of houses / # of simulations).

2.4.3 *Non-Correlated Variant Characteristics*

Beyond mutual dependence on archetype parameters, statistical data on relationships between variant characteristics (e.g., insulation levels, window type) are mostly lacking and, therefore, no direct dependencies are assumed. Archetype variant buildings are defined based on random combinations of these characteristics.

If further detailed data were available, additional archetype parameters could be developed where appropriate. For example, if relationships between insulation levels for different envelope building components (e.g., walls, attic/roof, foundation) beyond vintage dependencies were found, an archetype parameter that qualitatively describes the building envelope as well-insulated, moderately insulated, or poorly insulated could be developed with the aforementioned envelope building components dependent on it.

2.4.4 *Visualizing the Parameter Space*

The parameter space can be visualized as a hierarchal tree structure covering all possible combinations of building characteristics in archetypes and variants. The tree structure branches out (based on the number of options in each probability distribution) through archetype parameters (in order of dependencies) and then through uncorrelated variant characteristics.[j] Each path from trunk to twig represents a theoretical archetype variant. Thickness at any point depends on the cumulative product of probabilities to that point; at the end of the branch, the thickness represents the archetype variant weighting factor (or house count). The modeling approaches select simulations in the tree structure as follows:

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variables; the approach used in this analysis incorporates dependencies for each sample by remapping variables "on-the-fly" to sample number ranges based on previously selected values for precursor variables.

[j] Because there are no dependencies assumed among uncorrelated characteristics, the sequential ordering is arbitrary. The appearance of the tree structure changes, but the archetype variants and analysis results do not. For example, consider a case in which one characteristic has two options and a second characteristic has three options. Then, "two branches each with three twigs" and "three branches each with two twigs" both have same six combinations and cumulative weighting factors: (ax+ay+az)+(bx+by+bz)=(xa+xb)+(ya+yb)+(za+zb).

- Entire parameter space—all the paths
- Typical prototype houses—a few "typical" paths
- Maximum house count—paths with the thickest ends
- LHS—number of paths proportional to branch thicknesses.

2.4.5 ***Pros and Cons of Each Approach***

Entire Parameter Space

If granular data are used, the entire domain space includes a very large number of all possible combinations of characteristics (theoretical archetype variants). Even after eliminating combinations for which no actual homes exist (a computational challenge in itself), the domain space is too large to run detailed building energy simulations, even using high performance computing resources, and can even exceed the actual number of buildings being represented.

Typical Prototype Houses

Theoretically, a very simple, not very granular model with correct (perhaps calibrated) inputs could accurately reflect large-scale energy consumption, but would have limited utility for answering analysis questions. Historically, a limited number of "prototype" buildings have been used, often with each characteristic represented by a single typical, predominant, or average option rather than a probability distribution. The limited sensitivity of such models may impose limitations regarding the sort of analysis questions that can be accurately addressed (see section 2.2: Motivation for High Granularity).

Maximum House Count

Simulations are targeted to high house-count archetype variants, and energy results for those variants are multiplied by the associated house-count weighting factors. *Sampled archetype variants, selected to have the highest possible house counts, maximize the number of actual houses directly represented.* High-probability archetype parameters and characteristics are overrepresented while low-probability archetype parameters and characteristics are underrepresented.

Latin Hypercube Sampling

Simulations are distributed across a wide variety of archetype variants according to archetype and variant characteristic probabilities. The house count that would be directly associated with each simulated archetype variant is not used as a weighting factor, because each simulated archetype variant also indirectly represents additional (similar) archetype variants (not simulated). For each characteristic, an option is randomly selected from equally probable options. Therefore, each simulated archetype variant has equal probability and the same weighting factor (= total # of houses / # of simulations).

The LHS approach naturally includes simulations for many archetype variants with high direct house counts resulting from high probabilities for some variant characteristics and combinations thereof, but does not focus exclusively on such variants (as the maximum house-count approach does). Some archetype variants with lower direct house counts are included to match the overall probability distributions. Sampled archetype variants represent fewer actual houses directly than the maximum house-count approach does, but are designed to statistically represent the entire housing stock as accurately as possible for a given number of simulations.

Summary of Approaches

For a highly dimensional space, such as the U.S. residential building stock:

- Entire parameter space—number of simulations prohibitive
- Typical prototype houses—granularity may be insufficient for answering many analysis questions
- Maximum house count—overrepresents high probability building characteristics
- LHS—complex, but best represents characteristics of the overall housing stock.

Therefore, the LHS approach, with probability distributions and dependencies, is used for the ResStock methodology.

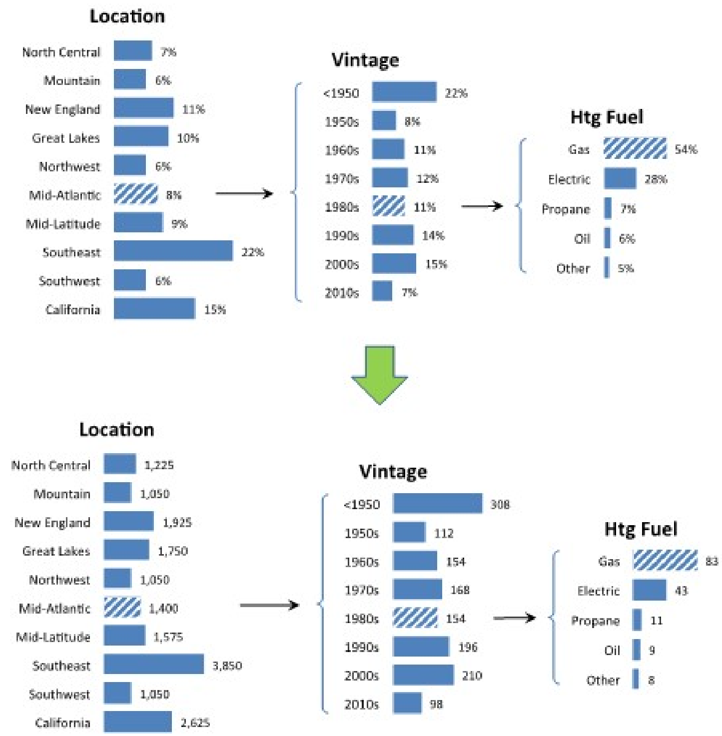
2.4.6 Number of Simulations

The Motivation for High Granularity section above describes benefits of granularity and also includes some qualitative comments on the degree of granularity needed. The total number of simulations needed often depends on the analysis question(s) to be answered. In general, the larger the number of simulations the better the coverage of the domain space and the better the accuracy and sensitivity of the model. If the total number of simulations is insufficient, the number of simulations available after applying dependencies may be insufficient to accurately reflect the probability distributions for some characteristics.

In the LHS approach, the sampling process attempts to run simulations such that probability distributions are preserved. Therefore, the simulation distributions should match the input probability distributions as closely as possible (Figure 19) for archetype parameters.

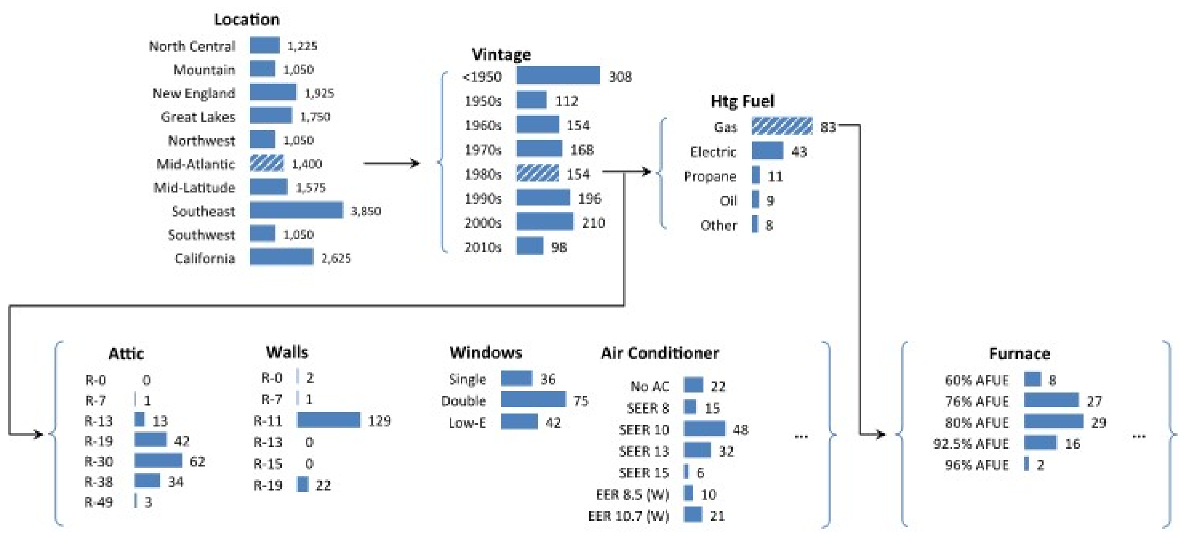
The multiple simulations associated with an archetype (i.e., 83 simulations for the example archetype) are used to create simulation distributions (Figure 20) that best match the variant characteristic probability distributions (as seen in Figure 8).

Figure 19. Archetype simulation[k] distributions based on probability distributions



With Latin hypercube sampling, simulations are allocated based on the probability distributions.

Figure 20. Archetype simulations to variant characteristic simulations



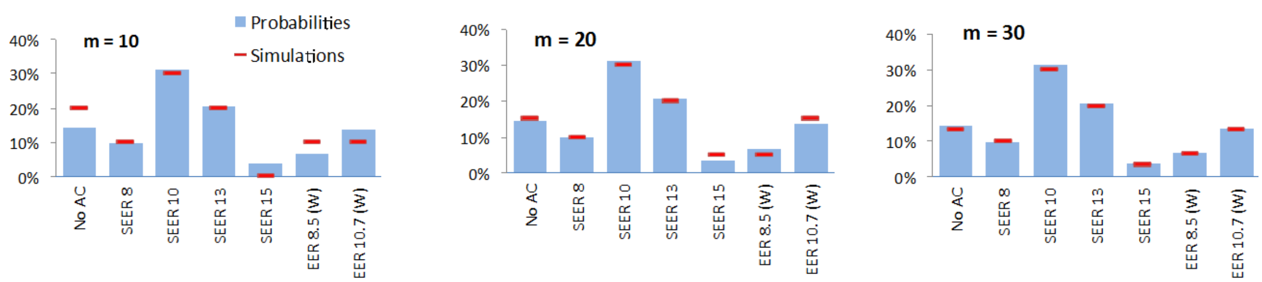
In the Latin hypercube sampling approach, the 154 simulations for the "Mid-Atlantic, 1980s" archetypes are allocated to the attic, walls, windows, and air conditioner values as shown. Similarly, the 83 "Mid-Atlantic, 1980s, Gas" archetypes are allocated to the furnace efficiency values as shown.

[k] These examples assume 350,000 total simulations with ~20 TMYs per location (region). Therefore, 17,500 simulations are available for the location distribution at the start of the LHS approach.

As is seen in the previous figures, as an archetype specification becomes further defined (moving from left to right) the number of available simulations attributed to the archetype decreases.[1] Using a finite number of simulations to match a probability distribution can lead to resolution problems. With 10 simulations, for example, simulation-based probabilities are to the nearest 10%; with 20 simulations, to the nearest 5%, with 30 simulations, to the nearest 3.3% (as seen on Figure 21a, b, and c, respectively).

For options with small probabilities (as can occur especially in distributions with many options), limited resolution can lead to some non-zero options with no simulations (see seasonal energy efficiency ratio [SEER] 15 in Figure 21a) and other options with simulations that nearly double the appropriate probability (see energy efficiency ratio [EER] 8.5 in Figure 21a).

Figure 21. Air-conditioner simulation distributions versus probability distributions: a) 10 simulations, b) 20 simulations, and c) 30 simulations



The probability distribution for air conditioners is represented accurately with 30 simulations; however, with 10 simulations, several of the bins are over or under represented.

For the example archetype, which has 83 simulations available for representing the variant characteristics, the resolution is more than adequate. If the archetype had electric heat (43 available simulations) the resolution would still be adequate. For propane heat (11 available simulations) or oil heat (9 available simulations), the resolution would be poor for variant characteristic categories such as ACs that include low-probability options.

The risk of inadequate resolution and significant (percentage) discrepancies is highest for low-probability options within low-probability archetypes. Such cases are typically associated with relatively low house counts. However, if key to an analysis (for example, part of the target for a particular retrofit), such situations can be important. As an alternative to increasing the total number of simulations, one possibility is to focus the analysis on part of the domain space and a number of simulations that is proportionately higher.

Convergence Testing

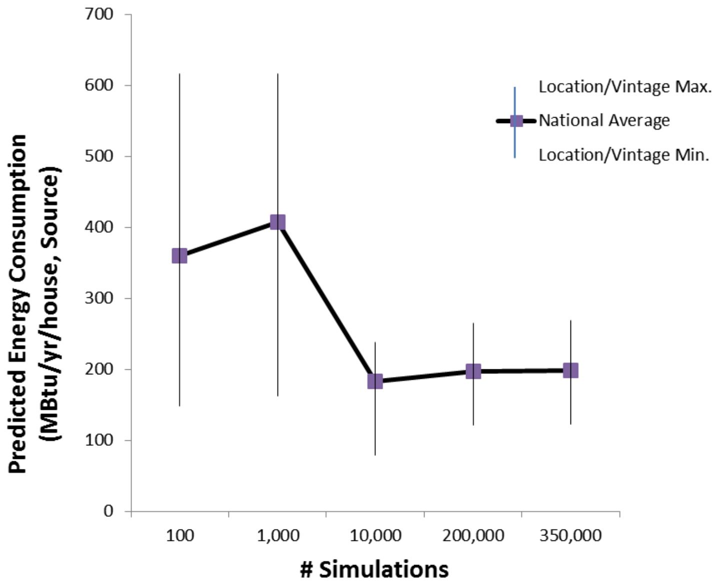
The overall impact of the choice of the total number of simulations is difficult to accurately predict because the effect of using fewer simulations is to introduce discrepancies at specific points in the results space. An alternative to prediction is to monitor outputs of interest as

[1] Moving left to right Figure 19 and Figure 20, the numbers of simulations decrease, because the hierarchical tree is dividing into a growing number of increasingly thin branches—with one path shown. Beyond the path shown, location simulations are split off to cover multiple, not-shown vintages, and vintage simulations are split off to cover multiple not-shown heating fuel types.

additional simulations are run, looking for convergence toward a stable result by tracking the minimum, maximum, and average results. This approach has the advantage of finding the appropriate number of simulations depending on the specifics of different analyses.

Figure 22 shows an example of convergence testing for baseline energy consumption; convergence can be tested for prediction of energy savings as well. Figure 22 suggests that 200,000 simulations may be sufficient for simulation of the U.S. housing stock, but more qualitative testing of geospatial maps led us to choose a more conservative 350,000 simulations for the current analysis.

Figure 22. Convergence testing



This figure shows that predicted source energy consumption converges around 200,000 simulations, for both the national average and the maximum and minimum of the location/vintage bin averages (of which there are 70). However, qualitative testing of geospatial maps led us to choose the more conservative 350,000 simulations for this analysis.

2.5 Baseline Building Simulations

The ResStock workflow involves running detailed subhourly building energy simulations for each of the statistically sampled archetype variant buildings. For this analysis, 350,000 archetype variant buildings are defined to ensure sufficient coverage of the housing stock. After the building descriptions have been sampled from the housing stock parameter space, simulation input files for each are automatically generated. Simulation input files are also generated for archetype variant buildings with upgrades applied, adding up to 350,000 additional simulations for each efficiency upgrade.

2.5.1 *Geometry Algorithm*

ResStock uses an algorithm for automatically determining building geometry based on the home's conditioned floor area, number of stories, foundation type, and whether or not there is an attached garage. The full algorithm is provided in Appendix A.

There are five house size bins (one of the archetype parameters) used for ResStock analysis. The geometry characteristics—floor area, number of bedrooms and bathrooms—for each house size bin are listed in Table 8 (shading indicates the values used for analysis). The floor area and number of bedrooms (a proxy for number of occupants) are used as inputs for all occupant behavior-related models (hot water, lighting, appliance, and miscellaneous electric load usage). The number of bathrooms is used along with number of bedrooms to determine water heater storage volumes, based on the Building America HSP.[32]

The values in Table 8 are derived from queries of RECS 2009 microdata[33] and rounded for use in ResStock. The value queried for conditioned floor area was the maximum of the heated floor area and the cooled floor area for each RECS household.

Table 8. Geometry Characteristics for the House Size Bins Used in ResStock

House Size Bin	Average Conditioned Floor Area (RECS) [ft²]	N_{occ}, Average Number of Occupants (RECS)	N_{baths}, Average Number of Bathrooms (RECS)	N_{beds}, Number of Bedrooms Based on N_{occ}[i]	ResStock Floor Area,[ii] Rounded [ft²]	ResStock N_{beds},[ii] Rounded	ResStock N_{baths},[ii] Rounded
0–1499	1,122	2.5	1.6	2.8	1,000	3.0	1.5
1500–2499	1,941	2.8	2.0	3.3	2,000	3.0	2.0
2500–3499	2,935	3.0	2.4	3.6	3,000	4.0	2.5
3500–4499	3,914	3.1	2.8	3.8	4,000	4.0	3.0
4500+	5,858	3.5	3.5	4.4	5,860	4.0	3.5

[i] The number of bedrooms for each house size bin was derived from the number of occupants using $N_{occ} = 0.59 \times N_{beds} + 0.87$, which is derived from RECS.[34]
[ii] Shading indicates values used for analysis

This table summarizes the floor area, numbers of bedrooms (as an indicator of occupancy), and number of bathrooms for each of the house size bins used for the simulations in this analysis.

2.5.2 *Batch Simulation*

ResStock leverages the BEopt software's open architecture batch simulation capabilities to generate input files for the EnergyPlus™ simulation engine and run these simulations on high-performance computing resources.[35] [m] EnergyPlus is DOE's flagship whole building energy simulation engine used by engineers, architects, and researchers to model energy consumption in buildings. EnergyPlus is funded by the DOE's Building Technologies Office and developed in collaboration with NREL, other national laboratories, academic institutions, and private firms.[36] EnergyPlus version 8.4 was used for the simulations conducted for this analysis.

The batch simulations leverage many of the residential component models and algorithms developed for BEopt over its 10+ years of development. These models and algorithms take high-level inputs used to describe residential buildings/technologies and convert them into appropriate sets of EnergyPlus inputs.

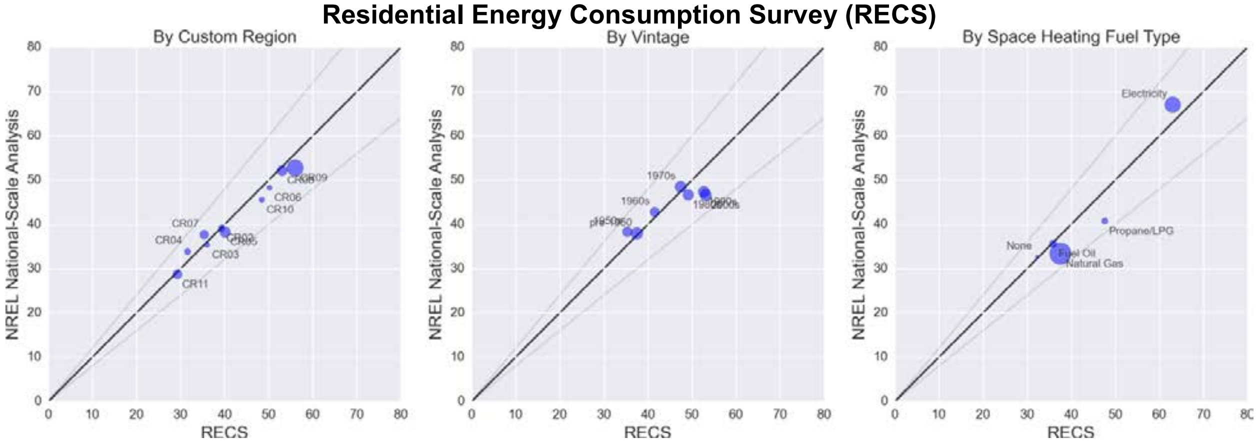
[m] A description of BEopt's open architecture batch simulation modeling framework can be found in the BEopt help file: https://beopt.nrel.gov/sites/beopt.nrel.gov/files/help/Modeling_Framework.htm

2.6 Validation

For simulation of individual buildings, validation addresses accuracy of inputs, algorithms, and software implementation. For large-scale analysis, there are also issues related to archetype definitions, house counts, and dependencies. For large-scale analysis, validation involves comparing aggregated model predictions to reference data. RECS 2009 consumption values were used as the reference data for this analysis.[37]

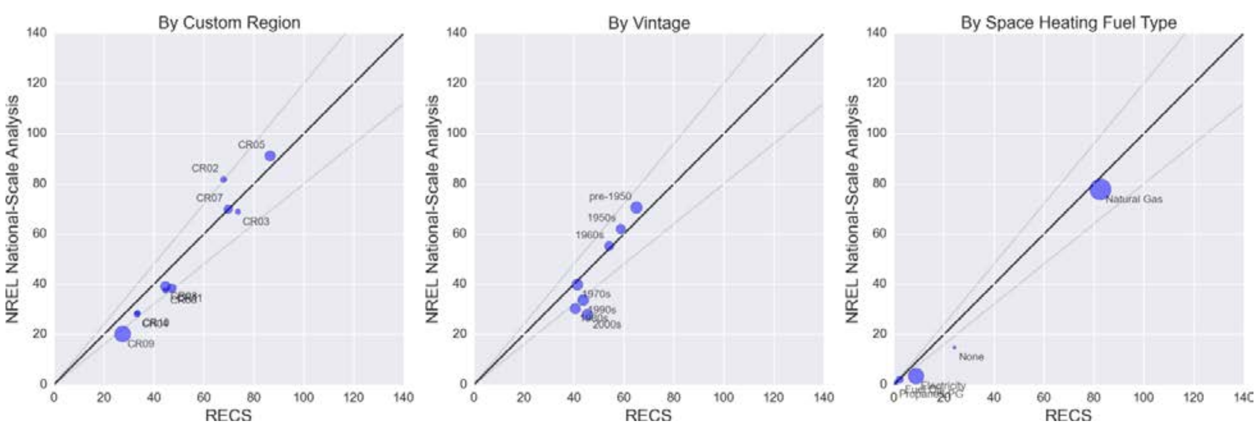
The most basic validation is based on comparison of results aggregated at the highest level (e.g., national level). Comparisons of results at lower levels of aggregation (sliced by different archetype parameters, for example), as shown in Figure 23 through Figure 26, can reveal the accuracy of the model under different circumstances and provide an indication of the model's likely usefulness for answering a range of analysis questions. In these figures, the size of the circle indicates the relative number of homes in the slice of data. The validation figures show the results after the input calibration process described below.

Figure 23. Electricity consumption (source energy per house: 10^6 Btu/year) modeled versus Residential Energy Consumption Survey (RECS)



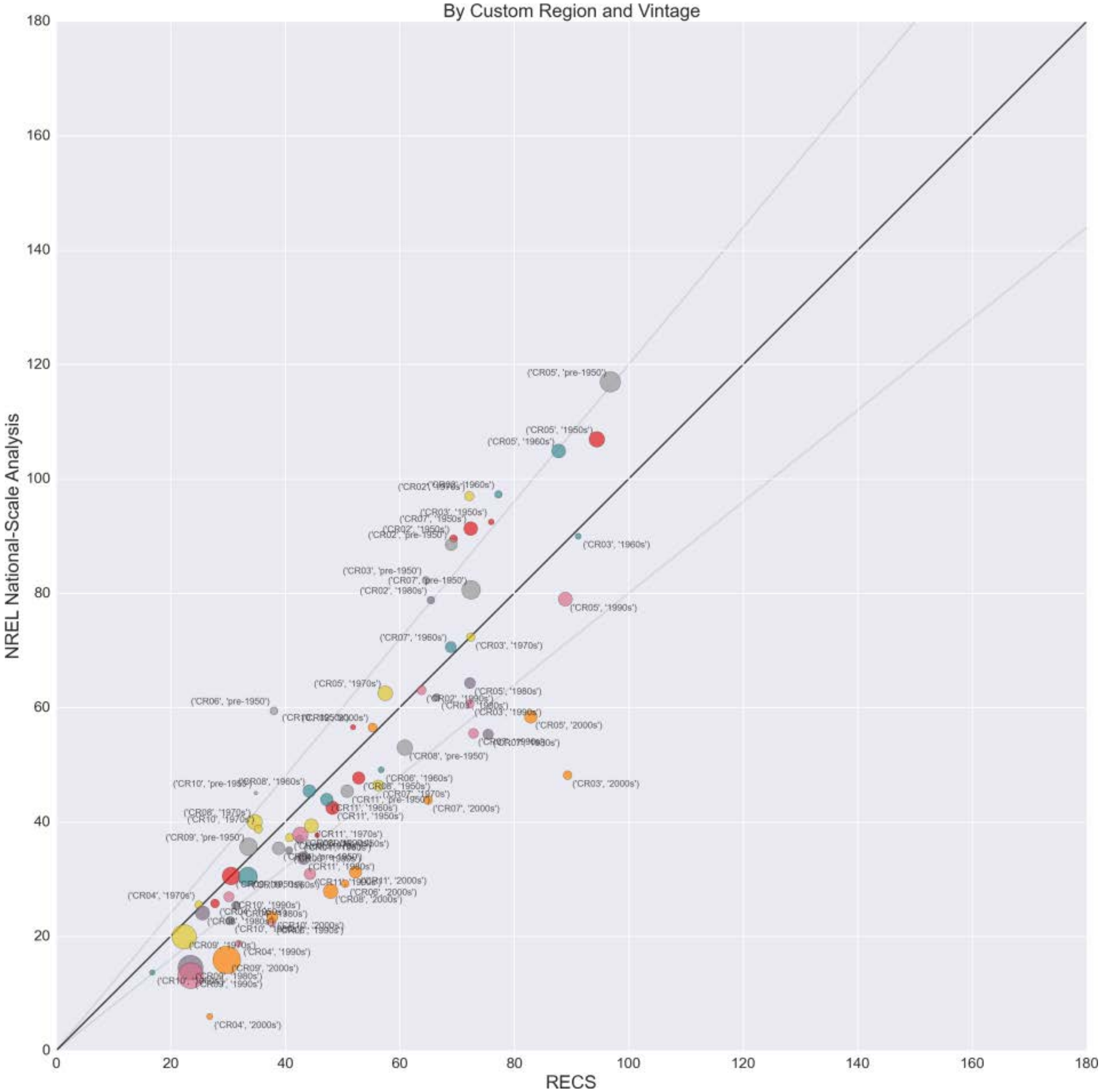
Modeled average electricity consumption for different aggregations of the housing stock is compared against corresponding values from RECS. The marker area indicates the aggregated number of homes.

Figure 24. Gas consumption (source energy per house: 10^6 Btu/year) modeled versus Residential Energy Consumption Survey (RECS)



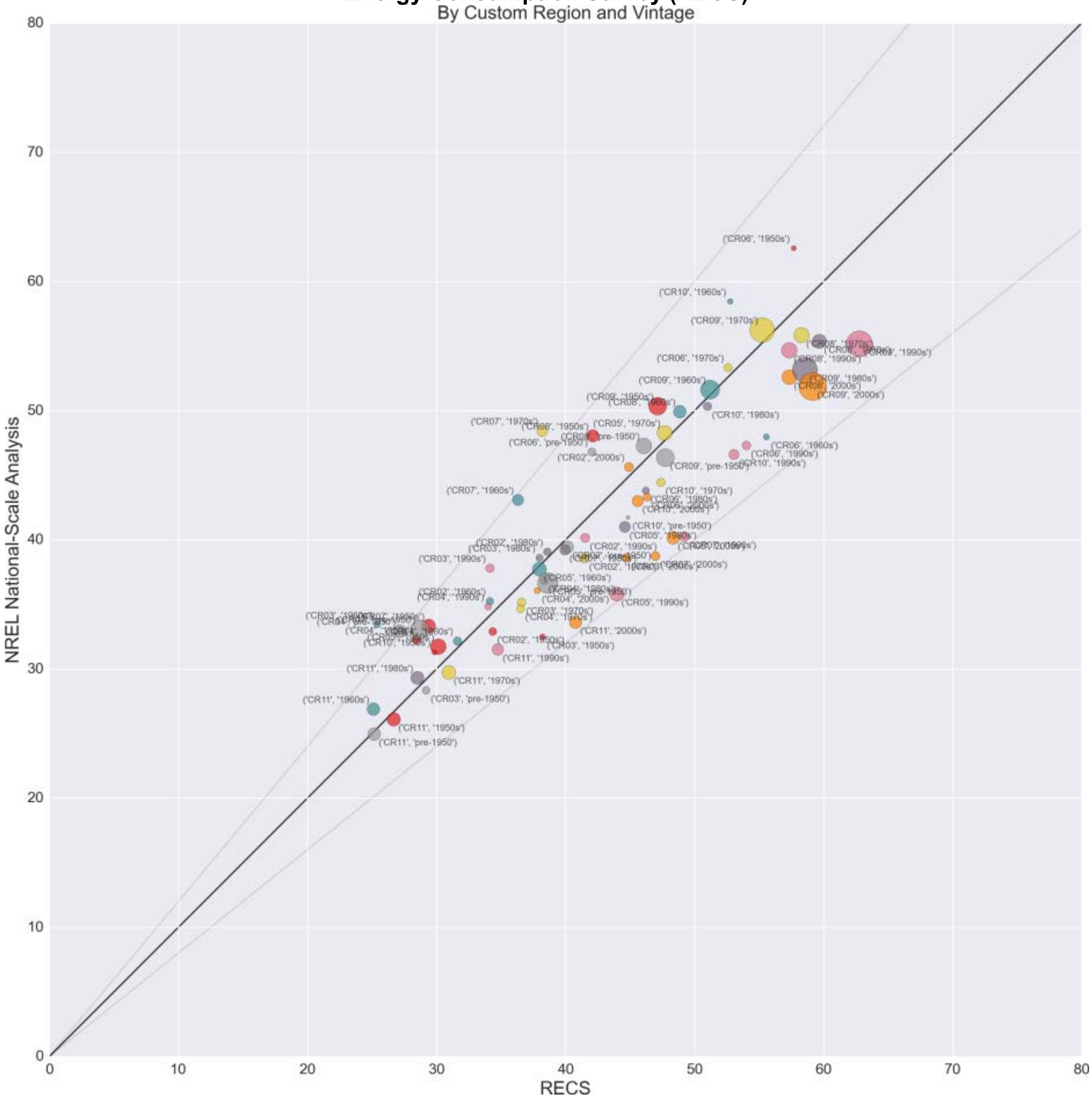
Modeled average natural gas consumption for different aggregations of the housing stock is compared against corresponding values from RECS. The marker area indicates the aggregated number of homes.

Figure 25. Electricity consumption (source energy per house: 10^6 Btu/year) modeled versus Residential Energy Consumption Survey (RECS)



Modeled average electricity consumption for the 70 combinations of region and vintage is compared against corresponding values from RECS. The marker area indicates the aggregated number of homes. The grey lines indicate plus or minus 20%, which was used as a rough indicator for validation.

Figure 26. Gas consumption (source energy per house: 10^6 Btu/year) modeled versus Residential Energy Consumption Survey (RECS)



Modeled average natural gas consumption for the 70 combinations of region and vintage is compared against corresponding values from RECS. The marker area indicates the aggregated number of homes. The grey lines indicate plus or minus 20%, which was used as a rough indicator of satisfactory validation.

2.6.1 *Calibration*

Beyond the physical characteristics captured in archetype variants, various occupant and operational factors are known to significantly affect building energy use. Simulations rely on assumed values[38]; actual field values are not well known. Similarly, it is not well known how they vary with archetype parameters such as location and vintage. Such uncertainties may be a significant cause of lack of agreement between model results and reference data.

Input Calibration

The validation/calibration process included 12 rounds of modifications to model inputs in order to bring predicted consumption more in agreement with the reference consumption. Examples of changes made during this process include: adding new data sources for probability distributions, changing dependencies for variant characteristic probability distributions, changing probability distribution bins, and reducing the number of TMY weather locations (to allow additional granularity in other areas).

Output Calibration

Output calibration factors can be applied to true up results to better match the reference data. Output calibration may, in fact, be adjusting for a "multitude of sins" in the model, and it is not clear to what degree the resulting calibrated model correctly preserves sensitivities for particular analysis questions. Therefore, output calibration is a last resort. A model that validates well with minimum calibration is preferable. ResStock does not currently include output calibration.

2.7 Efficiency Upgrade Simulations

More than 50 efficiency upgrades were defined for application to the baseline housing stock. Each upgrade involves rules that apply the upgrade to an appropriate subset of the 350,000 simulations, with development of EnergyPlus models, corresponding models for *reference scenarios*[n], and definition of incremental costs for the upgrade and reference scenarios in each modeled home.

This section provides detailed descriptions of the upgrades evaluated for this analysis. Each efficiency upgrade has been assigned a "short name" that is used as shorthand to refer to the scenario throughout this report and associated graphical reports. Table 9 and Table 10 list the short name and longer description for each upgrade, along with the reference for each.

While this report is focused on electric end uses, several upgrades addressing natural gas, propane, and oil use were included in the larger analysis. Descriptions of those upgrades are documented here for reference.

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[n] *Reference scenario* is used to refer to the business-as-usual point of comparison for upgrade scenarios. For some upgrades, such as insulation upgrades, the reference is the existing condition. For other upgrades, such as equipment upgraded at wear out, the reference is the current federal standard.

Table 9. Thermal Enclosure Upgrades

Short name	Long name	Reference
Air sealing	Air sealing - 25% reduction in ACH_{50}[i]	Baseline (do nothing)
R-38 Attic Ins.	Add R-38 blown-in cellulose or fiberglass to attic floor	Baseline (do nothing)
R-49 Attic Ins.	Add R-49 blown-in cellulose or fiberglass to attic floor	Baseline (do nothing)
R-60 Attic Ins.	Add R-60 blown-in cellulose or fiberglass to attic floor	Baseline (do nothing)
R-10 Bsmt Walls (Finished)	Add R-10 interior XPS[ii] (whole wall height) to walls and rim joists of finished basement	Baseline (do nothing)
R-10 Bsmt Walls (Unfinished)	Add R-10 interior XPS (whole wall height) to walls and rim joists of unfinished basement	Baseline (do nothing)
R-10 Crawlspace Walls	Add R-10 interior XPS (whole wall height) to walls and rim joists of crawlspace	Baseline (do nothing)
Drill-and-Fill	Add cellulose or fiberglass cavity insulation to uninsulated wood frame walls	Baseline (do nothing)
R-5 Wall Sheathing	Add 1" (R-5) insulated sheathing at siding wear out	Baseline (do nothing)
Low-E Storm 1	Install low-e storm window on single-pane windows	Baseline (do nothing)
Low-E Storm 2	Install low-e storm window on double-pane windows	Baseline (do nothing)

[i]air changes per hour at 50 pascals pressure difference between indoors and outdoors
[ii]extruded polystyrene

This table describes the thermal enclosure upgrades included in the analysis.

Table 10. Equipment Upgrades

Short Name	Long Name	Reference
ENERGY STAR Room AC (EER 12)	Replace room (window) AC with ENERGY STAR® (EER 12) at wear out (assume 50% conditioning)	EER 9.8 (50% cond.)
SEER 16 Central AC	Upgrade central AC to SEER 16 (single-stage) at wear out	Fed. min. (SEER 14/13)
SEER 18 Central AC	Upgrade central AC to SEER 18 (two-stage) at wear out	Fed. min. (SEER 14/13)
Duct Sealing	Seal and insulate ducts located in unconditioned space	Baseline (do nothing)
DHP[i] (displaces electric baseboard) (60%)	Displace electric baseboard with DHP (SEER 27, HSPF[ii] 11.5) (60% displacement)	Baseline (do nothing)
DHP (replaces gas boiler at wear out) (60%)	Replace boiler with DHP (SEER 27, HSPF 11.5) at wear out—natural gas (60% displacement)	Fed. min. (82% AFUE)
DHP (replaces gas boiler today) (60%)	Replace boiler with DHP (SEER 27, HSPF 11.5) today—natural gas (60% displacement)	Baseline (do nothing)
DHP (replaces oil boiler at wear out) (60%)	Replace boiler with DHP (SEER 27, HSPF 11.5) at wear out—fuel oil (60% displacement)	Fed. min. (85% AFUE)
DHP (replaces oil boiler today) (60%)	Replace boiler with DHP (SEER 27, HSPF 11.5) today—fuel oil (60% displacement)	Baseline (do nothing)
DHP (replaces propane boiler at wear out) (60%)	Replace boiler with DHP (SEER 27, HSPF 11.5) at wear out—propane (60% displacement)	Fed. min. (82% AFUE)
DHP (replaces propane boiler today) (60%)	Replace boiler with DHP (SEER 27, HSPF 11.5) today—propane (60% displacement)	Baseline (do nothing)
ENERGY STAR Boiler—Gas	Upgrade boiler to ENERGY STAR (96% AFUE) at wear out—natural gas	Fed. min. (82% AFUE)
ENERGY STAR Boiler—Oil	Upgrade boiler to ENERGY STAR (96% AFUE) at wear out—fuel oil	Fed. min. (85% AFUE)
ENERGY STAR Boiler—Propane	Upgrade boiler to ENERGY STAR (96% AFUE) at wear out—propane	Fed. min. (82% AFUE)
ENERGY STAR Furnace—Gas	Upgrade furnace to ENERGY STAR (96% AFUE) at wear out—natural gas	Fed. min. (80% AFUE)
ENERGY STAR Furnace—Oil	Upgrade furnace to ENERGY STAR (96% AFUE) at wear out—fuel oil	Fed. min. (80% AFUE)
ENERGY STAR Furnace—Propane	Upgrade furnace to ENERGY STAR (96% AFUE) at wear out—propane	Fed. min. (80% AFUE)
Replace Gas Furnace with VSHP[iii]	Replace furnace with SEER 22 HSPF 10 VSHP at wear out—natural gas	Fed. min. (80% AFUE)
Replace Oil Furnace with VSHP	Replace furnace with SEER 22 HSPF 10 VSHP at wear out—fuel oil	Fed. min. (80% AFUE)

Short Name	Long Name	Reference
Replace Propane Furnace with VSHP	Replace furnace with SEER 22 HSPF 10 VSHP at wear out—propane	Fed. min. (80% AFUE)
Upgrade Elec Furn to VSHP at wear out	Upgrade electric furnace to SEER 22 HSPF 10 VSHP at wear out	Fed. min. (100% AFUE Elec. Furnace)
Upgrade Central ASHP to VSHP	Upgrade conventional heat pump to SEER 22 HSPF 10 VSHP at wear out (sized for max. of heating/cooling)	Fed. min. (HSPF 7.7)
Smart Thermostat (home during day)	Install smart thermostat (in homes that don't currently use programmed thermostats)—weekday daytime occupancy	Baseline (do nothing)
Smart Thermostat (not home during day)	Install smart thermostat (in homes that don't currently use programmed thermostats)—no weekday daytime occupancy	Baseline (do nothing)
Replace Oil WH[iv] with HPWH (50 gal)	Replace fuel water heater (≤50 gal) with electric HPWH (50 gal) at wear out—oil	Fed. min. (EF[v] 0.62)
Replace Oil WH with HPWH (80 gal)	Replace fuel water heater (≤50 gal) with electric HPWH (80 gal) at wear out—oil	Fed. min. (EF 0.62)
Replace Propane WH with HPWH (50 gal)	Replace fuel water heater (≤55 gal) with electric HPWH (50 gal) at wear out—propane	Fed. min. (EF 0.62)
Replace Propane WH with HPWH (80 gal)	Replace fuel water heater (≤55 gal) with electric HPWH (80 gal) at wear out—propane	Fed. min. (EF 0.82)
Upgrade Electric WH to HPWH (50 gal)	Upgrade electric water heater (≤55 gal) to HPWH (50 gal) at wear out	Fed. min. (EF 0.95)
Upgrade Electric WH to HPWH (80 gal)	Upgrade electric water heater (≤55 gal) to HPWH (80 gal) at wear out	Fed. min. (EF 0.95)
Upgrade WH to EF 0.67—Gas	Upgrade water heater (≤55 gal) to premium power vent unit (EF 0.67) at wear out—natural gas	Fed. min. (EF 0.62)
Upgrade WH to EF 0.67—Propane	Upgrade water heater (≤55 gal) to premium power vent unit (EF 0.67) at wear out—propane	Fed. min. (EF 0.62)
Upgrade WH to EF 0.68—Oil	Upgrade water heater (≤50 gal) to premium power vent unit (EF 0.68) at wear out—oil	Fed. min. (EF 0.62)
Upgrade WH to EF 0.82 (tank)—Gas	Upgrade water heater (≤55 gal) to condensing unit (EF 0.82) at wear out—natural gas	Fed. min. (EF 0.62)
Upgrade WH to EF 0.82 (tank)—Propane	Upgrade water heater (≤55 gal) to condensing unit (EF 0.82) at wear out—propane	Fed. min. (EF 0.62)
Upgrade WH to EF 0.82 (tankless)—Gas	Upgrade water heater (≤55 gal) to tankless unit (EF 0.82) at wear out—natural gas	Fed. min. (EF 0.62)
Upgrade WH to EF 0.82 (tankless)—Propane	Upgrade water heater (≤55 gal) to tankless unit (EF 0.82) at wear out—propane	Fed. min. (EF 0.62)
ENERGY STAR Clothes Washers	Upgrade clothes washer to ENERGY STAR at wear out	Fed. min.
ENERGY STAR Dishwashers	Upgrade dishwasher to ENERGY STAR at wear out	Fed. min.
ENERGY STAR Refrigerators	Upgrade refrigerator to ENERGY STAR at wear out	Fed. min.
LEDs[vi]	Replace 95% of lamps with LED (80 lumens per watt)	Baseline (do nothing)

[i]ductless heat pump
[ii]heating seasonal performance factor
[iii]variable-speed heat pump
[iv]water heater
[v]energy factor
[vi]light-emitting diode

This table describes the thermal enclosure upgrades included in the analysis.

2.7.1 *Reference Scenarios*

Each efficiency upgrade has an associated reference scenario, which is used to define the incremental cost and energy savings of the upgrade. For upgrades related to the thermal enclosure and lighting, the reference is the "do nothing" case that is equivalent to the baseline of existing housing stock. For equipment and appliance upgrades, the reference is usually the federal minimum standard currently in place. The reference for each upgrade is listed in Table 9 and Table 10.

2.7.2 *Upgrade Cost Data*

Each efficiency upgrade has an incremental cost, which is defined as the initial cost of the upgrade relative to the reference scenario. The incremental cost includes all material, labor, and overhead costs paid by the building owner or whoever is paying for the upgrade. Unless otherwise noted in Section 2.7.3, the incremental costs for each upgrade and reference scenario are sourced from the National Residential Efficiency Measures Database,[39] which is primarily based on cost data collected, organized, and processed by Navigant Consulting, Inc. under subcontract to NREL.[40]

2.7.3 *Detailed Upgrade Descriptions and Assumptions*

This section provides details about each efficiency upgrade, including a description of the reference case. A link is provided for upgrades with relevant content in the Building America Solution Center.[41]

2.7.3.1 Thermal Enclosure Upgrades

Air Sealing

This upgrade achieves a 25% reduction in building enclosure infiltration, as measured by a blower door test in units of air changes per hour at 50 pascals (ACH_{50}). For improvements resulting in measured infiltration of less than 7.0 ACH_{50} (maximum allowed by the 2009 International Energy Conservation Code; roughly equivalent to 0.35 natural ACH), mechanical ventilation in the form of a bathroom exhaust fan operating continuously with flow rate specified by ASHRAE Standard 62.2-2010 is added to maintain indoor air quality. The air-sealing upgrade applies to essentially all homes.

The value of 25% reduction was chosen based on a large-scale analysis of 23,000 before and after retrofit leakage measurements that found air sealing typically achieved a reduction in the 20%–30% range, with a median reduction of 25%.[42] A 25% reduction was also used for a savings analysis for the "Seal and Insulate with ENERGY STAR®" program.[43] Reductions of more than 25% are certainly possible, but they may require more aggressive air-sealing upgrades that are uncommon or involve other enclosure upgrades, such as R-5 wall sheathing insulation.

Other upgrades, such as window and insulation retrofits, can also reduce air infiltration. These reductions are not included in this analysis.

Building America Solution Center link:
https://basc.pnnl.gov/search/air sealing guide

Attic Insulation

R-38 Attic Insulation, R-49 Attic Insulation, R-60 Attic Insulation

These three upgrades bring the R-value of attic floor insulation up to R-38, R-49, or R-60, respectively. Blown-in fiberglass and blown-in cellulose insulation have similar costs and performance, so a distinction is not made for this analysis.

Blown-in attic insulation only applies to vented attics, not finished attics or cathedral ceilings. As a simplification to keep the number of geometry parameters manageable, the housing stock characterization model did not differentiate between attic/ceiling types (though these data exist in RECS). Therefore, all representative homes were simulated with vented attics. To account for the fraction of homes without a vented attic, the results from these attic insulation upgrades were post-processed to remove a fraction of the upgrades in accordance with the percentages shown in Table 11.

Building America Solution Center link:
https://basc.pnnl.gov/resource-guides/blown-insulation-existing-vented-attic

Table 11. Percentage of Homes Without a Vented Attic as a Function of Region and Vintage[i]

	Vintage							
Custom Region	pre-1950	1950s	1960s	1970s	1980s	1990s	2000s	Regional Average
2	9%	12%	7%	13%	24%	49%	32%	21%
3	5%	2%	8%	27%	46%	24%	52%	24%
4	18%	8%	17%	14%	40%	33%	40%	24%
5	13%	5%	8%	14%	41%	54%	46%	26%
6	8%	29%	16%	20%	27%	65%	55%	32%
7	18%	17%	18%	18%	32%	29%	54%	27%
8	13%	17%	7%	10%	25%	39%	51%	23%
9	8%	8%	11%	16%	27%	37%	40%	21%
10	12%	0%	7%	14%	40%	57%	26%	22%
11	13%	11%	15%	36%	47%	53%	50%	32%
Vintage Average	10%	9%	13%	16%	36%	41%	42%	24%

[i] red shading indicates the heatmap value in each cell

Homes built since 1980 less likely to have a vented attic suitable for attic floor insulation, due to presence of vaulted/cathedral ceilings and finished attics. Therefore, these vintages have less potential for traditional attic floor insulation upgrades.

Foundation Insulation

R-10 Basement Walls (Finished), R-10 Basement Walls (Unfinished), R-10 Crawlspace Walls

These three foundation insulation upgrades add R-10 (2 in.) of rigid extruded polystyrene foam to the interior side of foundation walls and rim joists in finished basements, unfinished basements, and crawlspaces. For this analysis, we assume that finished basements are heated and cooled, whereas unfinished basements are not directly heated or cooled.

While fiberglass batt insulation is sometimes used to insulate foundation walls, rigid foam board is considered best practice due to its superior durability when exposed to water.

Building America Solution Center link:
https://basc.pnnl.gov/resource-guides/unvented-crawlspaces-and-conditioned-basements

Exterior Walls

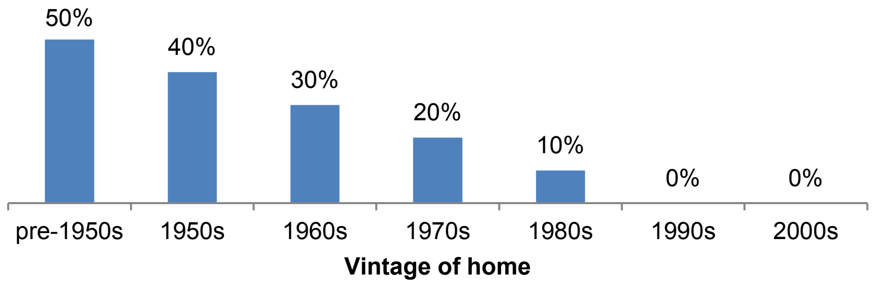
Drill-and-Fill

This upgrade involves adding densely packed cellulose or fiberglass insulation to existing wood-framed wall cavities that are empty. Holes for adding insulation are drilled in each wall cavity (every 16 inches). This can be done from the outside, when it is convenient to remove a row of siding, or from the inside, which requires patching the holes made in the drywall or plaster.

R-5 Wall Sheathing

This upgrade involves adding R-5 of rigid foam sheathing (e.g., 1-in. rigid extruded polystyrene foam) or an R-5 insulated siding product at the time of residing. Thus, the cost of this upgrade only includes the additional material and labor costs associated with the insulation; the removal of old siding and installation of new siding is not included. The results of this analysis assume a siding replacement rate as shown in Figure 27, based on engineering judgment. This assumption could be improved with actual siding replacement rate data.

Figure 27. Percentage of existing siding replaced over a 30-year period



Lacking good data on siding replacement rates, this analysis assumed that 10% of homes built in the 1980s would replace their siding in the next 30 years, increasing by 10% for each decade up to 50% of homes built before 1950.

Building America Solution Center links:
https://basc.pnnl.gov/resource-guides/continuous-rigid-insulation-sheathingsiding
https://basc.pnnl.gov/resource-guides/rigid-foam-insulation-existing-exterior-walls

Windows

Low-E Storm (single-pane primary), Low-E Storm 2 (double-pane primary)

These two upgrades install low-E storm windows on single-pane primary windows or double-pane primary windows, respectively. The before and after window properties used to evaluate the upgrades are shown in Table 12 and sourced from the National Residential Efficiency Measures Database[44] and a Pacific Northwest National Laboratory report.[45]

Table 12. Window Properties with and without the Addition of Low-E Storm Windows

Primary Window Type	U-value	SHGC	U-value w/Storm	SHGC w/Storm
Single-Pane, Clear, Metal Frame	1.16	0.76	0.69	0.59
Single-Pane, Clear, Non-Metal Frame	0.84	0.63	0.40	0.48
Double-Pane, Clear, Metal Frame	0.76	0.67	0.38	0.51
Double-Pane, Clear, Non-Metal Frame	0.49	0.56	0.29	0.42

This table documents the window properties used to evaluate the low-e storm window upgrades.

Two cost scenarios were considered: homeowner self-installation was assumed to cost \$8.30/ft^2 and installation by a professional was assumed to cost \$13.00/ft^2 (assuming 10 ft^2 per window).[46 47]

Building America Solution Center link:
https://basc.pnnl.gov/resource-guides/low-e-exterior-storm-windows

2.7.3.2 Equipment Upgrades

Cooling

SEER 16 Central Air Conditioner, SEER 18 Central Air Conditioner

These two upgrades involve installing a new central AC with a SEER rating of 16 or 18 upon failure of the existing AC. The reference for these upgrades is the current federal standard for central ACs, which is SEER 14 in southern states and SEER 13 in northern states.[o] The SEER 16 unit uses a single-stage compressor and the SEER 18 unit uses a two-stage compressor. These upgrades were not applied to homes that use heat pumps for space heating.

Both the upgrade and reference replacement AC capacities are sized in accordance with ANSI/ACCA Manuals J and S.[48 49]

Building America Solution Center link:
https://basc.pnnl.gov/resource-guides/compression-cooling

ENERGY STAR Room Air Conditioner (EER 12)

This upgrade involves replacing a room (window) AC with an ENERGY STAR unit upon failure. ENERGY STAR requirements vary based on capacity and whether or not the unit has louvered sides, but an EER 12 unit was used to represent ENERGY STAR-level performance for this analysis. The reference for this upgrade is the federal minimum standard, which varies, but EER 10.7 was used for this analysis. Data from the 2009 RECS indicate that the majority of homes that use room ACs for cooling do not condition the entire home; for these homes, it is assumed that only 50% of the finished floor area is cooled. Both the upgrade and reference replacement room AC capacities and number of units were determined in accordance with ANSI/ACCA Manual J.[50]

The National Residential Efficiency Measures Database does not have cost range estimates for EER 12 room ACs, so an incremental cost of \$10/(kBtu/h) was assumed (a \$60–\$120 premium for typical room AC sizes).

Building America Solution Center link:
https://basc.pnnl.gov/resource-guides/compression-cooling

[o] The states that have SEER 14 as the federal standard are: Alabama, Arkansas, Delaware, Florida, Georgia, Hawaii, Kentucky, Louisiana, Maryland, Mississippi, North Carolina, Oklahoma, South Carolina, Tennessee, Texas, Virginia, District of Columbia, Arizona, California, Nevada, and New Mexico.

Ducts

Duct Sealing

This upgrade involves sealing and insulating any HVAC supply and return ductwork that is outside of conditioned space. For this analysis, *duct leakage* is defined as the fraction of air handler fan flow rate that leaks out of pressurized supply ducts into unconditioned space, plus the fraction of fan flow rate that leaks into depressurized return ducts from unconditioned space, plus any leakage into or out of the air handler itself (all measured at 25 pascals pressure difference).

The Building Performance Institute, which sets quality assurance and technical standards for home performance professionals, recommends 10% as the maximum allowable duct leakage.[51] The Lawrence Berkeley National Laboratory's "Best Practices Guide for Residential HVAC Retrofits" also recommends a target duct leakage of less than 10% of air handler flow for duct sealing retrofits.[52] Thus, 10% was used as the post-retrofit duct leakage value for this analysis.

This upgrade also includes adding R-8 insulation to any uninsulated ducts located in unconditioned space. Ducts with existing insulation (typically R-4, R-6, or R-8) do not have any insulation added.

Duct location is a key parameter for this efficiency upgrade because there is not a great benefit to sealing or insulating ducts located in conditioned space, which are often inaccessible. Duct and air handler location are not fields available from RECS, so we infer it from foundation type. Based on the Building America HSP, homes with slab foundations have their ducts in the attic, homes with crawlspaces have their ducts in the crawlspaces, and homes with basements have their ducts in basements (conditioned or unconditioned).[53] Homes with two or more stories are assumed to have 35% of their supply ducts within conditioned space. Supply and return duct surface area is also specified as a function of finished floor area and number of stories.[54]

There is a lack of good data on the range of duct leakage in existing homes, but one field study found an average of 21% leakage.[55] For this analysis, we used a distribution as shown in Table 13. This distribution of leakage bins was based on a normal distribution centered at 20% leakage with a standard deviation of 8% leakage.[56]

Table 13. Distribution of Duct Leakage Values

Percentage of Air Handler Flow	10% Leakage	20% Leakage	30% Leakage
Percentage of All Homes with Ducts in Unconditioned Space	26%	47%	27%

This table documents the distribution of duct leakage values used in this analysis; three bins were used to represent a normal distribution centered at 20% with a standard deviation of 8% leakage.[57]

Building America Solution Center link:
https://basc.pnnl.gov/search/duct sealing

Heating

ENERGY STAR Furnace (Gas, Propane, Oil)

These three upgrades involve installing a new high-efficiency condensing furnace upon failure of the existing gas, propane, or oil furnace. ENERGY STAR requires 95% annual fuel utilization efficiency (AFUE) for gas/propane furnaces in northern states and 90% AFUE for gas/propane furnaces in southern states[p] and only 85% for oil furnaces in all states.[58] However, this analysis uses 96% AFUE for all furnace upgrades because the majority of ENERGY STAR gas/propane furnaces are in the 95%–96% AFUE range and because condensing 96% AFUE oil furnaces are indeed available.

The reference for these upgrades is based on the current federal standard for furnaces: 80% for gas/propane and 82% for oil.[59] [60] Both the upgrade and reference replacement furnace capacities are sized in accordance with ANSI/ACCA Manuals J and S.[61] [62]

Building America Solution Center link:
https://basc.pnnl.gov/resource-guides/combustion-furnaces

Upgrade Electric Furnace to Variable-Speed Heat Pump

This upgrade involves installing a new high-efficiency variable-speed heat pump (VSHP) (SEER 22, HSPF 10) upon failure of the existing centrally ducted electric furnace. This inverter-driven heat pump is representative of ducted VSHPs currently on the market. It meets the Northeast Energy Efficiency Partnerships' (NEEP's) "Cold Climate Air-Source Heat Pump Specification,"[63] so it can be considered a cold climate heat pump (CCHP). However, unlike some newer ducted CCHPs, the representative unit does not retain heat pump capacity at temperatures below 0ºF, so the scenario includes an electric resistance coil for backup heat in parts of the United States with winter temperatures reaching near or below 0ºF.[q] [64] [65] [66]

The reference for this upgrade is installation of an electric furnace identical to the existing one (100% AFUE). Both the heat pump and reference replacement furnace capacities are sized in accordance with ANSI/ACCA Manuals J and S,[67] [68] except that the heat pump is sized based on the larger of the heating or cooling loads ("cold climate sizing") rather than the cooling load priority specified by Manual S.

Heat pumps provide both heating and cooling, so this upgrade provides cooling energy savings in addition to the heating energy savings. This is especially significant because electric furnaces are most prevalent in hot climates. This upgrade could alternatively be triggered by failure of a home's AC, in which case the economics would be similar or better. We considered an alternative scenario using a less efficient (and less expensive) heat pump instead of the high-efficiency heat pump described here, but that scenario provided lower economic potential in almost all regions (using both NPV>0 and SPP<5 thresholds).

[p] Alabama, American Samoa, Arizona, Arkansas, California, Delaware, District of Columbia, Florida, Georgia, Guam, Hawaii, Kentucky, Louisiana, Maryland, Mississippi, Nevada, New Mexico, North Carolina, Oklahoma, Puerto Rico, South Carolina, Tennessee, Texas, and Virginia.

[q] Centrally ducted "very cold climate heat pumps" designed to continue operating at outdoor temperatures below 0ºF (and down to -13ºF or lower) are currently available from at least one manufacturer. One manufacturer has such a heat pump with a traditional air handler form factor suitable for drop-in retrofits. Several manufacturers have very cold climate mini-split heat pumps with compact horizontal air handlers designed for short-run ducts only, which would not be suitable for drop-in retrofits. The performance goals for CCHP research supported by the DOE Building Technologies Office also target this "very cold climate" category (See endnotes 64, 65, and 66).

Upgrade Central Air-Source Heat Pump to Variable-Speed Heat Pump

This upgrade involves installing a new high-efficiency VSHP (SEER 22, HSPF 10) upon failure of the existing centrally ducted air-source heat pump. This inverter-driven heat pump is representative of ducted VSHPs currently on the market. It meets NEEP's "Cold Climate Air-Source Heat Pump Specification,"[69] so it can be considered a CCHP. However, unlike some newer ducted CCHPs, the representative unit does not retain heat pump capacity at temperatures below 0ºF, so the scenario includes an electric resistance coil for backup heat in parts of the United States with winter temperatures reaching near or below 0ºF.

The reference for this upgrade is based on the current federal standard for heat pumps (SEER 14, HSPF 8.2), and also includes a backup electric resistance coil. The heat pump and backup coil capacities are sized in accordance with ANSI/ACCA Manuals J and S,[70] [71] except that the heat pump is sized based on the larger of the heating or cooling loads ("cold climate sizing") rather than the cooling load priority specified by Manual S.

Heat pumps provide both heating and cooling, so this upgrade provides cooling energy savings in addition to the heating energy savings.

Replace Gas/Propane/Oil Furnace with Variable-Speed Heat Pump

These upgrades involve installing a new high-efficiency VSHP (SEER 22, HSPF 10) upon failure of the existing centrally ducted gas, propane, or oil furnace. This inverter-driven heat pump is representative of ducted VSHPs currently on the market. It meets NEEP's "Cold Climate Air-Source Heat Pump Specification,"[72] so it can be considered a CCHP. However, unlike some newer ducted CCHPs, the representative unit does not retain heat pump capacity at temperatures below 0ºF, so the scenario includes an electric resistance coil for backup heat in parts of the United States with winter temperatures reaching near or below 0ºF. An alternative would be to retain the existing fuel-fired furnace for backup heat, but that scenario is not considered in this analysis.

The reference for these upgrades is based on the current federal standard for furnaces: 80% for gas/propane and 82% for oil.[73] [74] Both the heat pump and reference replacement furnace capacities are sized in accordance with ANSI/ACCA Manuals J and S,[75] [76] except that the heat pump is sized based on the larger of the heating or cooling loads ("cold climate sizing") rather than the cooling load priority specified by Manual S.

Heat pumps provide both heating and cooling, so these upgrades provide cooling energy savings in addition to the heating energy savings. The upgrades could alternatively be triggered by failure of a home's AC, in which case the economics would be similar or better.

ENERGY STAR Boiler (Gas, Propane, Oil)

These three upgrades involve installing a new high-efficiency condensing hot water boiler upon failure of the existing gas, propane, or oil hot water boiler. ENERGY STAR requires 90% annual fuel utilization efficiency (AFUE) for gas/propane and oil boilers.[77] However, this analysis uses 96% AFUE for all furnace upgrades because the majority of ENERGY STAR gas/propane boilers are in the 95%–96% AFUE range, and because condensing 96% AFUE oil boilers are indeed available. These upgrades are only applied to hot water boilers; condensing steam boilers are not available and conversion from steam to hot water distribution is expensive.

The reference for these upgrades is based on the current federal standard for hot water boilers: 82% for gas/propane and 84% for oil.[78] Both the upgrade and reference replacement boiler capacities are sized in accordance with ANSI/ACCA Manuals J and S.[79] [80]

Building America Solution Center link:
https://basc.pnnl.gov/resource-guides/gas-fired-boilers

Ductless Heat Pump (displace electric baseboard today)

This upgrade involves installing one or more high-efficiency ductless heat pumps (DHPs) in homes heated with electric baseboards. DHPs are a subset of mini-split heat pumps that use a wall-, floor-, or ceiling-mounted indoor unit to distribute heated and cooled air. Thus they are applicable to homes without existing duct systems. The unit used for this analysis has one of the highest efficiencies on the market: SEER 27 and HSPF 11.5. It meets NEEP's "Cold Climate Air-Source Heat Pump Specification,"[81] so it can be considered a CCHP. The modeled unit retains heat pump capacity at temperatures down to -15ºF, so it could also be classified as a "very cold climate heat pump."

DHP installations typically have one or two indoor units per story rather than one or more baseboards, radiators, or supply duct registers in every room. Thus it is common to supplement the "point-source" heat they provide with another heat source. For this scenario, the existing electric baseboards are left in place to provide this supplemental heat. The baseboards are also used during hours of the year when the heating load exceeds the DHP heating capacity.

Field studies using this "displacement" model suggest that DHPs typically cover 70%–80% of the heating load .[82] [83] Other studies have used values ranging from 60%–80% displacement of the heating load.[84] [85] In practice, the amount of displacement is highly dependent on occupant behavior and control strategy (set point of supplement heat relative to DHP, doors left open or closed, insulating value of the thermal enclosure, comfort preferences, etc.). A conservative value of 60% load displacement was used for this analysis.

Because this upgrade happens *today* instead of *at wear out*, the reference is to make no change. The heat pump is sized in accordance with ANSI/ACCA Manuals J and S,[86] [87]except that the heat pump is sized based on the larger of the heating or cooling loads ("cold climate sizing") rather than the cooling load priority specified by Manual S.

Heat pumps provide both heating and cooling, so this upgrade provides cooling energy savings in homes that already have cooling (room ACs or, less commonly, central AC). In homes that did not have cooling equipment previously, this upgrade causes an increase in electricity consumption.

Building America Solution Center link:
https://basc.pnnl.gov/resource-guides/mini-split-ductless-heat-pumps

Ductless Heat Pump (replace gas/propane/oil boiler at wear out)

These upgrades involve installing one or more high-efficiency ductless heat pumps (DHPs) in homes heated with gas, propane, or oil boilers, upon wear out of the boiler. The DHP specifications and displacement assumptions are identical to those used for the "Ductless Heat Pump (displace electric baseboard today)" scenario described above.

For this scenario, the existing boiler is removed and electric resistance heaters are installed in each room to provide supplemental heat. One could consider the scenario of leaving an existing functional boiler in place to provide the supplemental heat, but that scenario was not included in this analysis.

The reference for these upgrades is based on the current federal standard for hot water boilers: 82% for gas/propane and 84% for oil.[88] Both the upgrade and reference replacement boiler capacities are sized in accordance with ANSI/ACCA Manuals J and S,[89] [90] except that the heat pump is sized based on the larger of the heating or cooling loads ("cold climate sizing") rather than the cooling load priority specified by Manual S.

Heat pumps provide both heating and cooling, so these upgrades provide cooling energy savings in homes that already have cooling (room ACs or less commonly central AC). In homes that did not have cooling equipment previously, the upgrades cause an increase in electricity consumption.

Building America Solution Center link:
https://basc.pnnl.gov/resource-guides/mini-split-ductless-heat-pumps

Thermostat

Smart Thermostat

This upgrade involves installing a smart thermostat to control a home's central heating and/or cooling system. Chapter 5 of the American Council for an Energy-Efficient Economy *New Horizons* report provides a detailed description of smart thermostat technology and a summary of findings related to energy savings.[91] That report estimated heating and cooling energy savings from smart thermostats to be in the 8%–15% range, with 12% being the midrange estimate.

With a smart thermostat, the primary energy-saving mechanism is reducing heating set points and increasing cooling set points during times when occupants are away or sleeping. This is comparable to how programmable thermostats save energy, but the set point changes are automatic and do not rely on the occupant to program the thermostat and consistently use the programmed schedule.

For this analysis, smart thermostats were modeled in a way analogous to programmable thermostats rather than attempting to model the specific control algorithms of one or more brands of smart thermostat and the associated occupant behavior patterns that would drive those control algorithms.

A study of 1,420 customers who installed one brand of smart thermostat found that the average nighttime setback was around 4ºF.[92] With this in mind, a 4ºF thermostat setback in heating mode and a 4ºF thermostat setup in cooling mode was used to model the smart thermostat in the subhourly building energy simulations. The schedule for these thermostat changes is shown in Table 14 and varies based on whether or not there is an occupant home during the day on weekdays, which was accounted for in the analysis. The base thermostat set points are as described in section 2.3.5 Occupant Behavior.

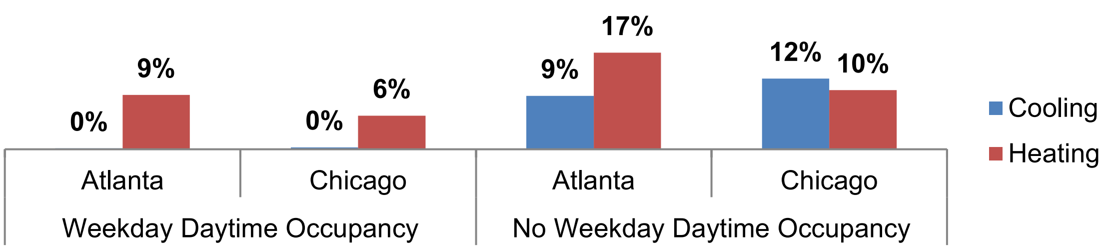
Table 14. Thermostat Setup and Setback Schedule for Modeling Smart Thermostats

Weekday Daytime Occupancy?		Weekday Daytime (9 a.m.–5 p.m.)	Nighttime (11 p.m.–6 a.m.)
Yes	Heating	-	-4ºF
	Cooling	-	-
No	Heating	-4ºF	-4ºF
	Cooling	+4ºF	-

Smart thermostats were assumed to decrease heating set points by 4ºF when occupants are sleeping (11 p.m.–6 a.m. everyday) or are not at home (9 a.m.–5 p.m. weekdays for a subset of households). Cooling set points are assumed to increase 4ºF only when occupants are not home.

We confirmed that this degree of setback/setup resulted in a similar range of heating and cooling energy savings as observed in field studies.[93] Figure 28 shows heating and cooling energy savings resulting from these modeling assumptions for sample homes in Atlanta and Chicago. While these assumptions do not exactly represent how smart thermostats work and the full diversity of occupant behavior, the model provides a reasonable estimate of smart thermostat savings and the sensitivity of those savings to climate and building characteristics.

Figure 28. Heating and cooling energy savings resulting from smart thermostat model assumptions for sample homes in Atlanta and Chicago



The assumed degree of thermostat setback/setup resulted in a similar range of heating and cooling energy savings as observed in field studies.[94]

This upgrade applies only to homes with central heating or cooling systems, including furnaces, boilers, central ACs, and central heat pumps. Of those homes, we removed 25% to account for the fraction of homes that have programmable thermostats and consistently use them, according to a query of 2009 RECS microdata.[95] Of the remaining homes, 60% were assigned weekday daytime occupancy and 40% were assigned no weekday daytime occupancy, based on 2009 RECS microdata.[96]

Smart thermostat costs were not available in the National Residential Efficiency Measures Database, so an installed cost of $300 ($250 material and $50 labor) was assumed.

Water Heating

Upgrade Water Heater to Energy Factor 0.67—Gas/Propane

This upgrade involves installing a mid-level efficiency gas/propane storage tank water heater with an energy factor (EF) of 0.67 (ENERGY STAR) upon failure of an existing gas/propane storage tank water heater. “Power-vent” type water heaters—characterized by a fan that vents combustion exhaust instead of relying on a natural draft—are representative of this mid-level efficiency class.

This upgrade was applied to storage water heaters with a rated storage volume ≤55 gallons (96% of residential gas storage water heaters) because the federal standard for larger water heaters exceeds EF 0.67. The distribution of water heater sizes was derived from the national impact analysis for the federal residential water heater final rulemaking.[97] The small number of larger (>55-gallon) water heaters were assumed to all be installed in the largest bin of house sizes, as shown in Table 15.

Table 15. Assumed Distribution of Gas/Propane Storage Tank Water Heater Sizes

Home Finished Floor Area (ft^2)	≤55 Gallons	>55 Gallons
0–1499	100%	0%
1500–2499	100%	0%
2500–3499	100%	0%
3500–4499	100%	0%
4500+	28%	72%
Overall	96.1%	3.9%

The percentage of gas/propane storage tank water heaters that are larger than 55 gallons was obtained from the national impact analysis for the federal residential water heater final rulemaking.[98] It was assumed that these are correlated with larger home floor areas.

The reference for this upgrade is based on the current federal standard for residential water heaters ≤55 gallons, which varies based on storage volume, but is approximately EF 0.62 for a 40-gallon tank.[99] Within the “≤55-gallon” category, the water heater storage volume and burner capacity are assigned based on Table 8 in the Building America HSP.[100]

Upgrade Water Heater to Energy Factor 0.68—Oil

This upgrade involves installing a mid-level efficiency oil storage tank water heater with an EF of 0.68 upon failure of an existing oil storage tank water heater. “Power-vent” type water heaters—characterized by a fan that vents combustion exhaust—are representative of this mid-level efficiency class. This upgrade was applied to all storage tank volumes because the federal standard for oil water heater efficiency is less than 0.68 EF for all tank sizes.

The reference for this upgrade is based on the current federal standard for residential oil water heaters, which varies slightly based on storage volume, but is approximately EF 0.60 for a 40-gallon tank.[101] The water heater storage volume and burner capacity are assigned based on the number of bedrooms and bathrooms, as specified in Table 8 of the Building America HSP.[102]

Upgrade Water Heater to Energy Factor 0.82 Tank—Gas/Propane

This upgrade involves installing a high-efficiency gas/propane storage tank water heater with an EF of 0.82 upon failure of an existing gas/propane storage tank water heater. This efficiency class is represented by "condensing" water heaters that extract additional heat from the combustion gases (90+% combustion efficiency).

This upgrade was applied to storage water heaters with a rated storage volume ≤ 55 gallons (96% of residential gas storage water heaters) because the federal standard requires that larger water heaters be condensing. The distribution of water heater sizes was as described above and listed in Table 15.

The reference for this upgrade is the same as for "Upgrade Water Heater to Energy Factor 0.67—Gas/Propane."

Upgrade Water Heater to Energy Factor 0.82 (Tankless)—Gas/Propane

This upgrade involves installing a high-efficiency gas/propane non-condensing tankless water heater with an EF of 0.82 upon failure of an existing gas/propane storage tank water heater. Condensing tankless water heaters were not included in this analysis because field studies have found that their installed performance is only about 3% better than the performance of non-condensing tankless water heaters.[103]

This upgrade was applied to storage water heaters with a rated storage volume ≤55 gallons (96% of residential gas storage water heaters). The federal standard requires that larger water heaters be condensing, which would have comparable performance to this tankless option. The distribution of water heater sizes was as described above and listed in Table 15.

The reference for this upgrade is the same as for "Upgrade Water Heater to Energy Factor 0.67—Gas/Propane."

Upgrade Electric Water Heater to Heat Pump Water Heater (50-gallon/80-gallon)

These upgrades involve installing either a 50-gallon or 80-gallon ENERGY STAR HPWH with an EF of at least 2.0 upon failure of an existing electric storage tank water heater (≤55 gallons only). Both 50-gallon and 80-gallon HPWH sizes were analyzed because there may be hot water delivery (i.e., comfort) or cost-effectiveness advantages for the larger tank size. Chapter 7 of the American Council for an Energy-Efficient Economy's *New Horizons* report provides a detailed description of HPWH technology.[104] The 50-gallon and 80-gallon units modeled for this analysis are in Tier 1 of NEEA's Northern Climate Specification for HPWHs (version 5.0,[105]).[r]

These upgrades were applied to electric storage water heaters with a rated storage volume ≤55 gallons (91% of residential electric storage water heaters) because the federal standard for larger water heaters requires heat pump water heaters (with EF ≥ 2.0). The distribution of water heater sizes was derived from the national impact analysis for the federal residential water heater final

[r] These circa 2011 models were used for the analysis because they underwent extensive lab testing to derive performance maps; newer models have higher efficiencies but do not have similar performance maps available.

rulemaking.[106] The small number of larger (>55-gallon) water heaters were assumed to be installed primarily in the largest two bins of house sizes, as shown in Table 16.

Table 16. Assumed Distribution of Electric Storage Tank Water Heater Sizes

Home Finished Floor Area (ft^2)	≤55 gallons	>55 gallons
0–1499	100%	0%
1500–2499	100%	0%
2500–3499	98.6%	1.4%
3500–4499	0%	100%
4500+	0%	100%
Overall	91.2%	8.8%

The percentage of electric storage tank water heaters that are larger than 55 gallons was obtained from the national impact analysis for the federal residential water heater final rulemaking.[107] It was assumed that these are correlated with larger home floor areas.

The reference for these upgrades is based on the current federal standard for residential electric tank water heaters ≤55 gallons, which varies based on storage volume, but is approximately EF 0.95 for a 50-gallon tank.[108] Within the "≤55-gallon" category, the water heater storage volume and input power for the reference are assigned based on Table 8 in the Building America HSP.[109] Table 17 summarizes how 50-gallon and 80-gallon HPWHs were considered to replace ≤55-gallon existing electric water heaters.

Table 17. Summary of Heat Pump Water Heater Upgrade Applicability

Existing Electric Water Heater Storage Volume	Percent of Market	Federal Standard	Upgrades Considered	
			50-gal HPWH	80-gal HPWH
≤55 gallons	91%	EF ≥ 0.95	Yes	Yes
>55 gallons	9%	EF ≥ 2.00	No	No

Heat pump water heater upgrades were only considered for existing electric water heaters with ≤55 gallons storage volume, because the federal standard for larger water heaters already requires heat pump water heaters (with EF ≥ 2.00). Both 50-gallon and 80-gallon HPWH upgrades were considered for the existing ≤55 gallons water heaters, because there may be hot water delivery (i.e., comfort) or cost-effectiveness advantages for the larger tank size.

Upgrade Oil/Propane Water Heater to Heat Pump Water Heater (50-gallon/80-gallon)

These upgrades involve installing either a 50-gallon or 80-gallon ENERGY STAR HPWH with an EF of at least 2.0 upon failure of an existing oil or propane storage tank water heater. Specifications and assumptions for the HPWH are the same as described in the "Upgrade Electric Water Heater to Heat Pump Water Heater (50-gallon/80-gallon)" section above.

These upgrades were applied to oil and propane storage water heaters with a rated storage volume ≤55 gallons (96% of residential electric storage water heaters); one could also analyze replacing larger oil and propane storage water heaters with HPWHs, but that scenario was not included in this analysis. The distribution of water heater sizes was as described in the "Upgrade Water Heater to EF 0.67—Gas/Propane" section and listed in Table 15.

The references for these upgrades are based on the current federal standard for residential propane and oil storage water heaters, which varies based on storage volume, but is approximately EF 0.62 for a 40-gallon tank.[110] Within the "≤55-gallon" category, the water heater storage volume and input capacity for the reference are assigned based on Table 8 in the Building America HSP.[111]

Appliances

ENERGY STAR Clothes Washers

This upgrade involves installing an ENERGY STAR qualified clothes washer upon failure of the existing clothes washer. The reference is installation of a standard clothes washer. Modeling specifications for these two clothes washer efficiency levels are listed in Table 18. A range of occupant usage levels (±20% of standard occupant usage from the Building America HSP[112]) was accounted for in the evaluation of this upgrade.

Table 18. Clothes Washer Modeling Specifications

	Modified Energy Factor [ft^3/kWh-cycle]	EnergyGuide Label Rated Annual Consumption (with electric water heating) [kWh/yr]
Standard	2.47	387
ENERGY STAR	1.41	123

ENERGY STAR qualified clothes washers have about one third of the rated consumption of standard clothes washers; much of the reduction comes from reduced hot water usage and reduced clothes dryer runtime.

ENERGY STAR Dishwashers

This upgrade involves installing an ENERGY STAR qualified dishwasher upon failure of the existing dishwasher. The reference is installation of a standard dishwasher. Modeling specifications for these two dishwasher efficiency levels are listed in Table 19. A range of occupant usage levels (±20% of standard occupant usage from the Building America HSP[113]) was accounted for in the evaluation of this upgrade.

Table 19. Dishwasher Modeling Specifications

	Hot Water Volume [gal/day]	EnergyGuide Label Rated Annual Consumption (with electric water heating) [kWh/yr]
Standard	3.1	318
ENERGY STAR	1.7	290

Rated energy consumption for ENERGY STAR dishwashers is about 9% lower than rated energy consumption for standard dishwashers.

ENERGY STAR Refrigerators

This upgrade involves installing an ENERGY STAR qualified refrigerator upon failure of the existing refrigerator. The reference is installation of a typical refrigerator meeting the federal standard. The EFs required by ENERGY STAR and the federal standard vary based on volume of the refrigerator, but for this analysis, EF 19.9 was used to represent ENERGY STAR refrigerators and EF 17.6 was used to represent the federal standard. These values were chosen based on a typical refrigerator "adjusted volume" of 20.9 ft^3 and the fact that ENERGY STAR specifications are generally about 10% more efficient than the federal minimum standard.[114]

A parametric analysis was conducted to inform which efficiency level(s) should be considered for this upgrade. The optimal EF depends on installation costs, electricity costs, refrigerator size, and usage level, but in general, the EF 19.9 option was found to be most cost-effective, using the installation costs from the National Residential Efficiency Measures Database.[115]

Table 20. Refrigerator Modeling Specifications

	Energy Factor (ft^3-day/kWh)	EnergyGuide Label Rated Annual Consumption (kWh/yr)
Standard	17.6	434
ENERGY STAR	19.9	384

Rated energy consumption for ENERGY STAR refrigerators is about 12% lower than the rated energy consumption for standard refrigerators.

Lighting

LEDs

This upgrade involves replacing 95% of the lamps (commonly called *bulbs*) in every home with high-efficacy light-emitting diode (LED) lamps (80 lumens per watt). A value of 95% replacement was assumed instead of 100% because of diminishing returns on replacing infrequently used lamps (e.g., in closets or storage areas). These diminishing returns are accounted for using the smart replacement algorithm in the Building America HSP.[116]

This upgrade is made *today* rather than *upon wear out* of existing lamps. The reference is to make no change. The distribution of existing lighting types was based on RECS 2009 microdata using the survey responses for "number of energy-efficient bulbs."[117] The values queried from RECS are shown in Table 21. These values are consistent with recent numbers for market penetration of ENERGY STAR certified lamps.[s] All existing "energy-efficient" lamps were assumed to be compact fluorescent lamps with an efficacy of 55 lumens per watt. The remaining lamps were assumed to be incandescent with an efficacy of 15 lumens per watt.

[s] ENERGY STAR lamp market penetration was 15% in 2009 and 18% in 2013 (87% compact fluorescent lamps [CFLs] and 13% LEDs; US EPA and US DOE 2016d). (Note that in 2013 only 83% of CFLs and 76% of LEDs were ENERGY STAR labeled, because ENERGY STAR has specific requirements for efficacy, lifetime, color temperature, etc.). Because CFLs and LEDs have longer lifetimes than incandescent lamps, a relatively low *annual* market penetration can result in a much higher fraction of the installed base.

Table 21. Percentage of Energy-Efficient Lamps in Residential Energy Consumption Survey Single-Family Detached Homes

Percentage Energy-Efficient Lamps	Percentage of Homes
0% (including "refused" or "don't know")	43.3%
Between 0% and 100% (represented by a weighted average of 60%)	7.4%
100%	49.3%

According to the 2009 Residential Energy Consumption Survey, about half of all single-family homes use 100% energy-efficient lamps (typically CFLs). Most of the remaining homes do not use any energy-efficient lamps, with about 7% partially using energy-efficient lamps.

The installed cost of LED lighting was assumed to be $0.40/ft^2 of living space.

2.8 Technical and Economic Potential Calculations

Technical potential was calculated as the aggregated annual savings in all homes in which the upgrade applies. Weighting factors were used to scale simulation results up to the total number of SFD homes represented in the analysis. An analysis was conducted to determine the subset of technical potential that is economic for each upgrade. This section describes the cost-effectiveness metrics and the process of calculating them for each efficiency upgrade.

The cost-effectiveness metrics presented here take the perspective of the homeowner, comparing utility bill savings to the incremental cost of the upgrade. When applied in the context of measuring the cost-effectiveness of utility-sponsored programs, this perspective is known as the participant cost test. This test upgrades economic attractiveness to customers and is useful for setting rebate levels and forecasting participation.[118]

Alternative approaches to cost-effectiveness analysis could take the perspective of a utility or of society at large. These perspectives require additional information or assumptions, such as the avoided costs of supplying electricity or specific incentives to be evaluated. Avoided costs—reduced transmission, distribution, generation, and capacity costs—with the necessary geographic and temporal granularity are available for some locations like California, but not for the entire United States. Therefore, we focus on the homeowner perspective, for which the avoided costs (utility bill savings) are well-defined and exhibit appropriate geographic variability (Figure 18).

2.8.1 *Assumptions and Limitations*

There are several key assumptions for this economic analysis. Differences in assumptions or format of results may make comparisons to other efficiency potential analyses invalid.[t] [119] The key assumptions include:

[t] We compared our results for several upgrades to results from a national impact analysis for Energy Conservation Standards for Central Air Conditioners and Heat Pumps (see endnote 119). Though a direct comparison of results could not be made because of differing assumptions and objectives, we worked with the authors of the national impact analysis to derive a set of comparable figures, which were found to be in agreement.

- Technical and economic potential are presented as annual energy savings rather than cumulative energy savings over a number of years.

- Economic potential calculations include net replacement costs at wear out assuming full turnover of the stock of equipment and appliances (over the 30-year cash-flow analysis period). This provides more consistency when comparing against non-equipment upgrades, because these would also take multiple years to reach full adoption.

- Cost-effectiveness is evaluated using costs and benefits from the building owner's perspective rather than a utility or societal perspective.

- Two versions of economic potential were calculated (see section 2.8.3 below). *NPV > 0* uses positive net present value (NPV) as the cost-effectiveness criterion and *SPP < 5* uses simple payback period less than five years as the criterion. As explained below, five years was chosen because market penetration drops off steeply for payback periods of five years or more.

- For NPV calculations, 30 years of future cash flows (utility bill savings, equipment replacement at end of life, and residual value in year 30) are brought to the present using a 3% real discount rate.

- The packages used to estimate overall economic potential were constructed using NPV as the cost-effectiveness metric (Figure 30).

- The same economic calculations are used for both owner-occupied and tenant-occupied homes. For tenant-occupied housing, it is assumed that either the building owner pays the utility bills or rent can be increased by an amount equal to utility bill savings.

- State, utility, and local incentives (e.g., rebates) were not included in the economic analysis due to the large number of unique incentives that exist. The federal income tax credit for residential energy efficiency was included and assumed to be available in future years (capped at $500 per household).[120]

The scope of this analysis is limited in the following ways:

- The analysis covers single-family detached (SFD) housing only. The housing stock characteristics tool developed for ResStock currently is limited to SFD housing and excludes all multifamily buildings (including duplexes and townhomes) as well as mobile homes.

- House counts and housing characteristics are a snapshot based on circa-2012 data. Projections of future construction and changes in housing characteristics were not included for this analysis.

- Geographic scope is limited to the 48 contiguous U.S. states and Washington, D.C. Source housing characteristics and consumption data (particularly RECS) for Alaska, Hawaii, and U.S. territories tend to have low sample sizes, resulting in high uncertainty in the data.

2.8.2 *Cost-Effectiveness Metrics*

Two different cost-effectiveness metrics were used in this analysis.

Net Present Value

The NPV of each efficiency upgrade was calculated using the following equation:

$$NPV = \sum_{k=0}^{N} \left(\frac{C_k}{1+d_r}\right)_{upgrade} - \sum_{k=0}^{N} \left(\frac{C_k}{1+d_r}\right)_{reference}$$

Where:

k = year of analysis

N = number of years in analysis period (30 years for this analysis)

C_k = annual cash flow in year k, including household utility costs, initial cost (in year 0), federal tax credit,[121] future equipment replacement costs, and the residual value of equipment in year 30, which is the equipment replacement cost, linearly prorated based on the remaining years of life (maintenance costs were excluded)

d_r = real discount rate (3.0% for this analysis)

Simple Payback Period

The simple payback period (SPP) of each efficiency upgrade was calculated using the following equation:

$$SPP = \frac{IC_{upgrade} - IC_{reference}}{UC_{upgrade} - UC_{reference}}$$

Where:

IC = initial cost of the upgrade or reference scenario

UC = first-year household utility costs of the upgrade or reference scenario

2.8.3 *Cost-Effectiveness Thresholds for Determining Economic Potential*

The NPV and SPP metrics described above were used to develop two different versions of economic potential, one based on an NPV threshold and one based on an SPP threshold.

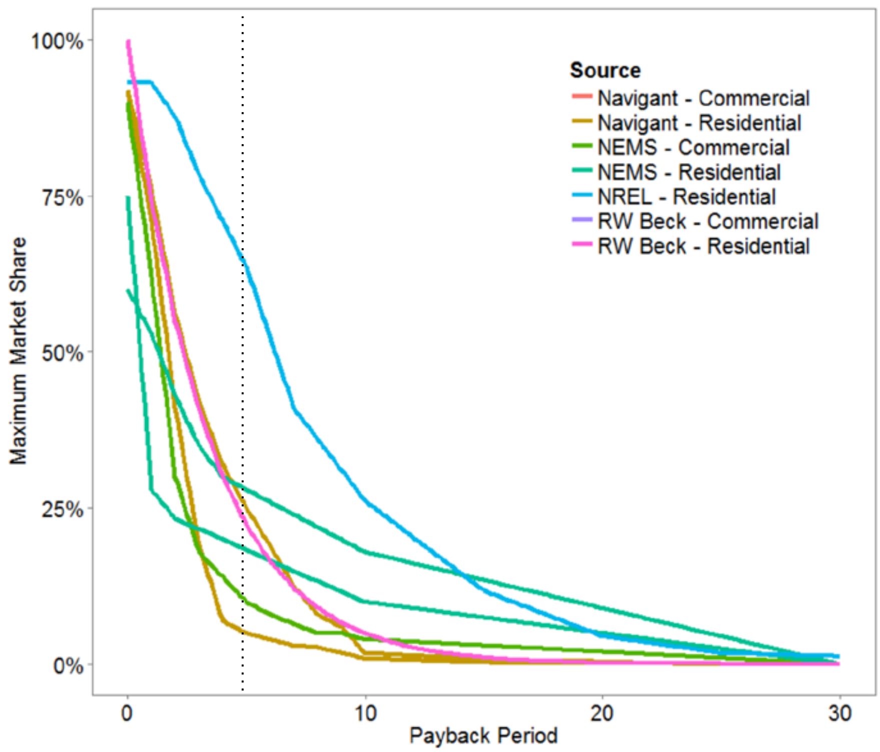
Economic Potential for Positive Net Present Value

This version of economic potential includes all upgrades with NPV>0. Therefore, it represents the energy efficiency potential assuming economically rational consumers, with long time horizons (corresponding to the assumed discount rate of 3%) and no market barriers such as lack of access to capital. This metric is overly optimistic because most homeowners do not plan to stay in their home for 30 years; however, mechanisms that transfer the costs and benefits of an upgrade to the new owner, such as on-bill or third-party financing, can help overcome the time horizon barrier and make this a more realistic metric.

Economic Potential for a Simple Payback Period Less than Five Years

This version of economic potential includes all upgrades with SPP<5. In most market adoption models, market penetration drops off steeply for payback periods around five years or more (see Figure 29), so this version of economic potential begins to incorporate some aspects of *market potential* or *achievable potential*, though it does not account for factors like access to capital, participation rates, demographics, or other market factors.

Figure 29. Maximum market share as a function of payback period based on different sources.



Source: Sigrin et al. 2016

The simply payback period less than five years threshold was chosen because market adoption curves such as these generally show market share dropping off significantly for payback periods beyond five years. Note that the "NREL – Residential" data series is from previous work not related to this analysis.

2.8.4 *Economic Calculation Procedure*

The following procedure was used to perform the economic calculations. Utility rates are as described in section 2.3.4.

For each *variant-state combination*[u] receiving the upgrade:

1. Calculate the upfront cost of the upgrade and reference scenarios.
2. Calculate the annual utility costs of the upgrade and reference scenarios.
    a. Apply the electricity rate (for the combination of TMY subregion and state) to the annual electricity consumption of the variant simulation.
    b. Apply the state-specific gas, propane, and oil rates to the respective fuel consumptions of the variant simulation.
3. Calculate cost-effectiveness metrics as defined in the NPV and SPP equations above.
4. For each version of economic potential, filter out variant-state combinations that do not meet the cost-effectiveness threshold.
5. Aggregate the remaining combinations into the desired geographic areas for reporting (e.g., state or region).

2.9 Package Simulations

The purpose of running package simulations was to estimate the total economic potential of residential energy efficiency, while accounting for interactions between upgrades. For example, building enclosure air sealing reduces the available savings of AC upgrades (negative interaction) but also allows the replacement AC capacity to be downsized (positive interaction). These interactions would be ignored if one simply added up the economic potential of individual upgrades.[v]

2.9.1 *Specification of Packages*

The procedure used to automatically construct packages of the most cost-effective upgrades in each home across all categories is illustrated in Figure 30 and described below. This procedure is comparable to how an energy auditor or home performance contractor may develop a recommended package of upgrades, but done automatically and on a large scale.

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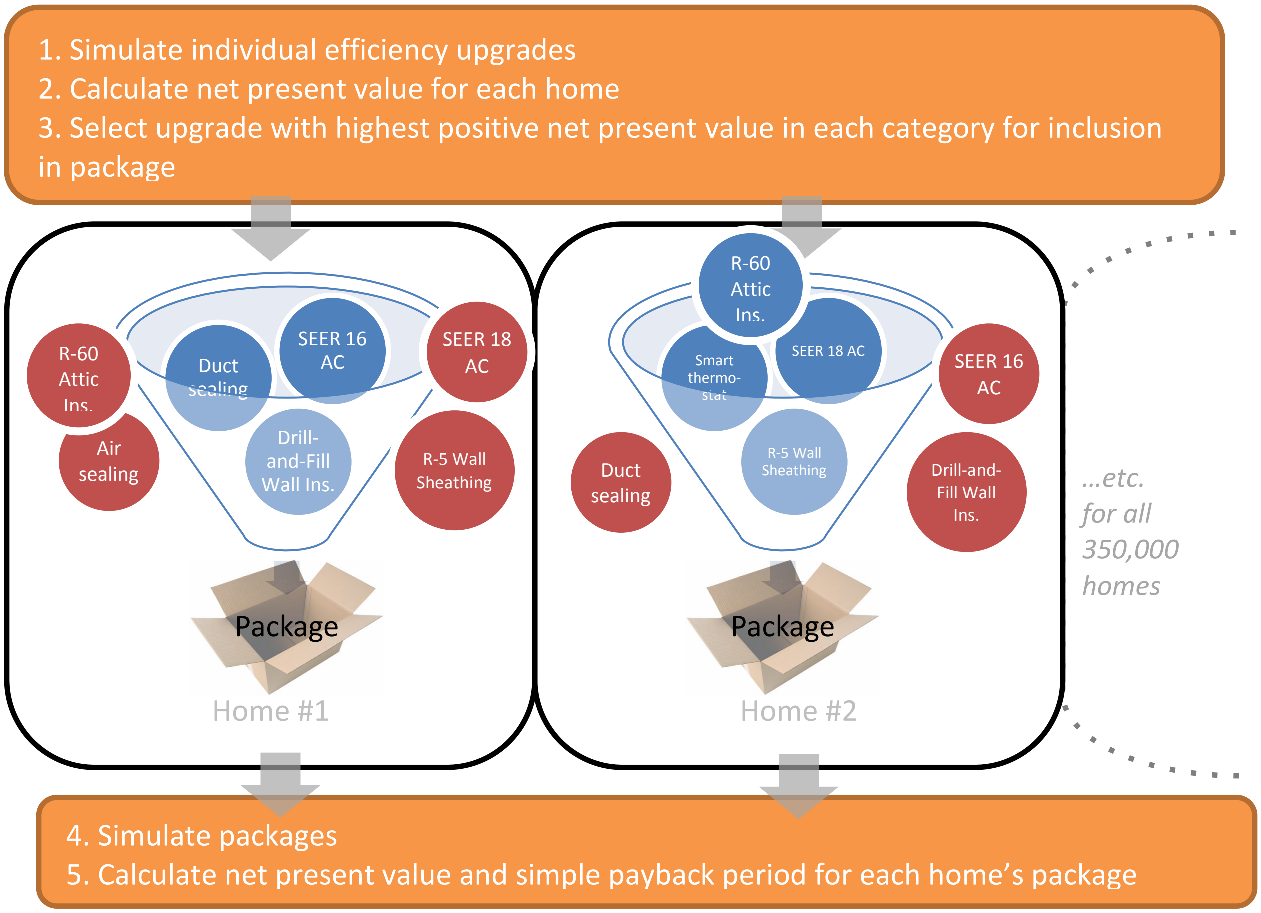
[u] If a variant's TMY subregion (Figure 17) spans multiple states, that variant's house count is divided among the states proportionally based on the location of the census tract house counts in each TMY subregion. This is necessary so that gas, propane, and oil rates, which are state averages, can be applied, and so results can be aggregated by state. This division of the 350,000 variant simulations results in around 832,000 rows in the results database. We refer to these as *variant-state* combinations.

[v] This procedure is not a true optimization because it does not account for interactions when evaluating upgrades for inclusion in the packages themselves. A true optimization would have dramatically longer runtime (~1000x), so these packages strike a balance between accuracy and runtime given today's computing resources. Improving this process is an area of interest for future work.

Figure 30. Illustration of how packages were developed for each archetype variant home



This diagram illustrates the automated process used to develop tailored packages of efficiency upgrades for each of the representative 350,000 homes.

For each of the 350,000 representative homes, we calculated the cost-effectiveness of the 50 upgrades (as described in Section 2.7 Efficiency Upgrade Simulations). NPV was the cost-effectiveness metric used for developing packages for this analysis, but any cost-effectiveness metric could be used. For each home, the upgrade in each category with largest NPV was chosen for inclusion in the package. Only upgrades with NPV>0 were considered for inclusion. As an example, if a SEER 16 central AC upgrade (in a particular 1950s home in Philadelphia) had a NPV of \$500 and the SEER 18 upgrade had a NPV of \$400, then the SEER 16 upgrade would be chosen for the package (even if the SEER 18 had larger energy savings).[w]

The NPV comparison process is repeated for all upgrade categories including upgrades for the thermal enclosure, water heating, appliances, lighting, ducts, and smart thermostats. Categories with no upgrades that apply to the home, or in which none of the upgrades had NPV>0, would not be included in the package for that home.

[w] This NPV comparison can get more complicated for upgrades that include fuel switching. Because heat pumps provide both heating and cooling, the heat pump upgrade NPV must be compared against the combined NPV of the AC and furnace upgrades.

For the set of 350,000 representative homes, around 142,000 unique package definitions were identified. While this may seem like a large number, it is much smaller than the 46 million possible combinations of 50 upgrades. It might seem simpler to apply a standard set of manually defined upgrade packages instead of automatically generating these packages for each home, but, depending on the method used to manually define packages, it would leave significant savings on the table or it would have much longer runtimes (or both). If one were to manually construct packages for consideration by selecting only the best upgrade in each of the 20 or so categories, there would still be 2^{20} = ~1 million combinations (the base is 2 because there is a binary choice of including or not including each category).

3 Results and Discussion

3.10 Overview

The results presented here can be used to help inform priorities for national, regional, state, or local residential electric efficiency initiatives. Results from the individual component upgrades and packages were visualized in different ways. Output variables available for visualization (typically after applying a cost-effectiveness filter and aggregating results by state) include the following:

- **Absolute annual savings**
  - Electricity savings (GWh/yr)
  - Natural gas savings (TBtu/yr)
  - Fuel oil savings (TBtu/yr)
  - Propane savings (TBtu/yr)
  - Primary energy savings (TBtu/yr)
  - Carbon emissions reduction (metric tons CO2e/yr).

- **Percentage savings**
  - Electricity savings (percentage of consumption by state's SFD homes)
  - Natural gas savings (percentage of consumption by state's SFD homes)
  - Oil savings (percentage of consumption by state's SFD homes)
  - Propane savings (percentage of consumption by state's SFD homes)
  - Primary energy savings (percentage of consumption by state's SFD homes)
  - Carbon savings (percentage of consumption by state's SFD homes).

- **Average per-house savings**
  - Per-house electricity savings (MWh/yr)
  - Per-house natural gas savings (MBtu/yr)
  - Per-house fuel oil savings (MBtu/yr)
  - Per-house propane savings (MBtu/yr)
  - Per-house primary energy savings (MBtu/yr)
  - Per-house carbon emissions reduction (metric tons CO_2e/yr).

- **Economic variables**
  - Utility bill savings ($/yr)
  - Per-house incremental cost ($)
  - Average NPV for upgraded homes ($)
  - Average SPP for upgraded homes (yrs).

- **Applicability and cost-effectiveness statistics**
  - Total number of homes in geographic area
  - Number of homes to which upgrade applies
  - Number of homes in which upgrade meets cost-effectiveness threshold
  - Percentage of homes to which upgrade applies (%)
  - Percentage of applicable homes in which upgrade meets cost-effectiveness threshold (%).

3.11 Package Results

From a national perspective, this analysis has estimated economic potential electricity savings of the packages to be 245 TWh per year, or 22% of electricity used by the residential SFD housing stock in 2012 (Table 22). This represents about 6.3% of the total annual U.S. electricity consumption in 2014. Using U.S. Energy Information Administration's Annual Energy Outlook projections for electricity consumption, the 245 TWh per year of potential savings would be about 5.7% of total U.S. electricity consumption in 2030.[122] [x]

Many of the upgrades also save natural gas, propane, and fuel oil. The packages save an estimated 4.2 quads (quadrillion Btu/yr) of source energy, which is 24% of consumption by the SFD housing stock. Similarly, the packages reduce carbon emissions of the stock by 24% (291 million metric tons CO_2e per year).

Table 22. Economic Potential (positive net present value) **Electricity Savings Relative to Consumption**

Economic Potential (NPV>0) Electricity Savings in U.S. SFD Homes	**245 TWh/yr**
As a percentage of	
Electricity consumption in U.S., SFD homes (1,118 TWh/yr; modeled)	21.9%
Electricity consumption in U.S., Residential sector (1,407 TWh/yr)	17.4%
Electricity consumption in U.S., Total (3,903 TWh/yr)	6.3%
Electricity consumption in U.S., 2030 AEO[i] Reference Case (4,326 TWh/yr)	5.7%

[i]U.S. Energy Information Administration's 2015 Annual Energy Outlook

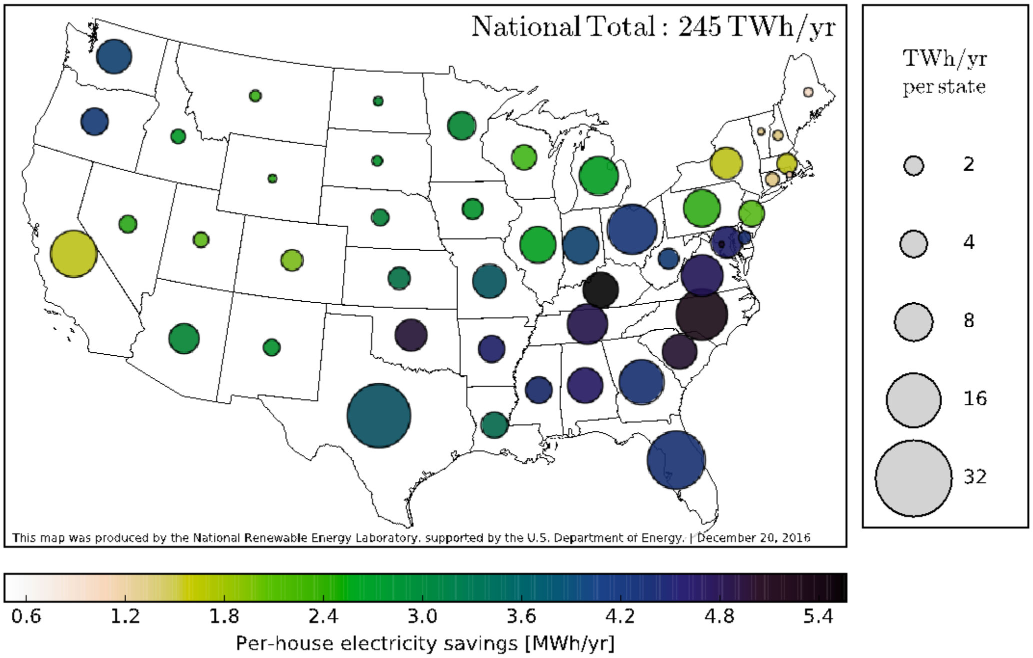
This table contextualizes the 245 TWh/yr of economic potential in single-family homes by comparing it to the electricity consumption of the single-family sector and the residential sector at large, as well as the total U.S. electricity consumption, both today and in 2030.

To understand how potential savings vary by state, one can use bubble maps or other types of graphical results. The bubble maps (also called Dorling cartograms) display two variables for each state: the area of each bubble marker represents the total annual electricity savings resulting from cost-effective upgrades in that state, while the color of the bubble represents average savings per house. The bubble map presented in Figure 31 below show economic potential of the packages using the NPV>0 filter. Figure 32 shows the savings as a percentage of each state's single-family detached electricity consumption..

In addition to the "all-inclusive" packages described above, results from an enclosure-only, HVAC-only, enclosure+HVAC, and enclosure+HVAC+Water Heating packages are included in Appendix D.

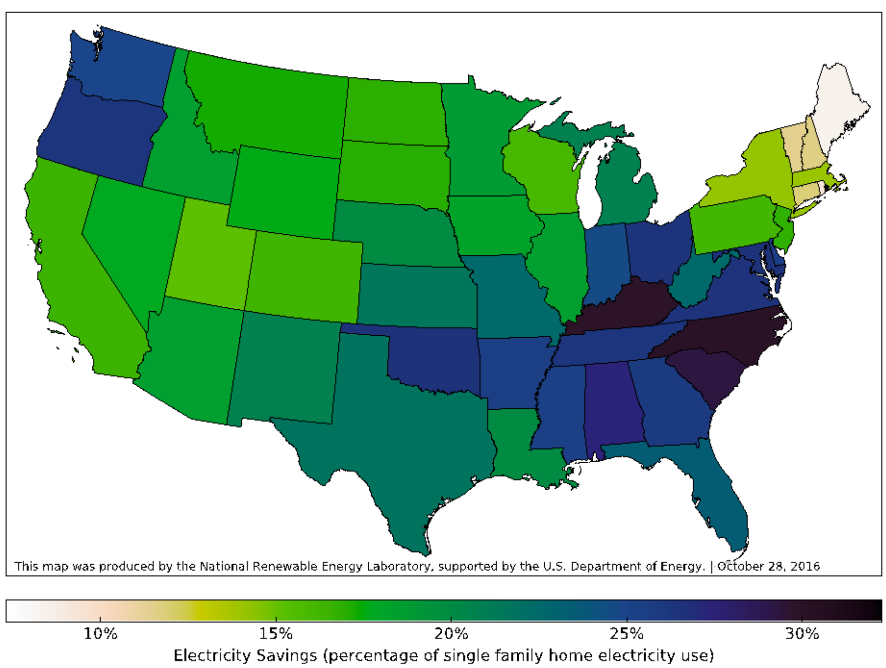
[x] As described in section 2.8.1, the economic potential results presented assume full turnover of equipment stock (i.e., over a 30-year period).

Figure 31. Aggregate and average electricity savings (NPV>0 economic potential) – Packages of the most cost-effective upgrades in each home across all categories



This figure shows the economic potential (NPV>0) electricity savings by state in aggregate (bubble area) and on average, per house (bubble color).

Figure 32. Percentage electricity savings (NPV>0 economic potential) – Packages of the most cost-effective upgrades in each home across all categories



Most states can save 15–30% of single-family home electricity use cost-effectively. Electricity savings are lower in New England, where oil-to-electric fuel switching for home heating is often NPV-optimal.

3.12 Efficiency Upgrade Results

Table 23 presents the technical and economic potential electricity savings for each upgrade related to electric end uses. It also shows the percentage of technical potential that is economic, using the two cost-effectiveness thresholds.

Table 23. Efficiency Upgrade Potential Electricity Savings

		Electricity Savings [TWh/yr]			Percentage of Tech.	
Category		Tech.	NPV>0	SPP<5	NPV>0	SPP<5
Air Sealing	Air sealing	1.5	9.5[i]	0.4	638%[i]	25%
Attic	R-38 attic ins.	17.3	16.3	3.5	95%	20%
	R-49 attic ins.	21.3	18.2	2.4	86%	11%
	R-60 attic ins.	24.0	18.3	1.8	76%	7%
Foundation	R-10 bsmt walls (finished)	7.4	7.2	0.3	97%	5%
	R-10 bsmt walls (unfin.)	1.7	1.7	0.0	100%	1%
	R-10 crawlspace walls	5.3	5.3	0.7	99%	13%
Walls	Drill-and-fill	30.8	30.5	7.8	99%	25%
	R-5 wall sheathing	7.8	7.7	4.4	99%	57%
Windows	Low-e storms on 1-pane	15.0	8.5	0.1	56%	0%
	Low-e storms on 2-pane	12.0	6.2	0.0	52%	0%
Cooling	ENERGY STAR room AC (EER 12)	10.9	10.5	7.2	96%	66%
	SEER 16 central AC	22.6	17.3	5.6	76%	25%
	SEER 18 central AC	30.8	20.7	11.8	67%	38%
Ducts	Duct sealing	18.4	17.6	6.0	96%	33%
Heating	DHP (displaces electric baseboard today)	27.5	26.4	13.1	96%	48%
	Upgrade central ASHP to VSHP	21.7	3.4	0.6	15%	3%
	Upgrade electric furnace to VSHP at wear out	82.9	83.1	78.3	100%	94%
Thermostat	Smart thermostat (home during day)	7.6	7.6	5.7	100%	75%
	Smart thermostat (not home during day)	13.4	13.4	12.6	100%	94%
DHW	Upgrade electric water heater to HPWH	34.8	20.3	7.0	58%	20%
Appliances	ENERGY STAR clothes washers	7.9	7.9	7.9	100%	100%
	ENERGY STAR dishwashers	1.7	1.3	0.2	76%	12%
	ENERGY STAR refrigerators	4.2	4.2	4.1	99%	97%
Lighting	LEDs	39.0	38.9	5.7	100%	15%

[i]Counterintuitively, air sealing economic potential (using NPV>0) is higher than its technical potential. This is because in many homes air sealing is accompanied by installation of continuous mechanical ventilation (meeting ASHRAE 62.2-2010), which increases electricity use (lowering the technical potential for electricity savings). In homes that don't use electricity for heating or air conditioning, there may be heating fuel savings from air sealing, but there are no electricity savings to counteract the increased electricity for the mechanical ventilation fan. The economic thresholds filter out many of the homes in which air sealing increases net electricity use (though there may be non-energy reasons, such as indoor air quality, to air seal and install controlled ventilation, despite the increased electricity use).

This table shows the technical and economic potential electricity savings for each upgrade related to electric end uses. It also shows the percentage of technical potential that is economic, using the two cost-effectiveness thresholds.

3.12.1 ***Economic Potential Using Positive Net Present Value***

Using the NPV>0 cost-effectiveness threshold, many of the upgrades have economic potential that is at least 90% of technical potential. This suggests that there are a significant number of homes where the upgrades are attractive investments for rational consumers with unlimited access to capital and sufficient time horizons.

For the packages of upgrades, 95% of the technical potential is economic (using NPV>0). This is by design, because the packages only included upgrades with NPV>0 when considered individually (see section 2.8 for details). However, this high percentage means that negative interactions between the upgrades are not significant enough to cause the packages to become not cost-effective (or they are outweighed by positive interactions).

Table 24 lists the top 11 efficiency upgrades contributing to economic potential electricity savings (using the NPV>0 filter). This list is based on electricity savings; when upgrades are ranked by source energy savings to include other fuels, the rank order changes, and notably, basement and crawlspace wall insulation upgrades become significant contributors.

Table 24. Top Efficiency Upgrades Contributing to Economic Potential (positive net present value)

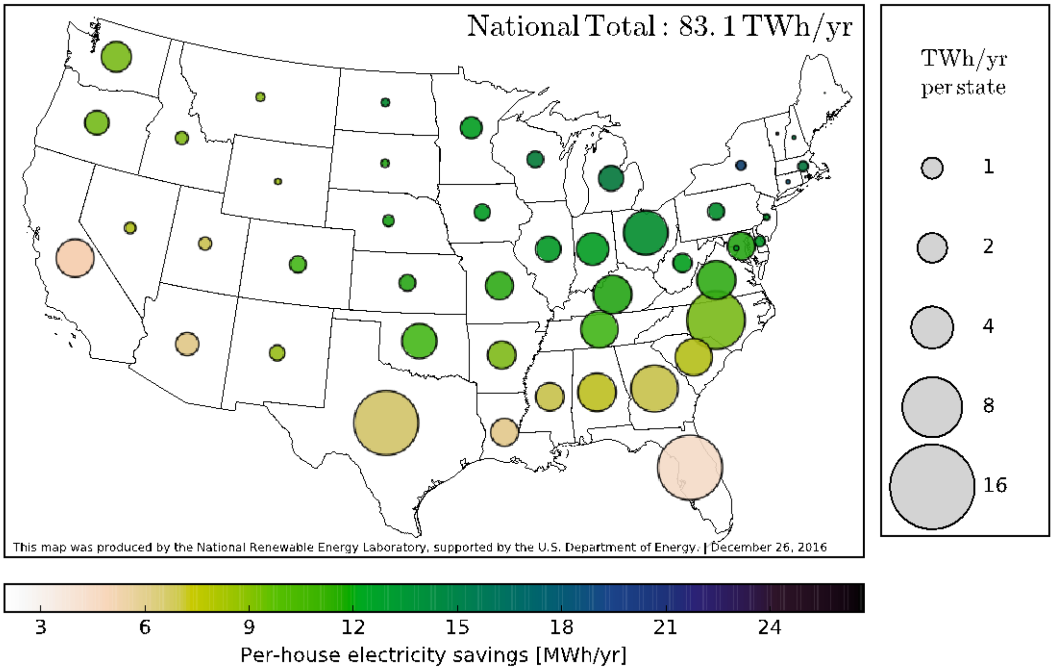
Efficiency Upgrade	Electricity Savings (TWh/yr)
Upgrade electric furnace/AC to high-efficiency heat pump at wear out	83
Install LED lighting in 95% of fixtures	39
Drill-and-fill wall cavity insulation	30
Install high-efficiency ductless heat pumps in homes with electric baseboard heating	26
Install smart thermostats in homes not currently using programmed thermostats	21
Upgrade central AC to SEER 18 at wear out	21
Upgrade electric water heater to heat pump water heater	20
Attic Insulation (to R-49 or R-60)	18
Duct sealing and insulating	18
Low-e storm windows	15
Air sealing (25% reduction in whole-home leakage)	9

Replacing electric furnaces (and air conditioners) with high-efficiency heat pumps provides the most economic potential electricity savings, with more than twice the potential of the second largest contributing upgrade.

One upgrade stands out as having the largest economic potential (NPV>0) for electricity savings. This is "Upgrade electric furnace/AC to high-efficiency heat pump at wear out." See section 2.7.3 above for details on this and other scenarios.

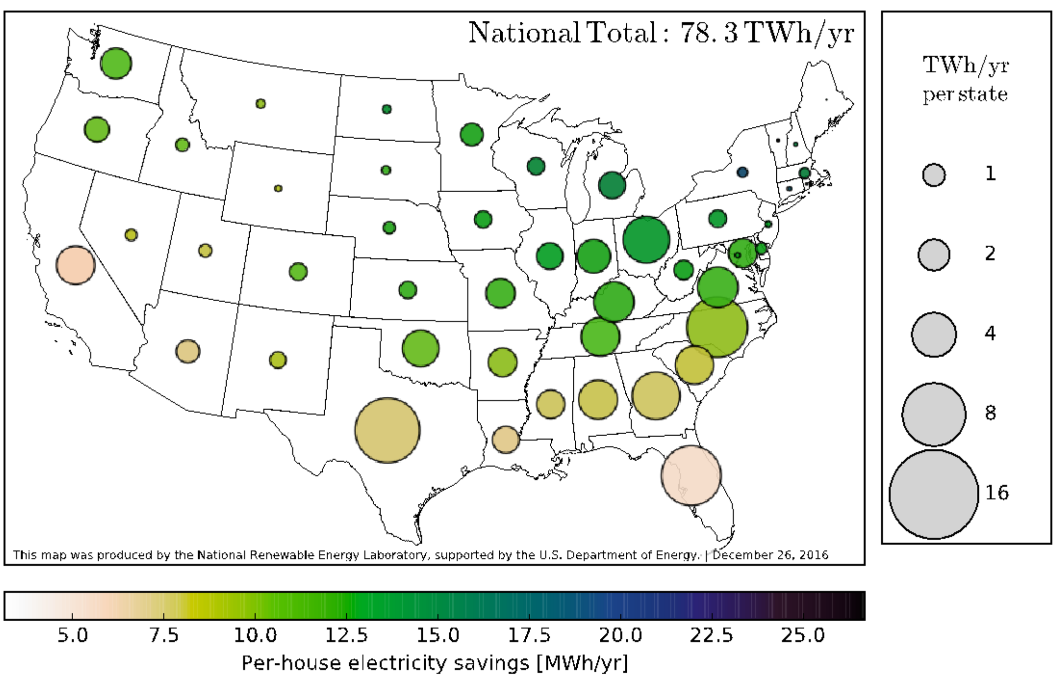
Figure 33 shows that much of the economic potential (NPV > 0) for the electric furnace upgrade is in the Southeast, where there are a large number of electric furnaces and where there are significant cooling energy savings that result from the high-efficiency VSHP. Figure 34 shows the economic potential using SPP < 5, which is only 6% less than the NPV > 0 potential.

Figure 33. Aggregate and average electricity savings (NPV>0 economic potential) – Upgrade electric furnace to variable-speed heat pump at wear out



Upgrading electric furnaces to variable-speed heat pumps provides the most cost-effective (positive net present value) savings in the Southeast.

Figure 34. Aggregate and average electricity savings (SPP<5 economic potential) – Upgrade electric furnace to variable-speed heat pump at wear out



For this electric furnace to variable-speed heat pump upgrade scenario, the more conservative cost-effectiveness threshold (simple payback period less than five years), results in only about 6% less savings potential than with the positive net present value threshold.

3.12.2 *Economic Potential Using Simple Payback Period Less Than Five Years*

In contrast to the NPV>0 results, the SPP<5 filter removes a large fraction of the potential savings for a majority of the upgrades (see Table 23).

Four upgrades stand out as retaining 90%–100% of technical potential after applying the SPP<5 years filter:

- Upgrade electric furnace to VSHP at wear out (94%)
- Smart thermostat (occupants not home during the day) (94%)
- ENERGY STAR clothes washers (100%)
- ENERGY STAR refrigerators (97%).

These four upgrades have excellent economics in almost every home to which they are applied. This suggests that the lack of return on investment (i.e., long payback period) is not likely to be a barrier to market adoption. ENERGY STAR clothes washers and refrigerators already have significant market penetration (66% and 74%, respectively, based on 2013 ENERGY STAR unit shipment data archives: US EPA and US DOE 2016d). Reasons why the other upgrades are not more widespread could include lack of homeowner/contractor awareness (electric furnace), new technology (smart thermostat), split incentives in rentals,[y] or access to capital or financing.

Most of the remaining efficiency upgrades have good economic potential when using the NPV>0 filter. However, because they often do not pass the SPP<5 filter, the longer payback periods are likely a barrier to market adoption in addition to the barriers mentioned above.

Utility or government incentives are a traditional way to address the long payback period market barrier, and involve designing incentives that bring payback periods down into an acceptable range for consumers. Newly emerging models for energy efficiency implementation may be able to address the long payback period and other market barriers. These emerging models include residential energy service companies, property-assessed clean energy (PACE) financing, and on-bill financing.

While not a focus of this analysis, it is estimated that a set of packages designed to maximize SPP<5 economic potential would result in 116 TWh/yr of savings. This estimate is simply the sum of economic potential (SPP<5) for the following upgrades:

- Upgrade central ASHP to VSHP (sized for max. htg-clg)
- Upgrade electric furnace to VSHP at wear out (sized for max. htg-clg)
- DHP (displaces electric baseboard today) (60%)
- LEDs
- ENERGY STAR clothes washers
- ENERGY STAR dishwashers
- ENERGY STAR refrigerators

[y] Building owners have little incentive to invest in efficiency upgrades when tenants pay utility bills. This term is also used to describe the opposite situation, when tenants have no incentive to use less energy because owners pay the bills.

These upgrades have relatively few interactions, so the simple sum of their potential is a reasonable approximation of the economic potential that would result from this SPP-based package.

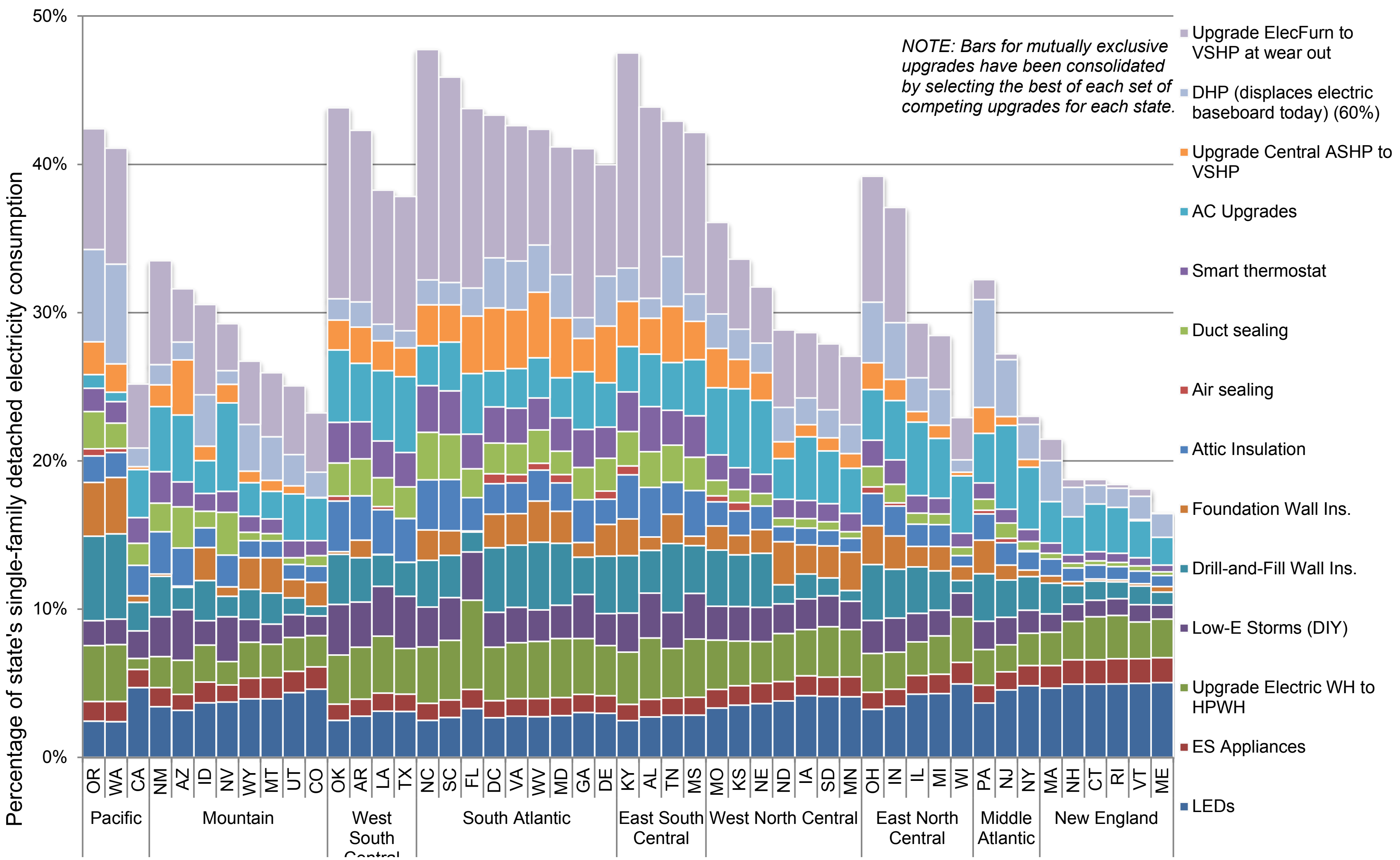
3.12.3 *Top Efficiency Upgrades by State*

From a state program or policy perspective, it is useful to see which upgrades have the greatest economic potential in a given state, and how much of the electricity used by the SFD homes can be saved. The following graphs show how individual upgrades contribute to the total potential electricity savings in each state. Figure 35 shows technical potential, while Figure 36 and Figure 37 show economic potential using the two types of cost-effectiveness threshold.

Each bar color represents the contribution of a particular upgrade to a reduction in states' electricity use by SFD homes. The total bar height represents a rough indicator of the total potential savings across all upgrades, *without accounting for interactions between upgrades*. Mutually exclusive upgrades (e.g., SEER 16 AC and SEER 18 AC) have generally been consolidated by picking the upgrade with the largest potential in each state, but interactions between upgrades (e.g., air sealing reduces the cooling load and therefore potential savings from a SEER 18 AC and vice versa) are not accounted for in this total bar height.

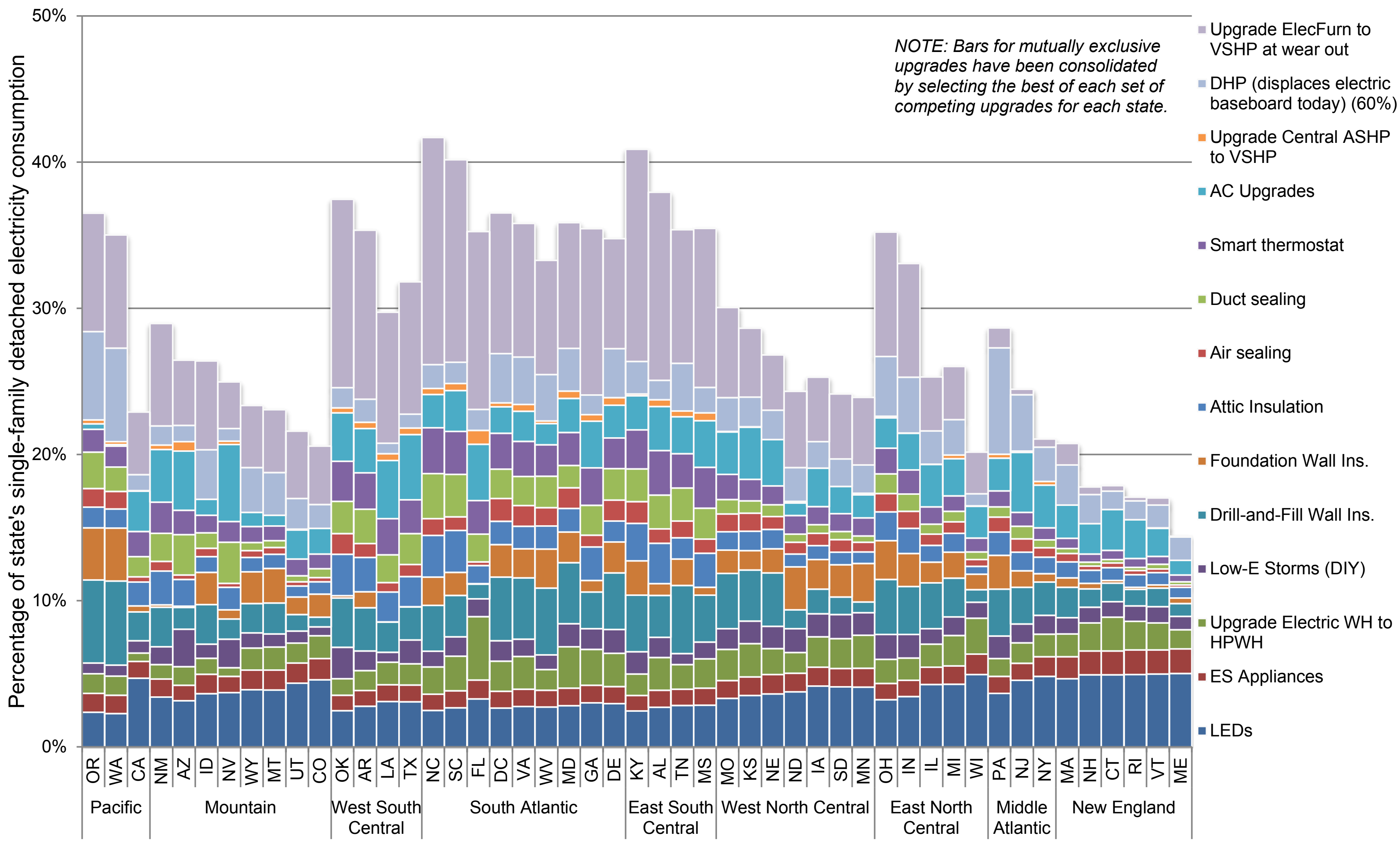
Using detailed energy simulations allows us to properly account for interactions between upgrades, and it is for this reason we construct and simulate the packages described in section 2.8 above. Figure 38 shows the impact of the interactive effects by comparing the sum of bar heights from Figure 36 to the savings from the packages (both using the NPV>0 threshold).

Figure 35. Technical potential for electricity savings in single-family detached homes



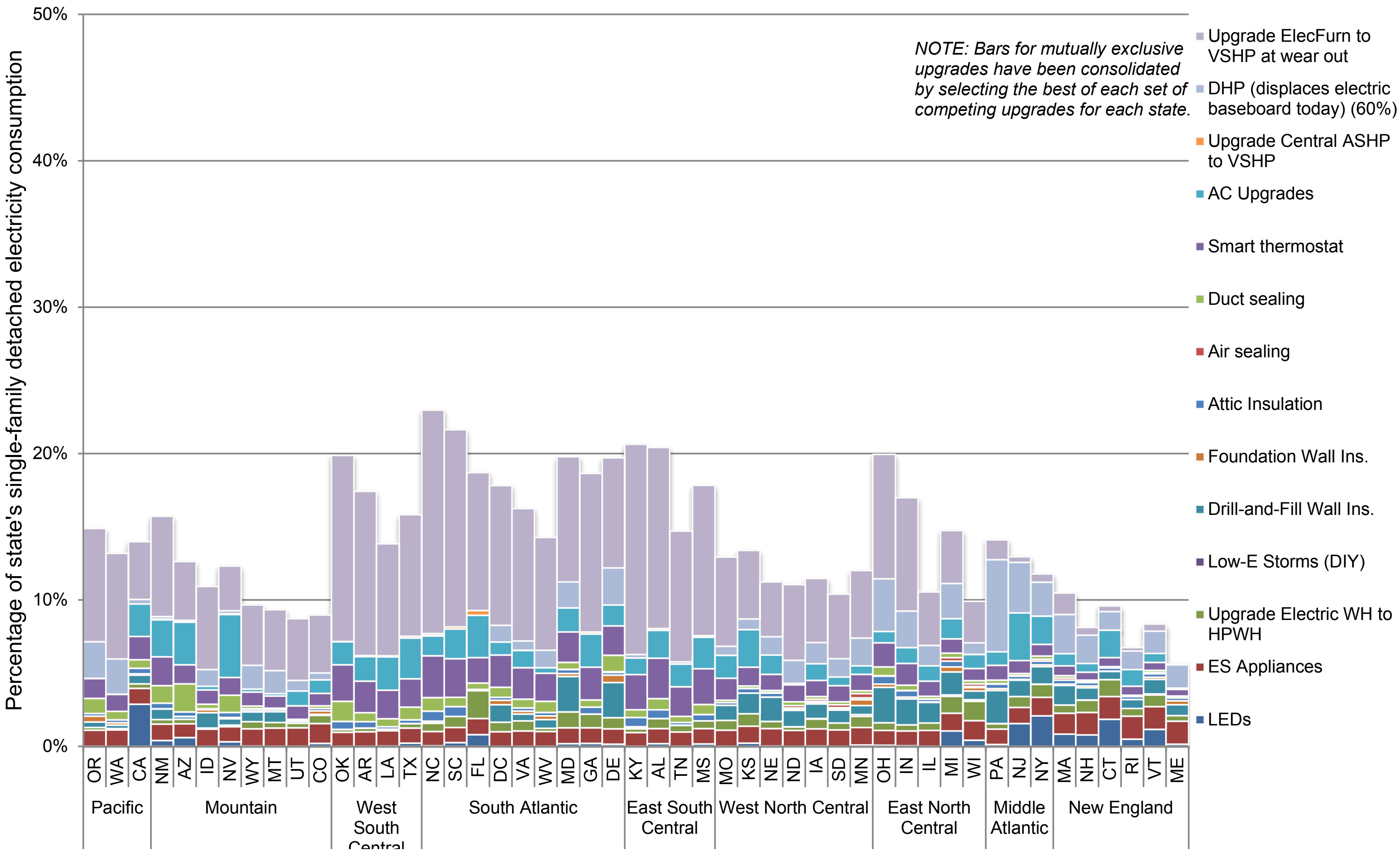
The greatest technical potential for electricity savings—relative to consumption—is found in the states with either a large fraction of homes heated with electricity, significant air conditioning usage, or both.

Figure 36. Economic potential (positive net present value) for electricity savings in single-family detached homes



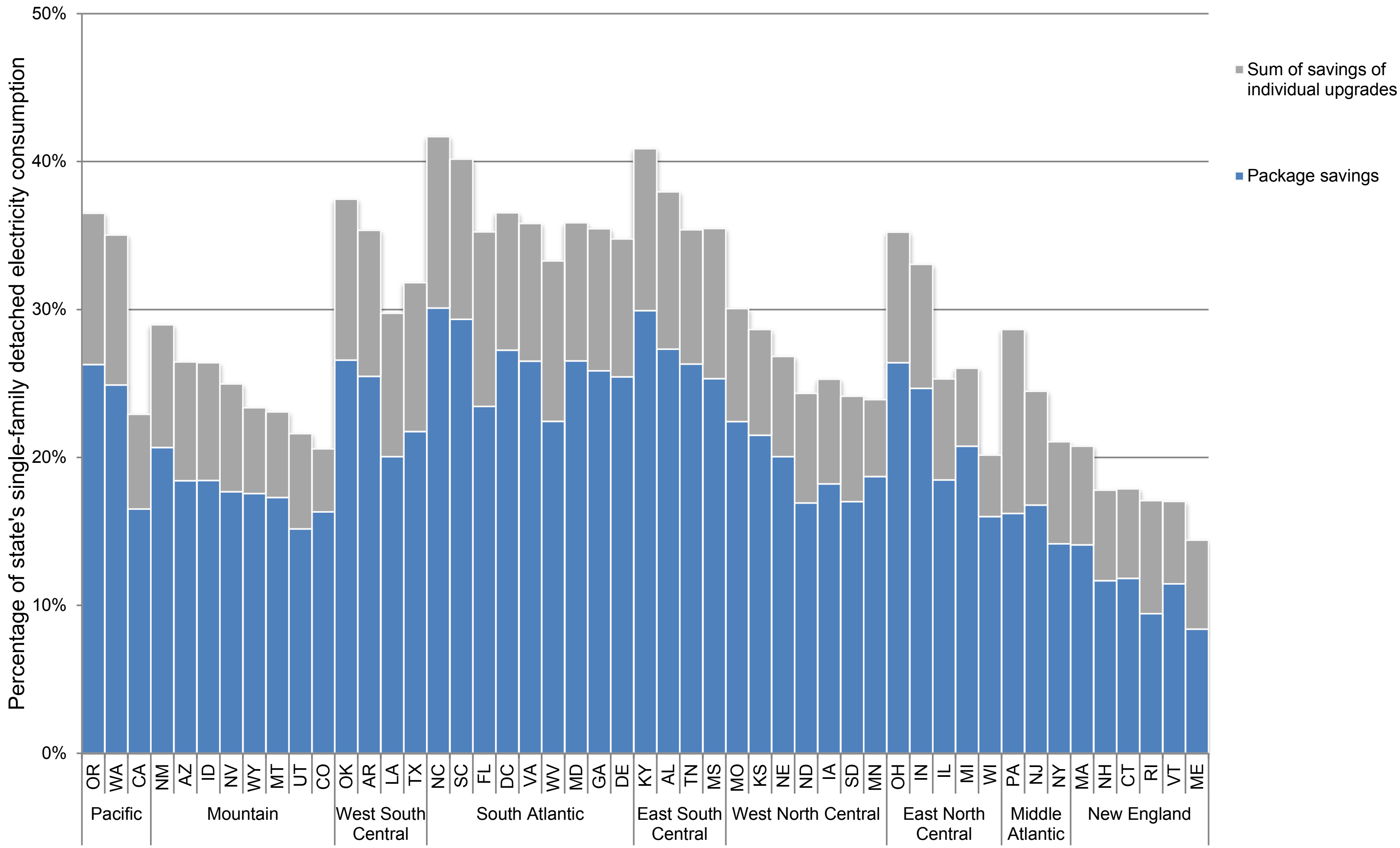
Much of the technical potential remains after applying the NPV>0 (positive net present value) filter for economic potential.

Figure 37. Economic potential (simple payback less than five years) for electricity savings in single-family detached homes



In contrast to the NPV>0 threshold, the SPP<5 (simple payback period less than five years) cost-effectiveness threshold filters out the majority of the technical potential savings in all states, with the "Upgrade electric furnace to variable-speed heat pump at wear out" upgrade standing out as the largest contributor in many states.

Figure 38. Economic potential (positive net present value) electricity savings of packages of most cost-effective upgrades across all categories in single-family detached homes



The sums of cost-effective savings from individual upgrades (total bar heights from Figure 36) are compared to the cost-effective savings that would result from the NPV-optimized packages, which account for interactions between individual upgrades.

3.12.4 ***Electric Efficiency Supply Curves***

All of the visualization techniques presented above lack a way to compare the magnitude of cost-effectiveness of one upgrade relative to another (e.g., barely cost-effective versus very cost-effective), instead using the NPV>0 or SPP<5 threshold to categorize upgrades for each archetype variant as either cost-effective or not.

Supply curves, introduced in section 2.2.2 above, can be a valuable way of presenting efficiency potential with a dimension for comparing cost-effectiveness. The most well-known examples of these are the energy efficiency supply curves published by McKinsey & Company.[123]

An example supply curve showing the electric end-use upgrades with the best cost-effectiveness for the United States is shown in Figure 39. Appendix C includes electric efficiency supply curves for each of the 48 contiguous states and D.C. The *x*-axis on these graphs shows cumulative electricity savings as a percentage of the annual electricity consumed by the state's SFD homes. The *y*-axis indicates the net cost of conserved energy, from the utility customer's perspective:

$$\text{Net cost of conserved electricity (NCCE) [\$/kWh]} = \frac{AERC}{\text{annual electricity savings}}$$

Where:

$AERC$ = annualized energy related costs [$/yr], calculated as follows:

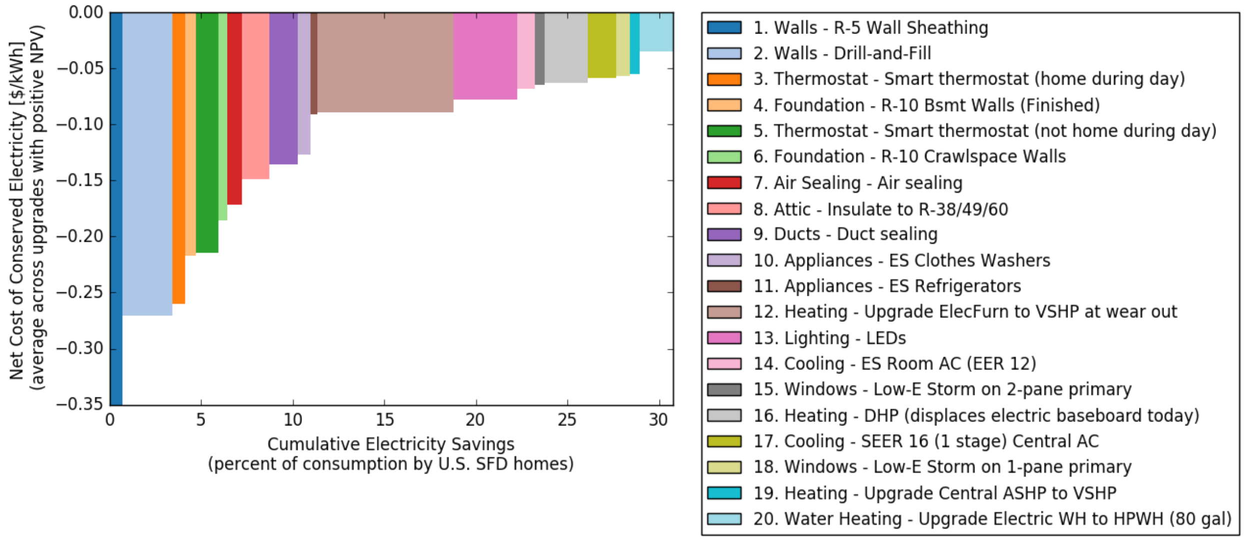
$$AERC = \frac{-NPV}{\left(1 - \frac{1}{(1+d_r)^N}\right)}$$

NPV = net present value of cash flows including incremental cost and utility bill savings for all fuels (as defined in section 1.1.1 above)

Note that these supply curves use *net* cost on the *y*-axis; this distinguishes them from the example supply curves presented in section 2.2.2 above, which did not include utility bill savings in the *y*-axis metric. Because utility bill savings include gas, propane, and oil utility bill savings, this approach accounts for the benefits to the utility customer from upgrades that save both electricity and other fuels (insulation and air sealing upgrades). Also note that mutually exclusive upgrades were not removed, as was done in the previous section.

To construct the supply curve graphs, we calculate the net cost of conserved electricity (NCCE) for all upgrades in all archetype variant homes in each state. Upgrades with positive NCCE are not cost-effective and are removed, while upgrades with negative NCCE are cost-effective and are aggregated. The aggregation results in the blocks drawn on each supply curve, where the width of the block is the economic electricity savings potential and the height of the block is the average NCCE of the cost-effective upgrades. In other words, tall blocks have very good economics and wide blocks have large potential savings.

Figure 39. Electric efficiency supply curve for the U.S. single-family detached housing stock



In this supply curve, each block represents a type of upgrade. The width of each block indicates the electricity savings provided by cost-effective (NPV>0) implementations of that upgrade, while the height of each block represents the average net cost of conserved energy for the implementations of that upgrade that have NPV>0. In other words, tall blocks have very good economics and wide blocks have large potential savings.

4 Conclusion

This report documents the methodology and results for an analysis of the technical and economic potential of electric end-use energy efficiency in the U.S. SFD housing stock. This analysis used the ResStock analysis framework, which is unique in the high level of granularity used to represent the diversity of housing stock characteristics and climates across the contiguous United States. The ResStock framework brings together the use of large public and private data sets, statistical sampling, detailed subhourly building energy simulations, and high-performance computing resources. The analysis used 350,000 representative building models to represent the SFD housing stock. More than 20 million simulations were conducted on NREL's *Peregrine* supercomputer to evaluate more than 50 efficiency upgrade and package scenarios.

An economic analysis was conducted to evaluate the cost-effectiveness of the upgrades in each of the representative homes from the perspective of the electricity end user. Packages of cost-effective upgrades (NPV>0) were developed for each of the representative homes, as might be done by an energy auditor or home performance contractor. These packages were simulated to evaluate the impact of interactions between upgrades. Ninety-four percent of the package savings retained cost-effectiveness after accounting for interactions. This set of cost-effective NPV-optimized packages was found to have potential savings of 245 TWh per year, which is about 22% of electricity use by the 2012 SFD housing stock in the contiguous United States. This represents about 6.3% of the total annual U.S. electricity consumption in 2014, and about 5.7% of the projected total U.S. electricity consumption in 2030.[124]

Many of the upgrades also save natural gas, propane, and fuel oil. The packages save an estimated 4.2 quads (quadrillion Btu/yr) of source energy, which is 24% of consumption by the SFD housing stock. Similarly, the packages reduce carbon emissions of the stock by 24% (291 million metric tons CO_2e per year).

SPPs were also calculated for the upgrades and packages. As might be expected when using this more conservative metric, only a fraction of potential savings meets the threshold of SPP<5. Because market penetration drops off steeply for SPPs of more than five years,[125] consumers' demand for short paybacks is likely a barrier to adoption of these upgrades. Four upgrades stand out has having excellent economic potential after applying the SPP<5 threshold, retaining at least 90% of their technical potential:

- Upgrade an electric furnace to VSHP at wear out (94%)
- Installing smart thermostats (occupants not home during the day) (94%)
- Installing ENERGY STAR clothes washers (100%)
- Installing ENERGY STAR refrigerators (97%).

ENERGY STAR clothes washers and refrigerators already have significant market penetration (66% and 74%, respectively, based on 2013 ENERGY STAR unit shipment data archives[126]). Reasons why the other upgrades are not more widespread could include lack of homeowner/contractor awareness (electric furnace), new technology (smart thermostat), split incentives in rentals, or access to capital or financing. Long payback periods and a lack of mechanisms to value home performance improvements in real estate transactions are two additional barriers that likely apply to the set of upgrades and packages that meet the NPV>0 threshold but have SPPs of more than five years.

Incentives and marketing campaigns are traditional ways of promoting energy efficiency adoption. The ResStock approach can be used to more optimally target such incentives or marketing, e.g., by vintage or heating fuel type of homes in a particular state or region. Emerging models for energy efficiency implementation and financing—such as residential energy service companies, property-assessed clean energy (PACE) financing, and on-bill financing—may be able to address these and other market barriers. These financing mechanisms enable a longer-term perspective on energy efficiency improvements, so they may play a role in unlocking economic potential that fails the SPP<5 threshold yet can provide a positive return on investment under the NPV>0 paradigm. These mechanisms can also use ResStock results to help prioritize and target upgrades in particular locations or types of homes.

4.13 Future Work

Opportunities to expand upon the ResStock analysis capabilities presented in this report include:

- **Multifamily buildings.** The current analysis is limited to SFD housing because the housing stock characteristics statistical model was initially developed with a focus on SFD housing. The characteristics data and geometry algorithm could be expanded to enable analysis of the multifamily housing stock.
- **Low-income communities.** Efficiency potential in low-income housing (defined by eligibility in income-qualified weatherization assistance programs or low-income home energy assistance programs) has been identified as an area of interest by a number of stakeholders.. It is of particular interest because low-income households spend a disproportionate amount of their income on energy costs. Direct heating fuels cost are more vulnerable to market price fluctuations, which are most harmful to low-income households with limited budgets. For these reasons there has been increased interest from states, localities, and utilities in reaching low-income households with clean energy and efficiency programs. The current analysis does not include demographics such as income as a variable on which housing characteristics could depend. Yet it is known that some characteristics can be correlated with income level.[127] The housing characteristics statistical model could be modified to account for the relationship between income or other demographics and housing characteristics. This would allow ResStock to be used to evaluate and target energy efficiency potential specifically for low-income communities.
- **Region, state, utility, or local applications.** The ResStock framework could be applied to specific regions, states, utilities, tribal areas, or cities. If data sources specific to the geographic area of interest are available, they can be used to drive ResStock simulations and provide a more accurate representation of the area. This would be especially critical for tribal areas, islands, or other areas where the housing stock is likely to differ in terms of characteristics (e.g., heating fuel types), construction practices, or demographics.
- **Transition to OpenStudio®.** We are in the process of transitioning the ResStock workflow into DOE's OpenStudio modeling ecosystem. OpenStudio is a collection of open-source software tools that serve as an "operating system" for building energy modeling. It automates many of the functions associated with creating energy models; modifying existing energy models; running simulations; and collating, visualizing, and

analyzing modeling results.[128] The OpenStudio implementation of ResStock will make residential building stock analysis more accessible for organizations wishing to employ this type of analysis. For example, OpenStudio will facilitate running simulations on distributed cloud computing.

- **Market adoption modeling.** ResStock could be paired with a detailed model for market adoption so that market adoption potential for residential energy efficiency could be evaluated. This would likely require that additional data on demographics be incorporated into the framework.

Glossary

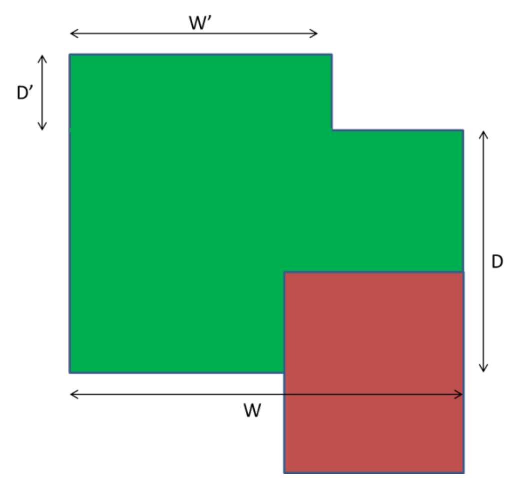
Archetype	A particular combination of archetype parameter values (e.g., Mid-Atlantic, 1980s, gas)
Archetype parameter	Building aspect upon which other building characteristics depend (e.g., location, vintage, heating fuel type)
Archetype variant	A particular combination of different archetype variant characteristics, selected from a set of probability distributions appropriate to the particular archetype
Archetype variant characteristic	Building characteristics that depend on archetype parameters (e.g., attic insulation level, wall insulation level, window type, AC type/efficiency)
Duct leakage	The fraction of air handler fan flow rate that leaks out of pressurized supply ducts into unconditioned space, plus the fraction of fan flow rate that leaks into depressurized return ducts from unconditioned space, plus any leakage into or out of the air handler itself (all measured at 25 pascals pressure difference).
Ductless heat pump	A type of mini-split heat pump that uses a wall, floor, or ceiling mounted indoor unit instead of ductwork
Granularity	The level of detail used to represent a building stock
Primary energy	Total amount of raw fuel energy including all transmission, delivery, and production losses. Also called *source energy.*
Regression	A statistical process that attempts to determine the strength of the relationship between one dependent variable and a series of other changing variables (known as independent variables)
Site energy	Fuel or electricity used by a building on site
Source energy	Total amount of raw fuel energy including all transmission, delivery, and production losses. Also called *primary energy.*
Variable-speed heat pump	Inverter-driven heat pumps that are more efficient and often perform better in cold climates than traditional air-source heat pumps

Appendix A: Geometry Algorithm

The following algorithm is used to automatically determining building geometry based on a home's conditioned floor area, number of stories, and whether or not there is a conditioned basement or attached garage. The algorithm was developed using engineering judgment.

Definitions

$A_{conditioned}$ = conditioned floor area
A_{garage} = garage area
$A_{footprint}$ = footprint area (including $0.5*A_{garage}$)
A = finished floor area, above grade
R = aspect ratio
D = depth
W = width
W' = width of back extension
D' = depth of back extension



Garage dimensions

Single Garage = 12 x 24 if A < 1500
Double Garage = 24 x 24 if A ≥ 1500
Triple Garage = 36 x 24 if A ≥ 3500

Algorithm

$A_{footprint} = [A_{conditioned} + 0.5*A_{garage} (1 + HB - (\#S - 1))]/(\#S + HB)$
where
HB = 1 if heated basement, 0 if no heated basement
#S = number of above grade stories
R = 1.8
$D = sqrt(A_{footprint}/R)$
W = D*R
If $A_{footprint} > 3000$
$W_{max} = 60$
Else
$W_{max} = 50$
If $W > W_{max}$
$W = W_{max}$
W' = D
If $W' > W_{max}$, $W' = W_{max}$
$D' = (A_{footprint} – D* W_{max})/W'$

Appendix B: Mapping Census Tracts to Typical Meteorological Year Locations

U.S. census tracts have between 1,200 and 8,000 inhabitants, with an average size of 4,000. Census tracts, especially those that are sparsely populated and therefore cover a large geographic area, may be in the proximity of multiple TMY3 weather file locations. It is desirable to associate house counts with the most appropriate TMY3 weather file location for simulation. Therefore, the following method was used to associate data for census tracts with TMY3 locations, using 10-kilometer resolution NSRDB gridcells as an intermediate.

Method

Tract-National Solar Radiation Data Base Crosswalk Table

The Tract-NSRDB Crosswalk Table was generated using an existing 200-m residential land mask that was derived from Landscan Nighttime and Daytime Gridded Population data[129] and Homeland Security Infrastructure Program facility location data.[130] This residential land mask grid is a binary raster, with each 200-m grid cell coded as either "residential" or "non-residential." A grid cell that is coded as "residential" represents land that is likely to contain residences. A residential grid cell is exclusive of "group quarters" (e.g., prisons, college campuses, hotels), but is not exclusive of other potential land uses (e.g., commercial, industrial, etc.). The grid does not distinguish between single-family and multi-family residential locations. We have not yet systematically validated this grid; however, visual comparison for metropolitan and suburban locations suggests it is a reasonably accurate representation of residential locations. It has been used in multiple distributed renewable energy modeling projects.

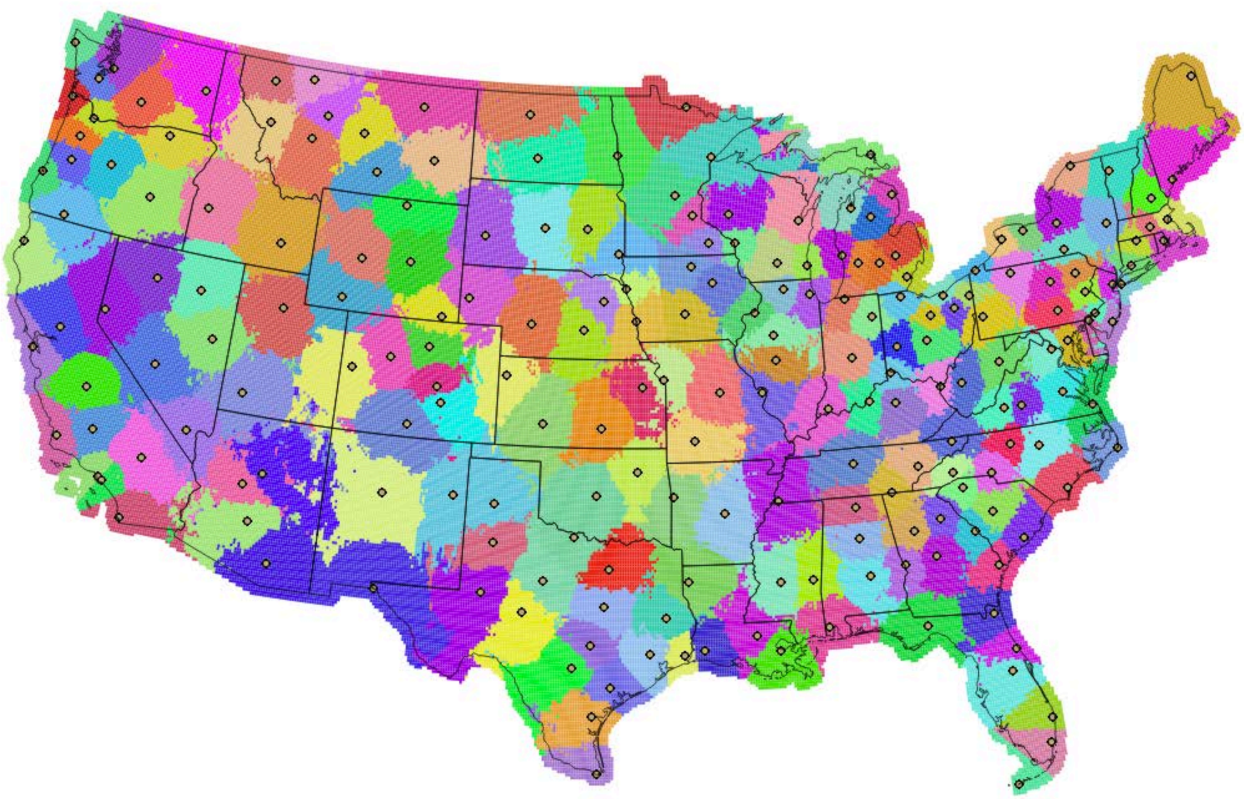
To derive the crosswalk table, we performed a spatial overlay of the American Community Survey (ACS) 2012 5-year census tract boundaries and NSRDB grid cells. For each unique intersection of a tract and grid cell, we calculated a ratio that was used to apportion residential count data from the ACS 2012 5-year survey to the intersection area. To do so, we calculated the total count of 200-m residential grid cells in each unique intersection area and the total count of residential grid cells within each tract. We then divided the intersection count by the related tract count to determine the allocation ratio to be stored in the crosswalk table. The resulting crosswalk table includes a row for each unique intersection area, and three columns: a unique identifier for the tract associated with the intersection area, a unique identifier for the NSRDB grid cell associated with the intersection area, and the allocation ratio.

The crosswalk table has certain limitations. The allocation method accounts for our current best estimate of the spatial distribution of residential land, weighting each unit of residential land equally. As a result, this method does not account for spatial variation in the number of housing units of different types (e.g., single-family versus multi-family, owner-occupied versus renter-occupied), nor is it weighted to account for variation in population density. The derived ratio should be interpreted as the weighting of residential land in each tract-NSRDB grid cell intersection relative to the total residential land in each tract.

Despite these limitations, this method is better for most applications than other techniques, such as area weighting or population centroids. It is consistent with other publicly available crosswalk methods, such as the HUD USPS Zip Crosswalk Files, which use ratios of postal addresses instead of residential land. Furthermore, it is a method that has been used in other recent and ongoing projects to allocate data such as housing units, electric customers, and annual energy load between various regional units.

National Solar Radiation Data Base-Typical Meteorological Year Location Lookup Table
To enable linking of the NSRDB Grid Cells back to individual TMY3 stations, we use a lookup table containing a unique row for each NSRDB grid cell, and three columns: a unique identifier for each NSRDB grid cell, a unique identifier for the associated TMY3 Station, and the abbreviation for the state that contains the center point of the grid cell. The unique identifier used for each TMY3 station is the USAF ID. This methodology for this linking is similar to that used in,[131] but with 216 TMY3 locations instead of 554. The mapping accounts for proximity, elevation, solar radiation, and data quality.

Figure B-1. Census tracts mapped to 216 Typical Meteorological Year (TMY3) locations (via National Solar Radiation Data Base gridcells)



Subregions for the 216 TMY3 locations were developed based on data quality, proximity, and elevation. These subregions are aggregations of National Solar Radiation Data Base 10-kilometer gridcells.

Appendix C: State Supply Curves

Section 3.12.4 describes supply curves that present the economic potential of upgrades with a dimension for comparing cost-effectiveness. This appendix includes a supply curve for each of the 48 contiguous U.S. states and D.C. Note that the *y*-axis scale is fixed at -1.0 to 0.0 ($/kWh), which truncates the bar for some upgrades that have an average net cost of conserved electricity of less than -1.0 ($/kWh).

Figure C-1. Electric efficiency supply curve for Alabama

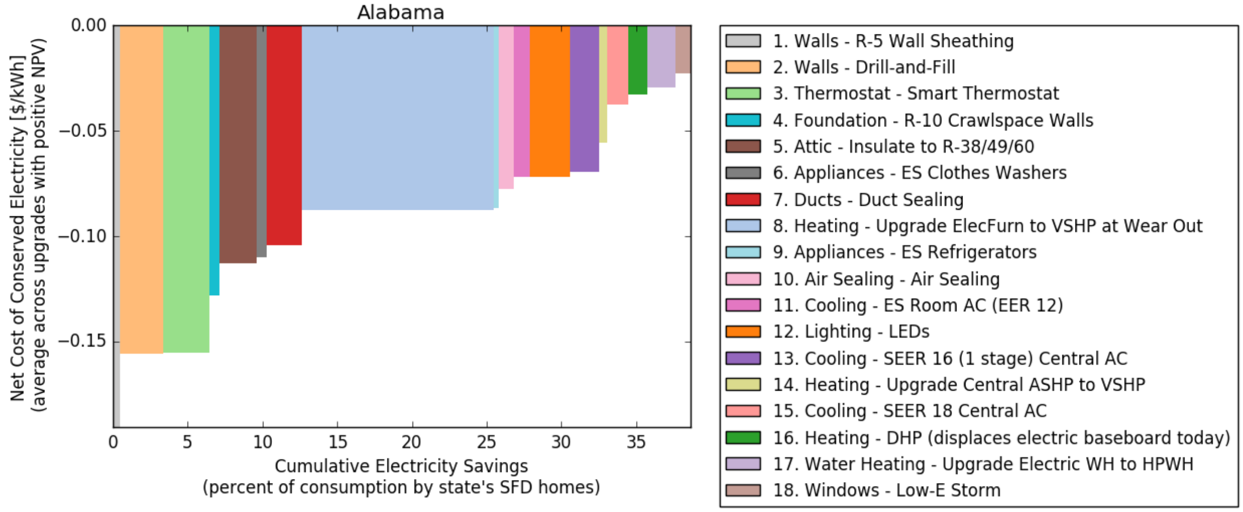


Figure C-2. Electric efficiency supply curve for Arizona

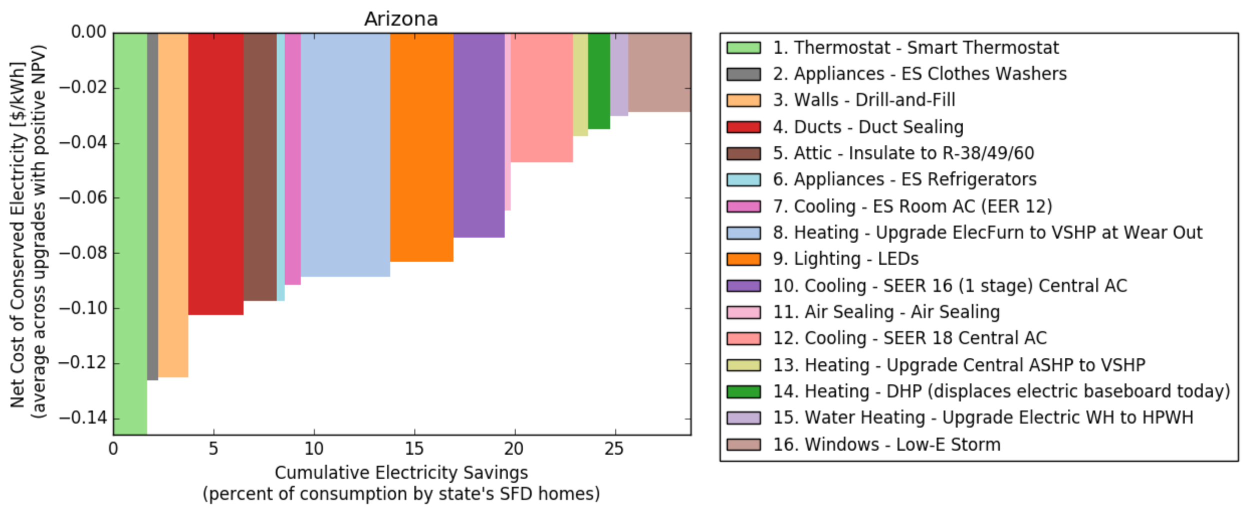


Figure C-3. Electric efficiency supply curve for Arkansas

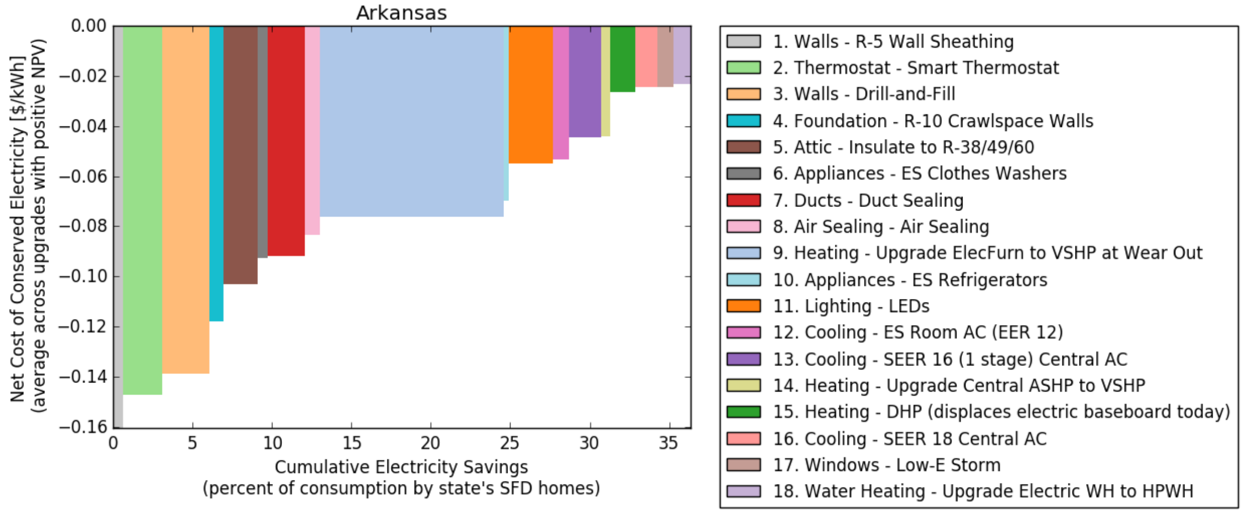


Figure C-4. Electric efficiency supply curve for California

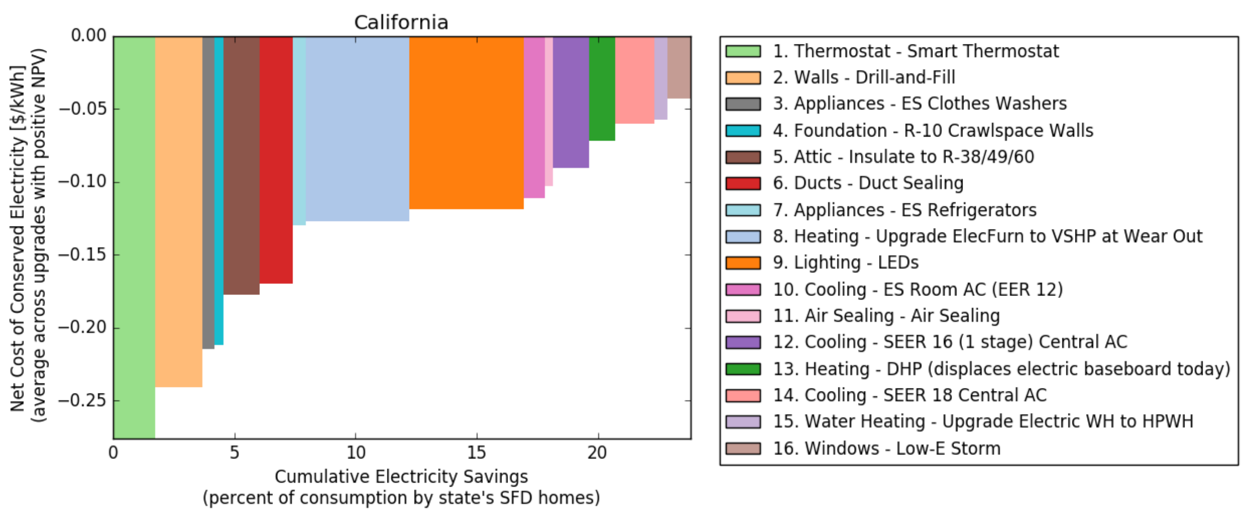


Figure C-5. Electric efficiency supply curve for Colorado

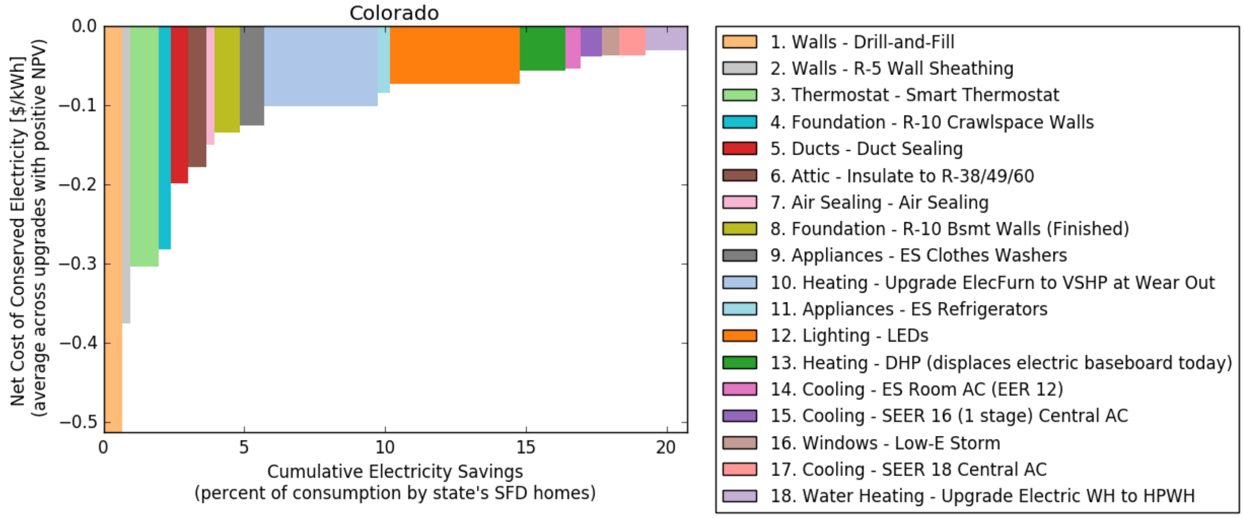


Figure C-6. Electric efficiency supply curve for Connecticut

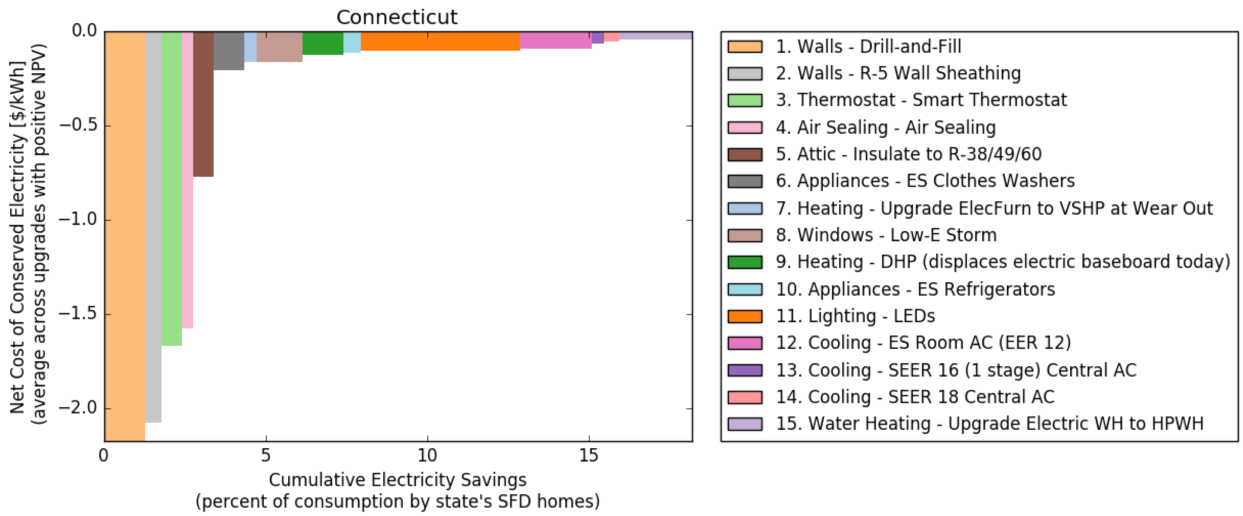


Figure C-7. Electric efficiency supply curve for Delaware

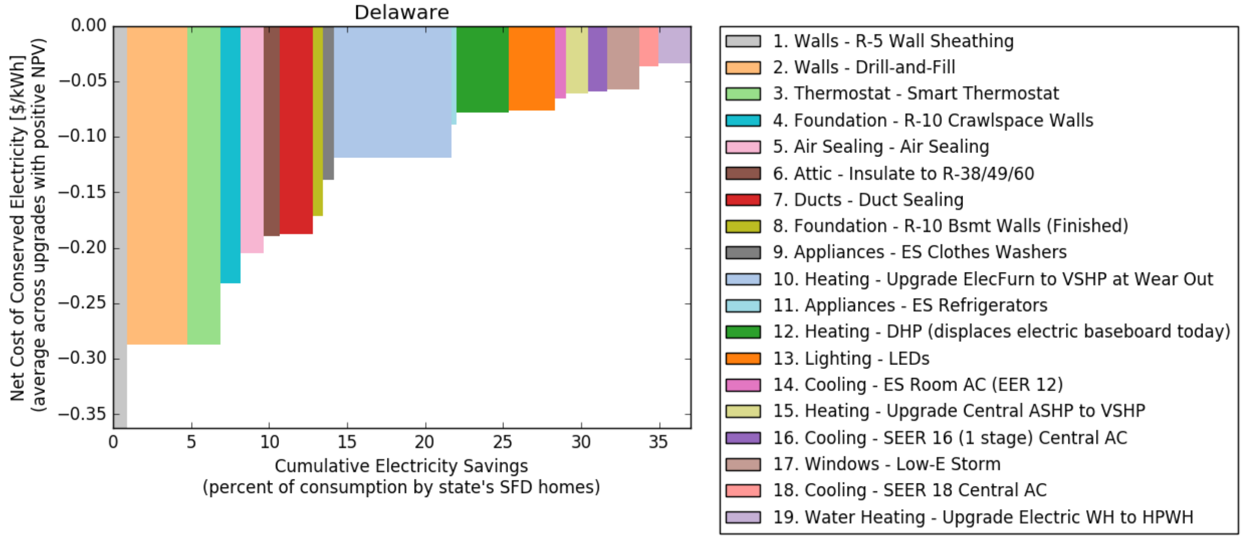


Figure C-8. Electric efficiency supply curve for District of Columbia

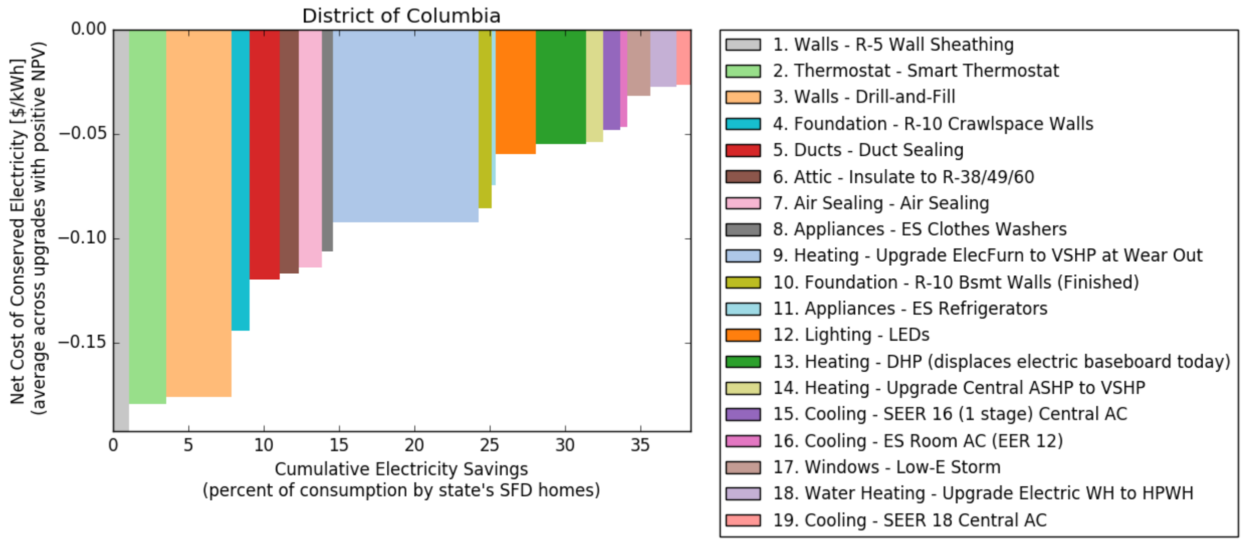


Figure C-9. Electric efficiency supply curve for Florida

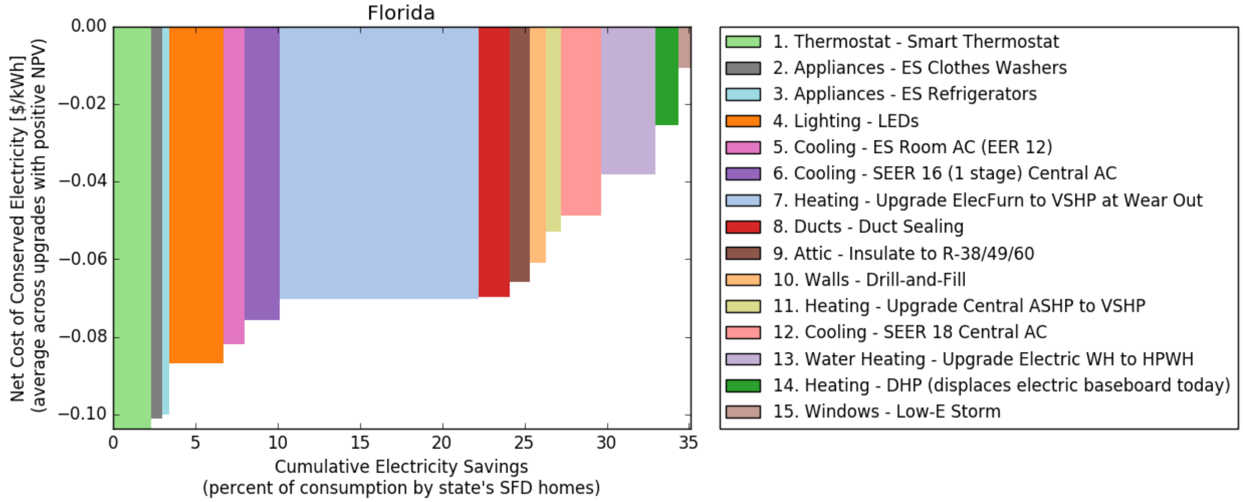


Figure C-10. Electric efficiency supply curve for Georgia

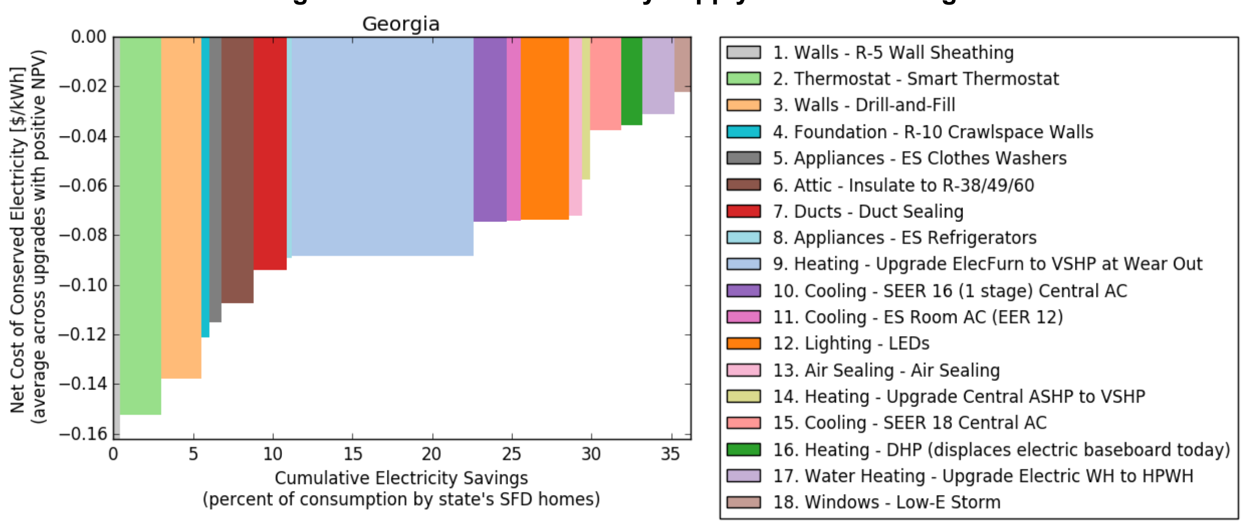


Figure C-11. Electric efficiency supply curve for Idaho

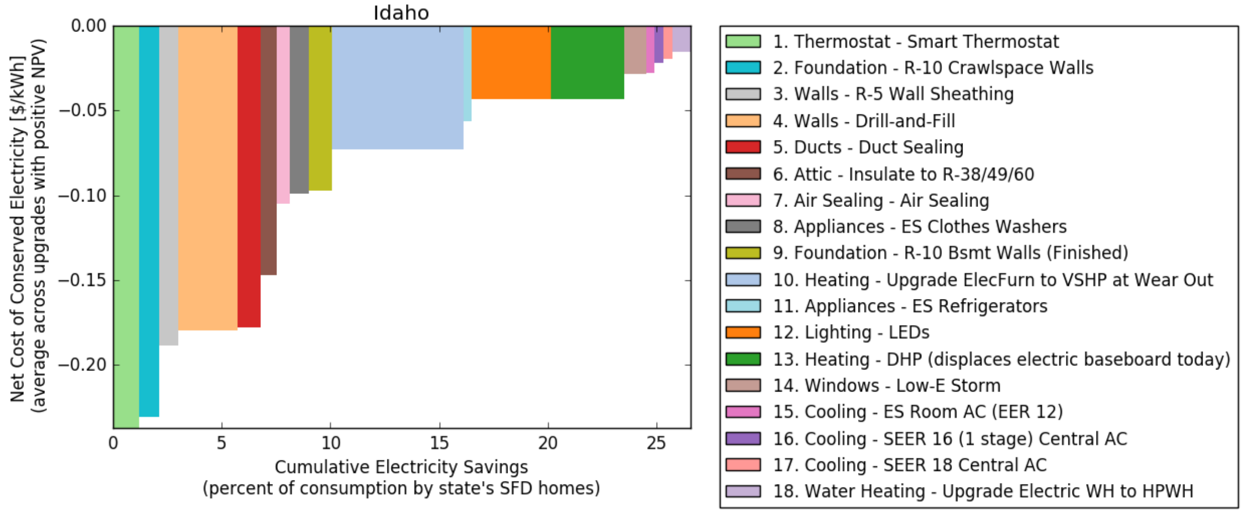


Figure C-12. Electric efficiency supply curve for Illinois

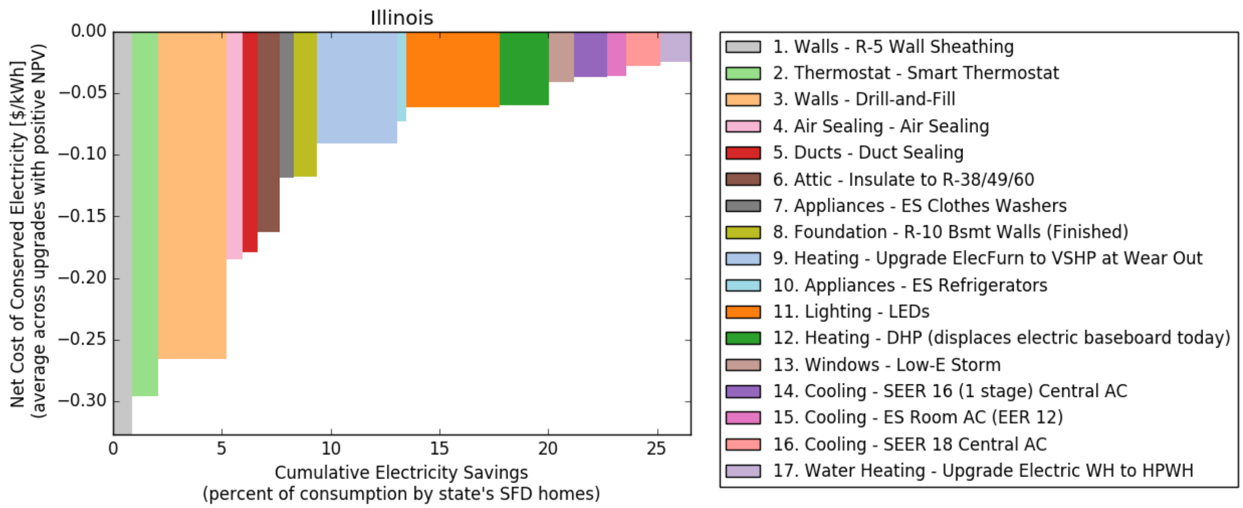


Figure C-13. Electric efficiency supply curve for Indiana

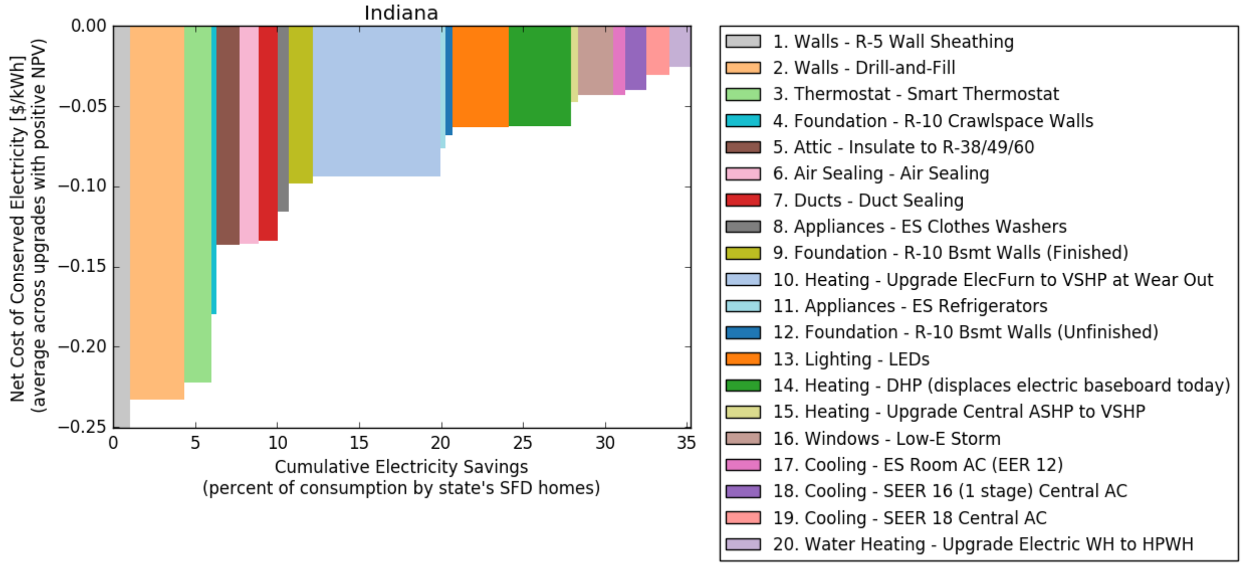


Figure C-14. Electric efficiency supply curve for Iowa

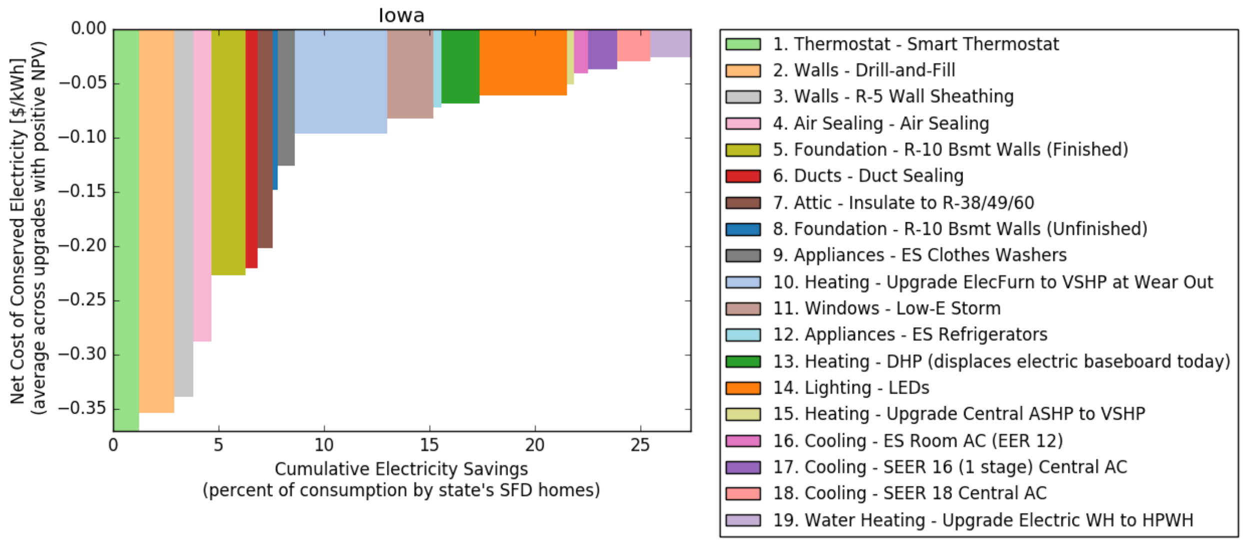
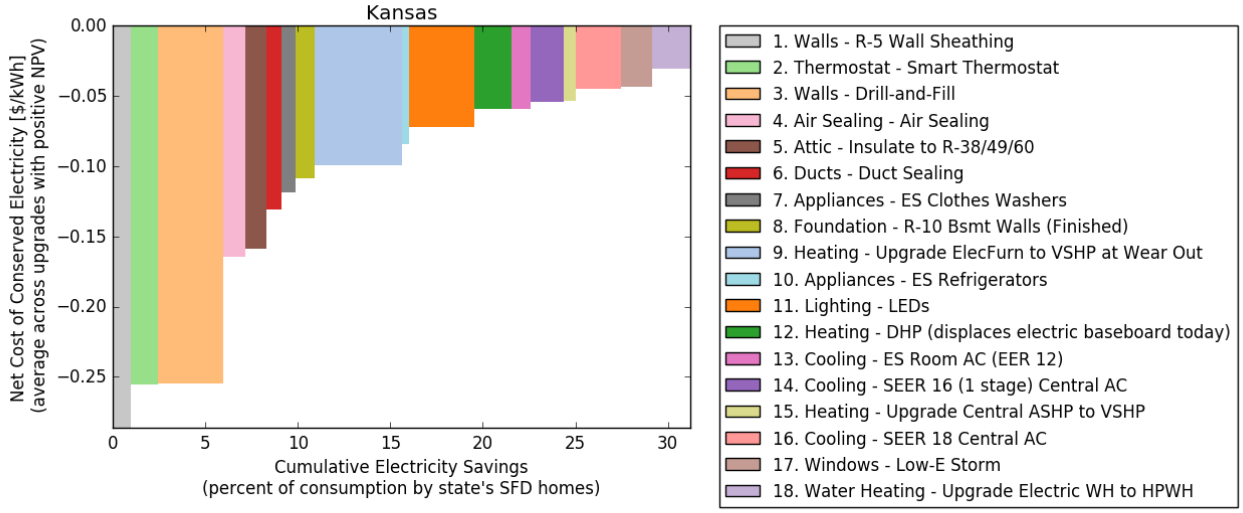


Figure C-15. Electric efficiency supply curve for Kansas



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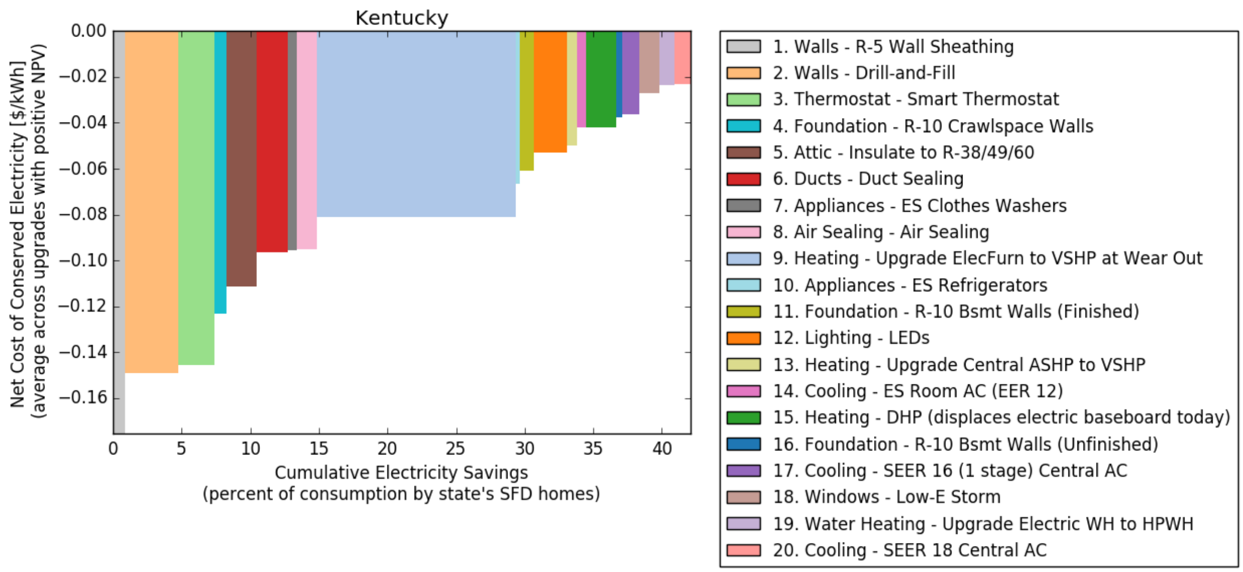

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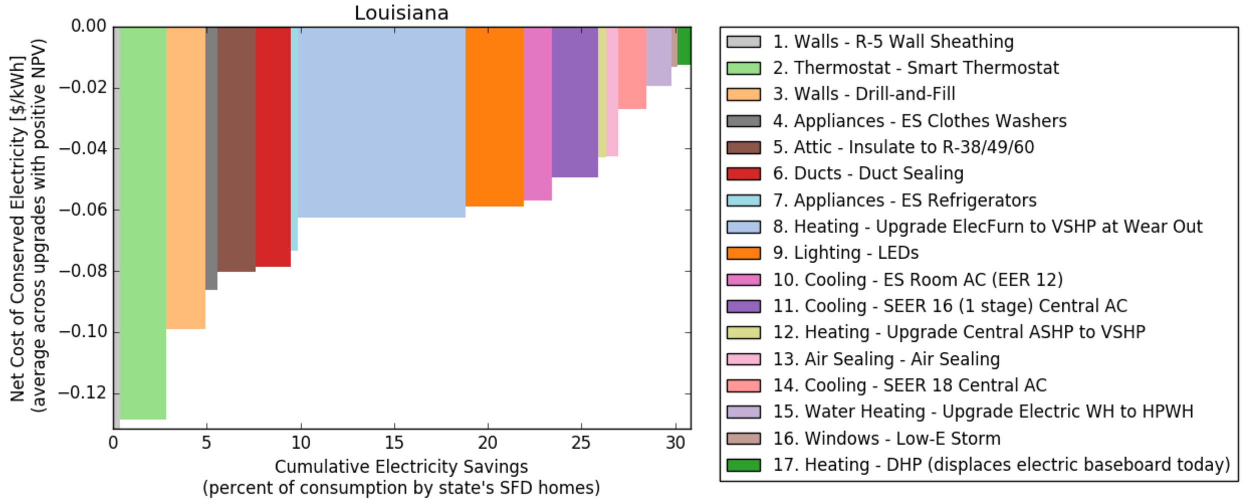
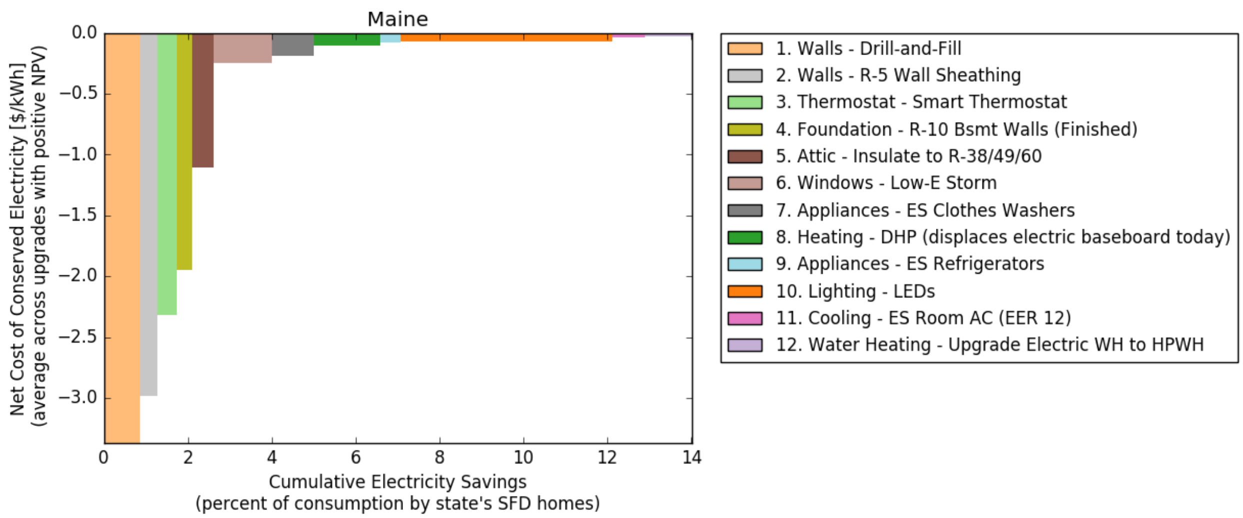


Figure C-18. Electric efficiency supply curve for Maine



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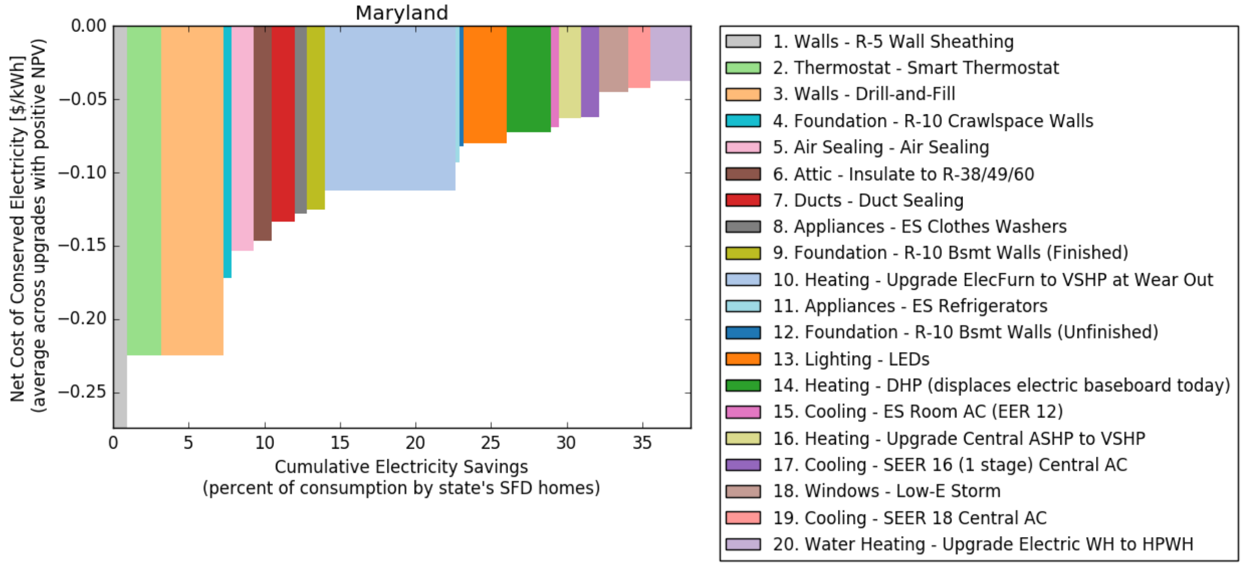

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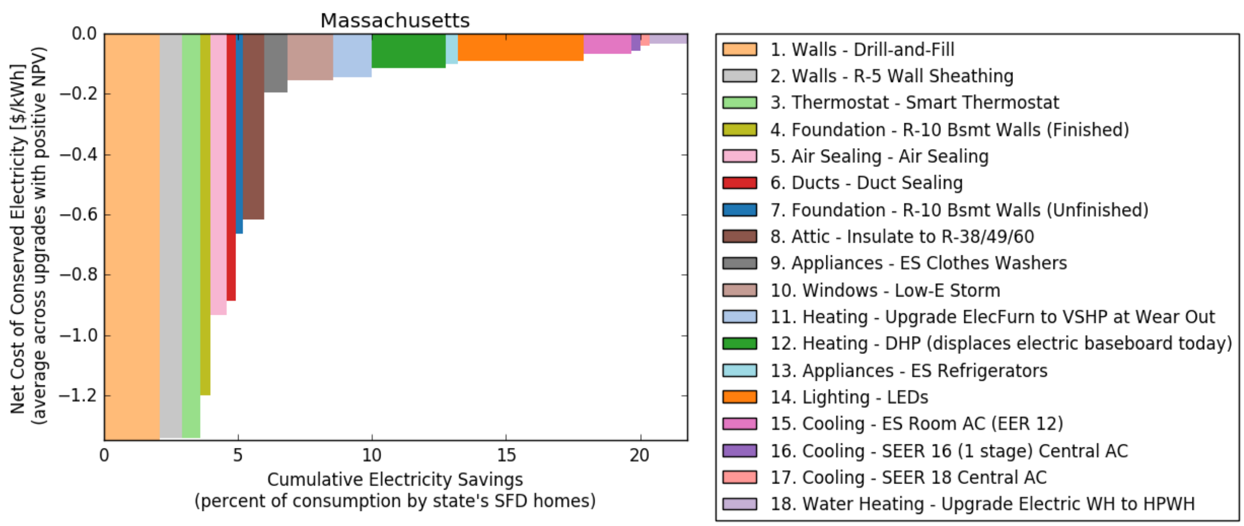

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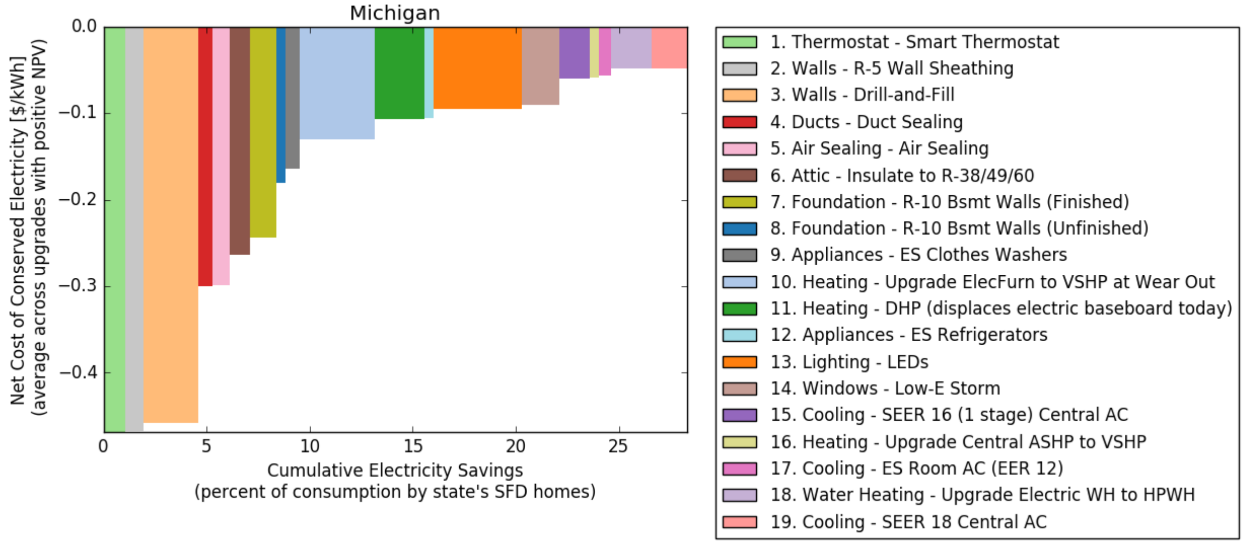

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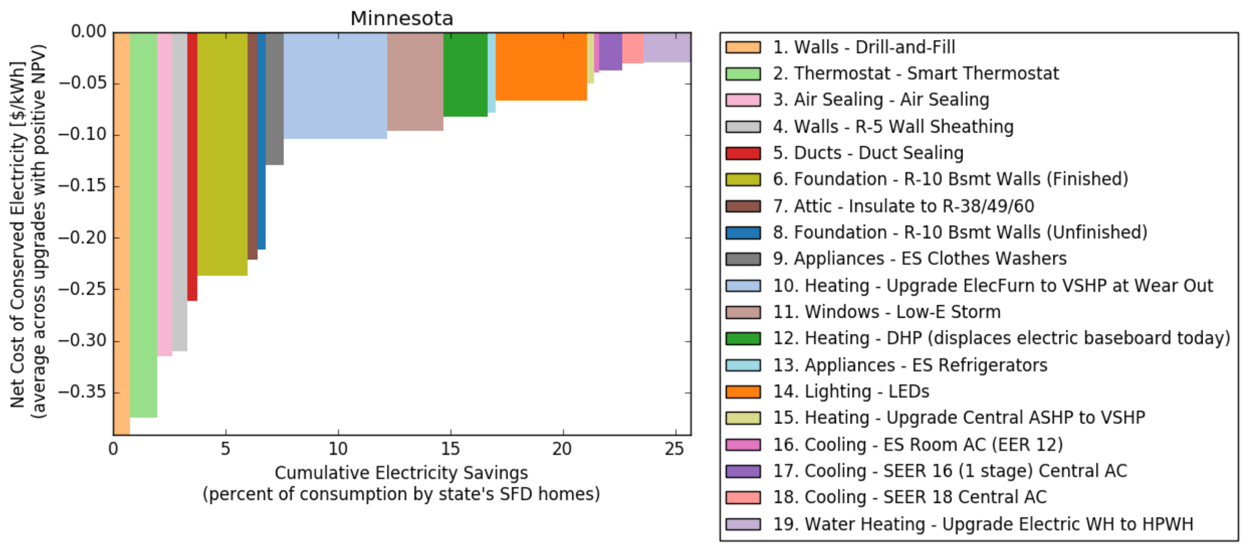

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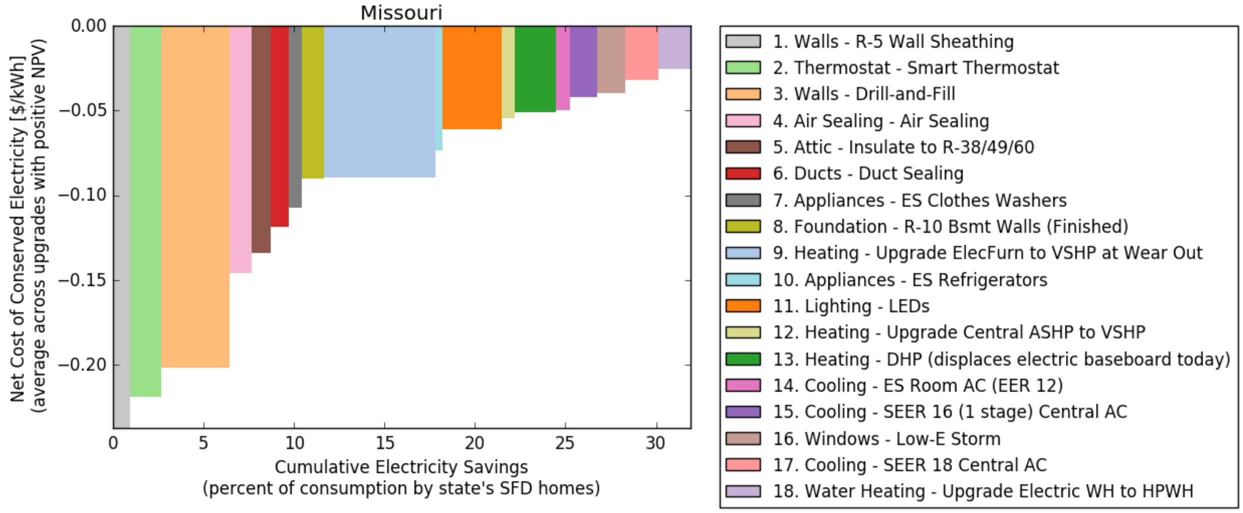

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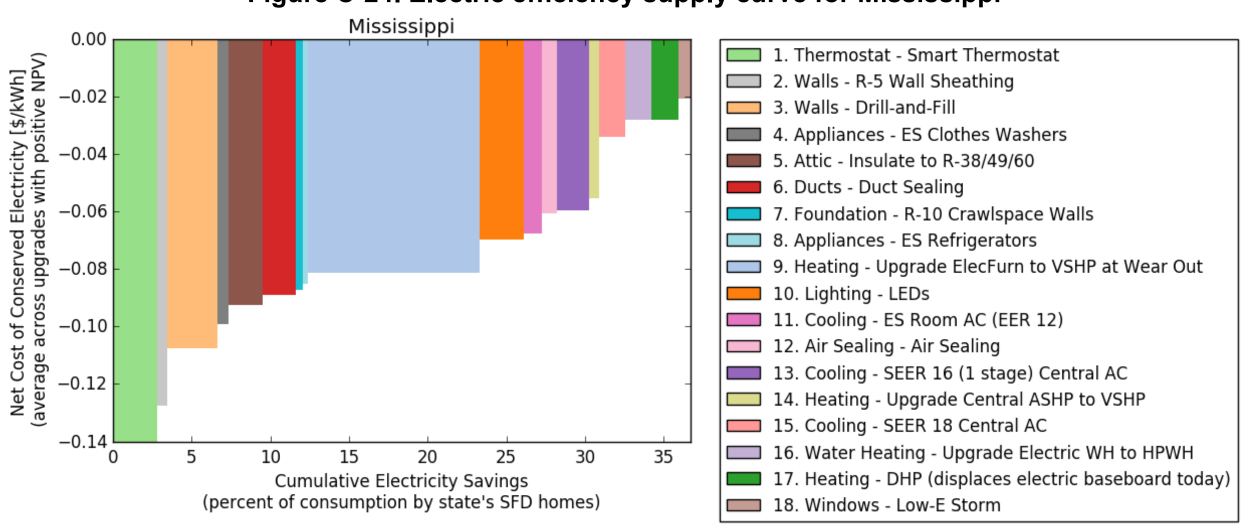

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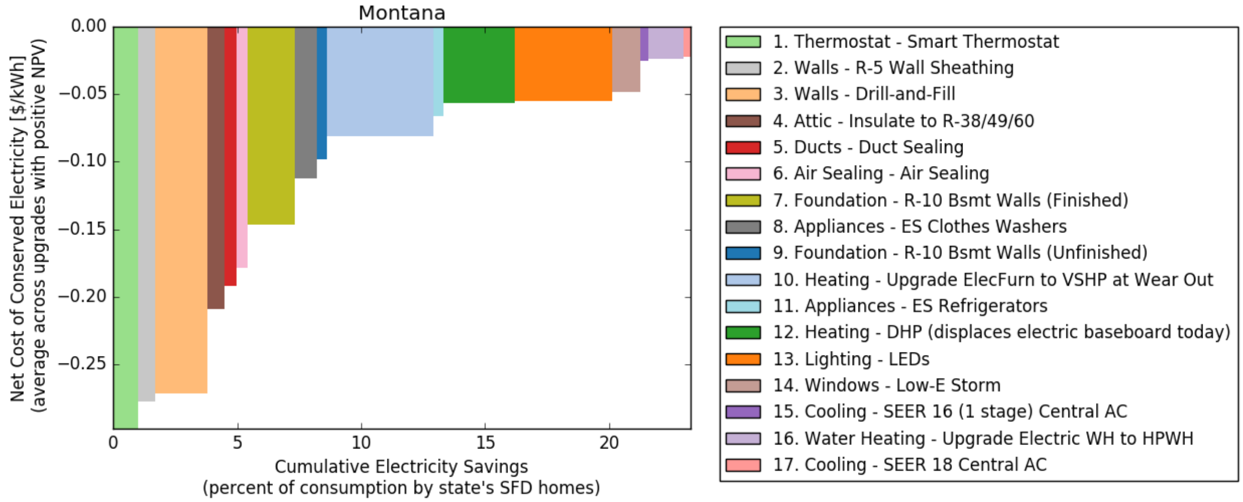


Figure C-26. Electric efficiency supply curve for Nebraska

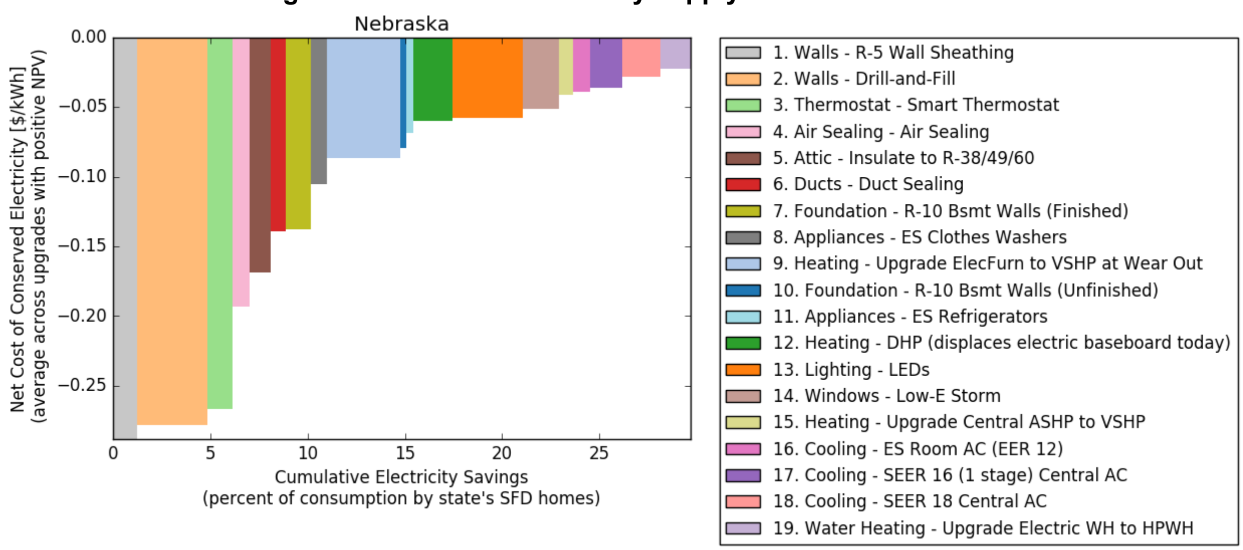


Figure C-27. Electric efficiency supply curve for Nevada

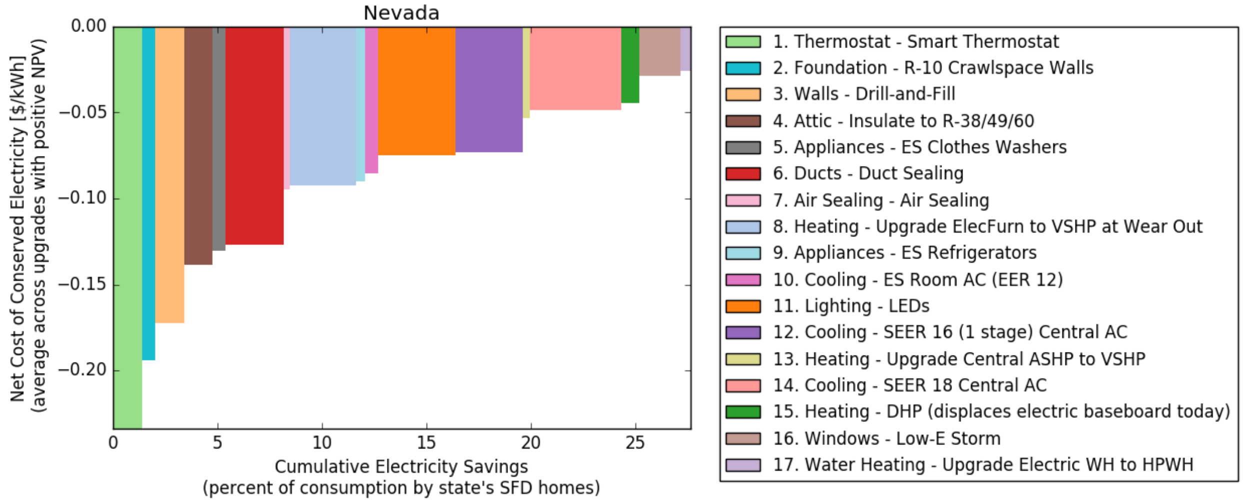
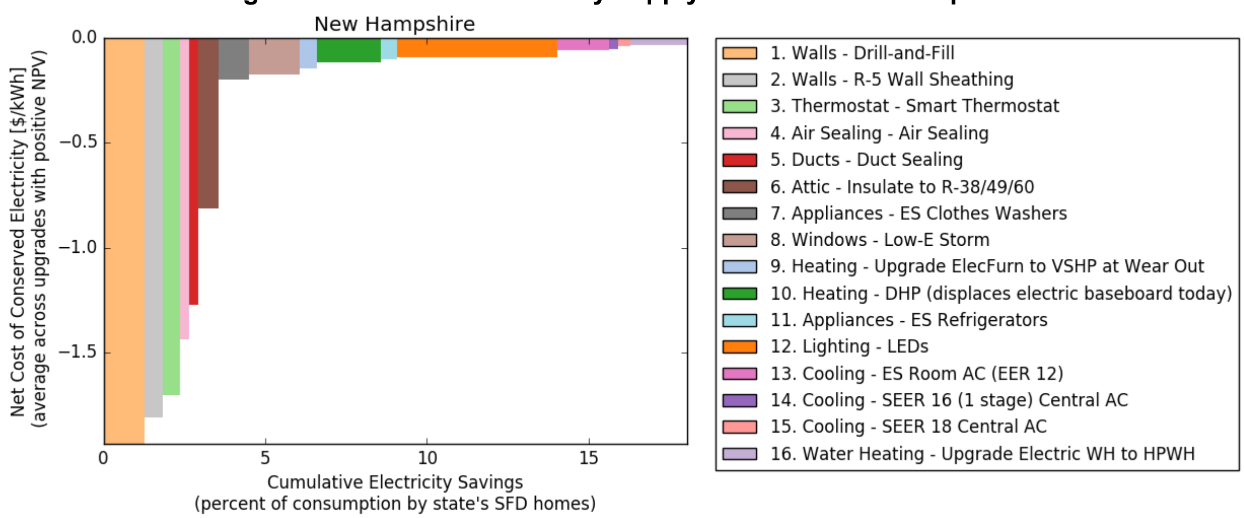


Figure C-28. Electric efficiency supply curve for New Hampshire



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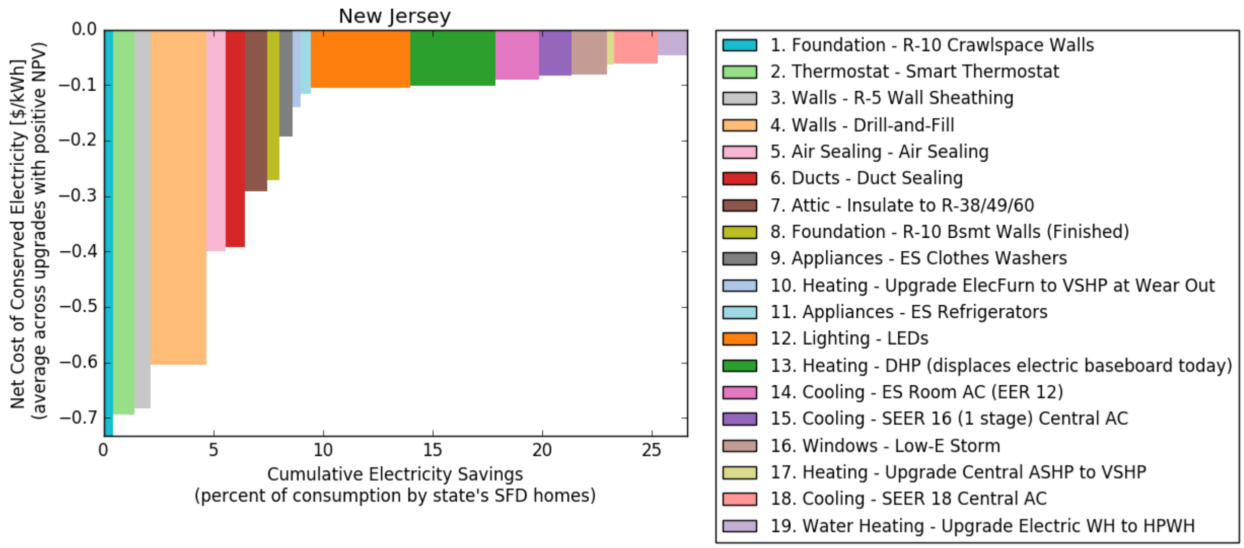


Figure C-30. Electric efficiency supply curve for New Mexico

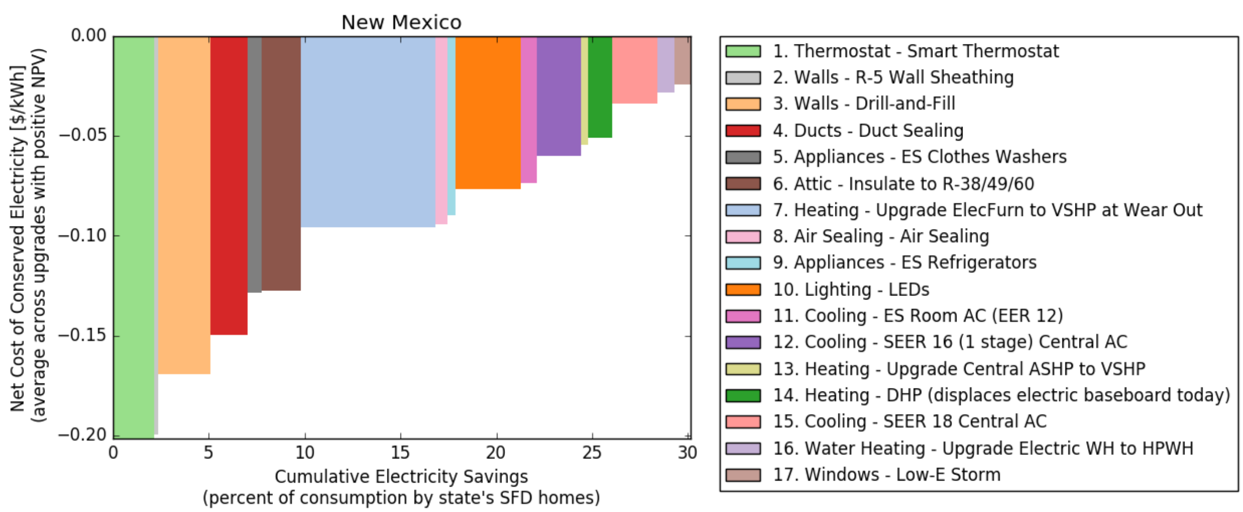


Figure C-31. Electric efficiency supply curve for New York

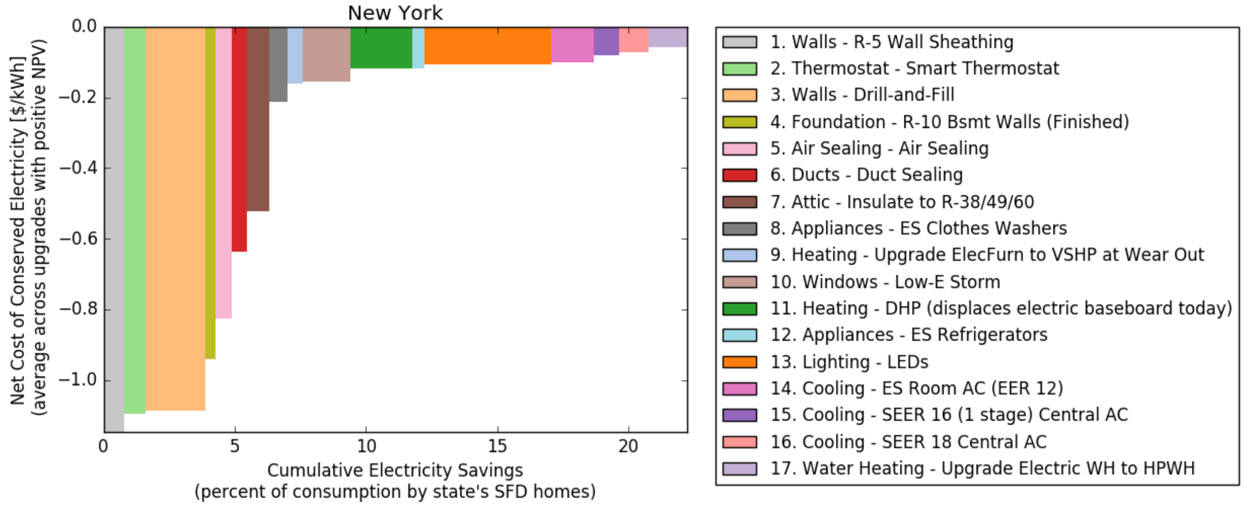


Figure C-32. Electric efficiency supply curve for North Carolina

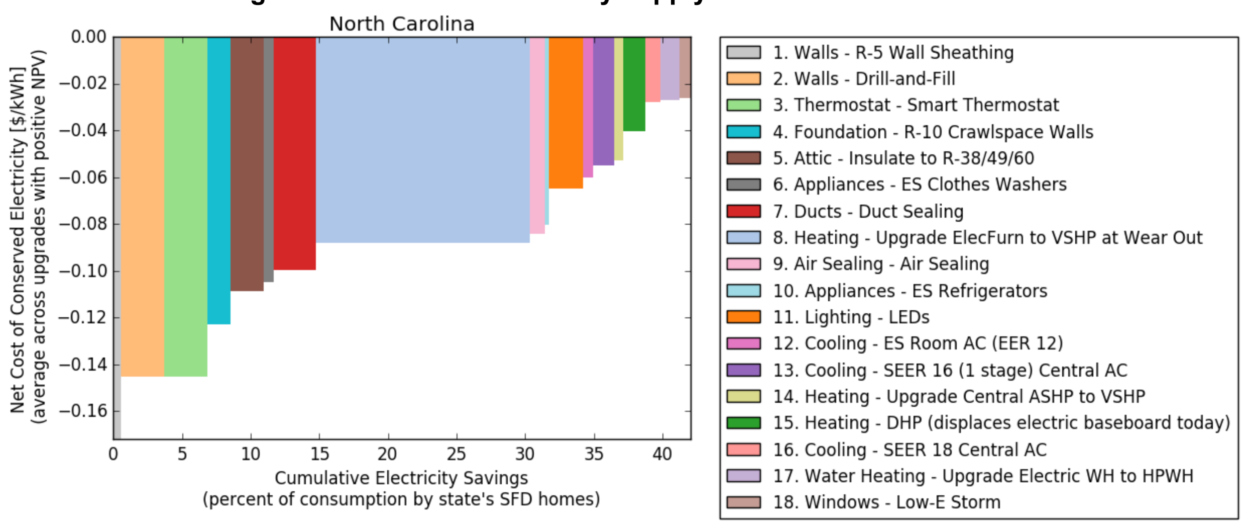


Figure C-33. Electric efficiency supply curve for North Dakota

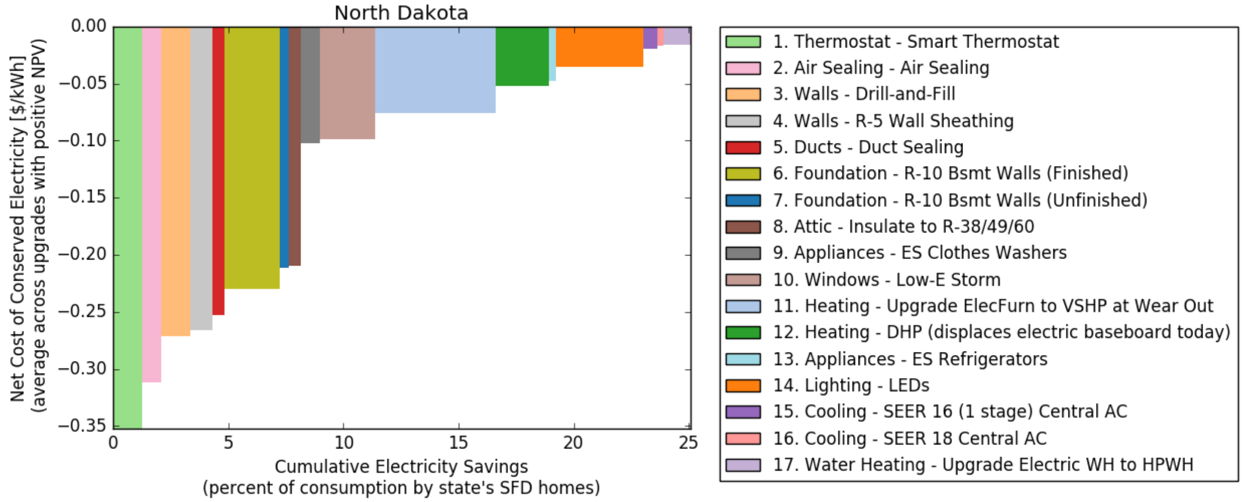


Figure C-34. Electric efficiency supply curve for Ohio

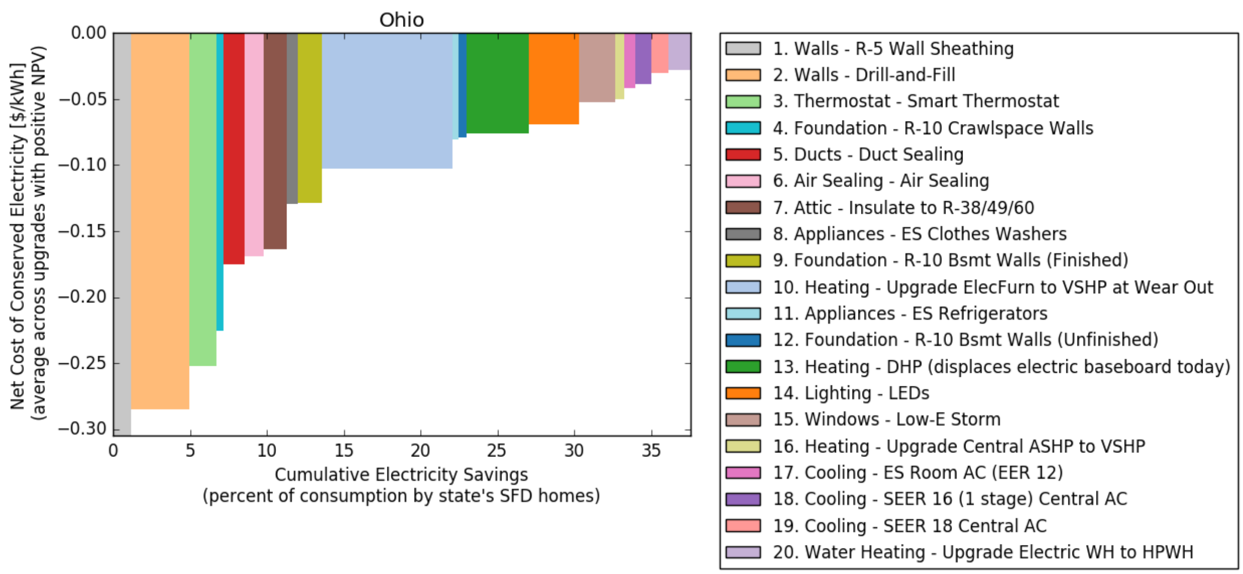


Figure C-35. Electric efficiency supply curve for Oklahoma

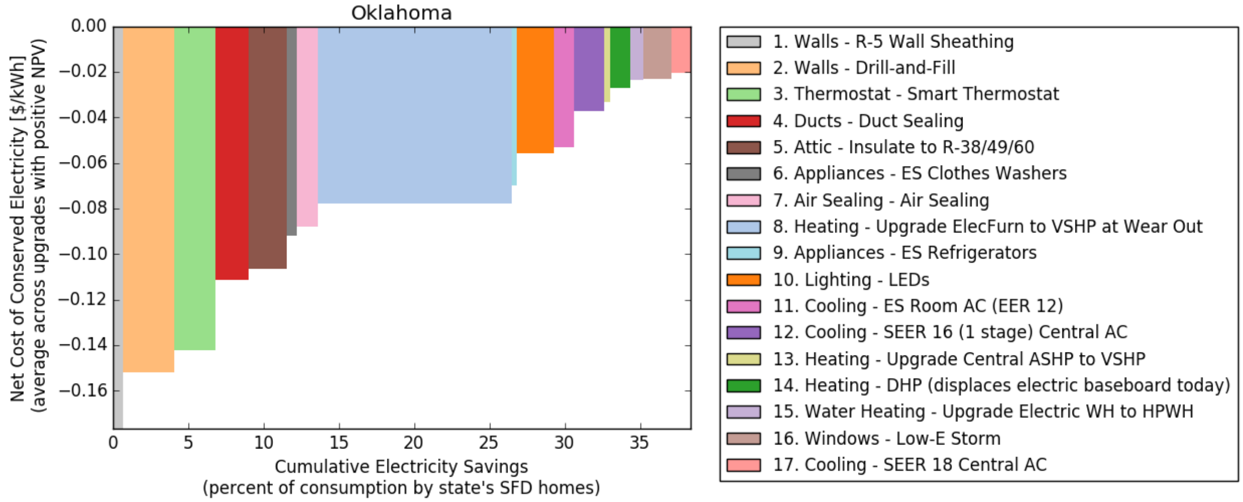


Figure C-36. Electric efficiency supply curve for Oregon

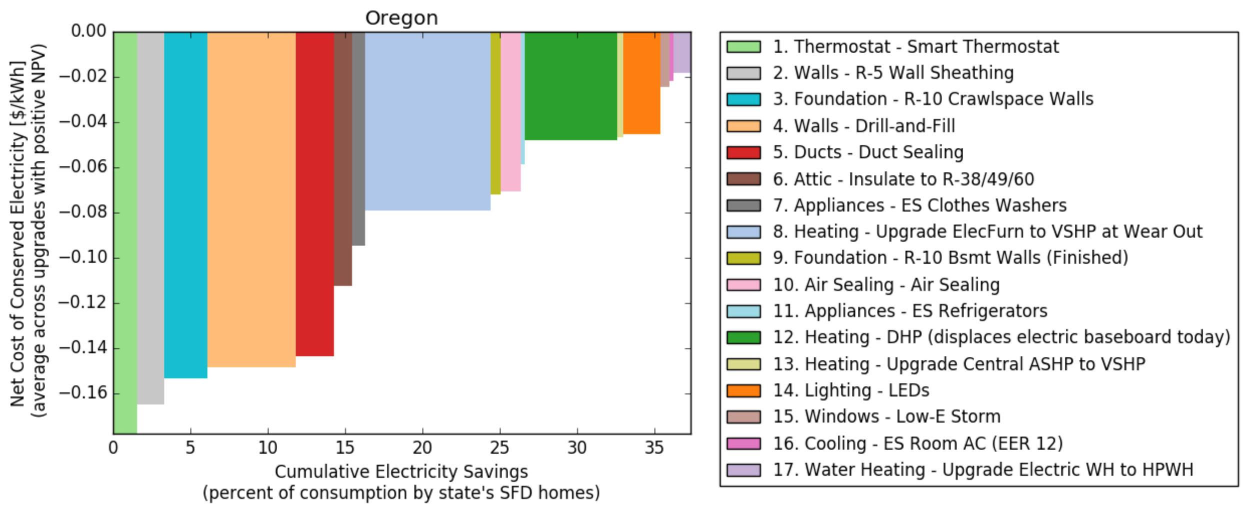


Figure C-37. Electric efficiency supply curve for Pennsylvania

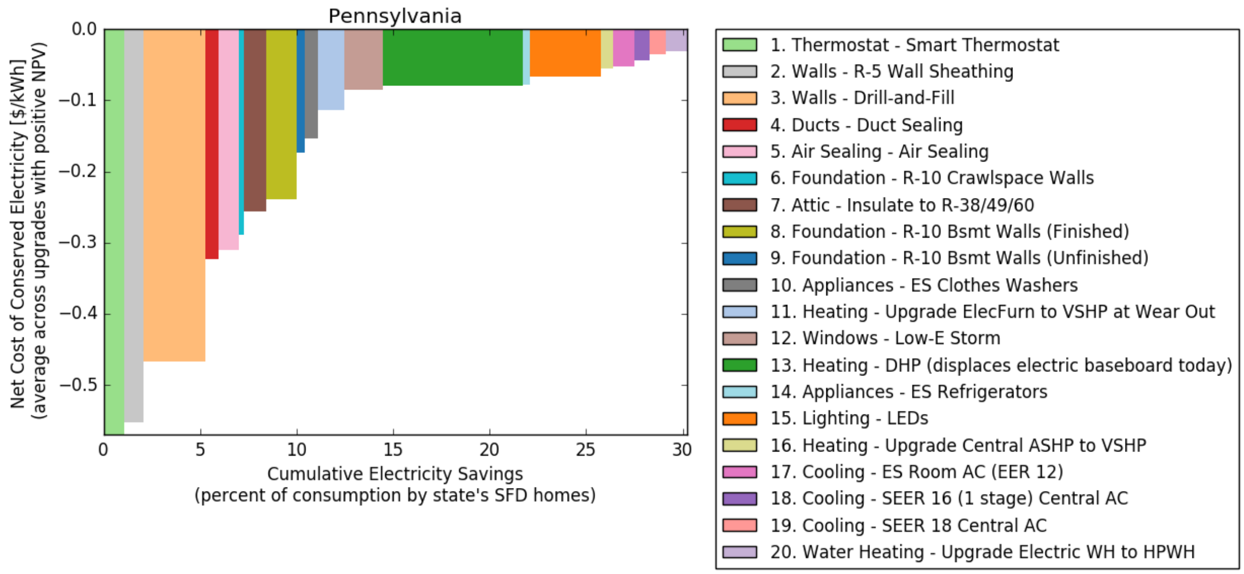


Figure C-38. Electric efficiency supply curve for Rhode Island

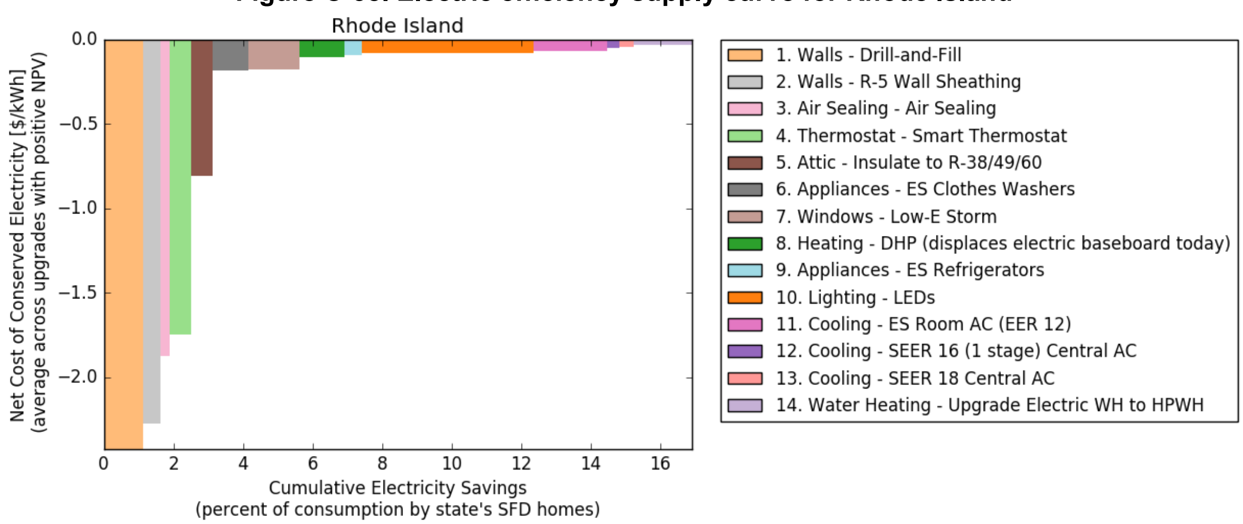


Figure C-39. Electric efficiency supply curve for South Carolina

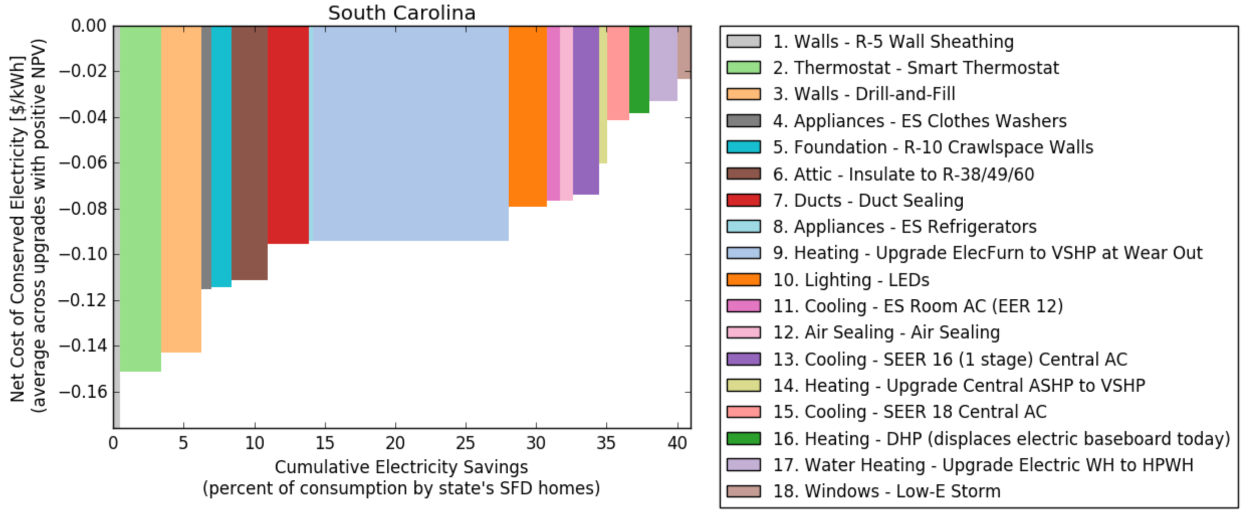


Figure C-40. Electric efficiency supply curve for South Dakota

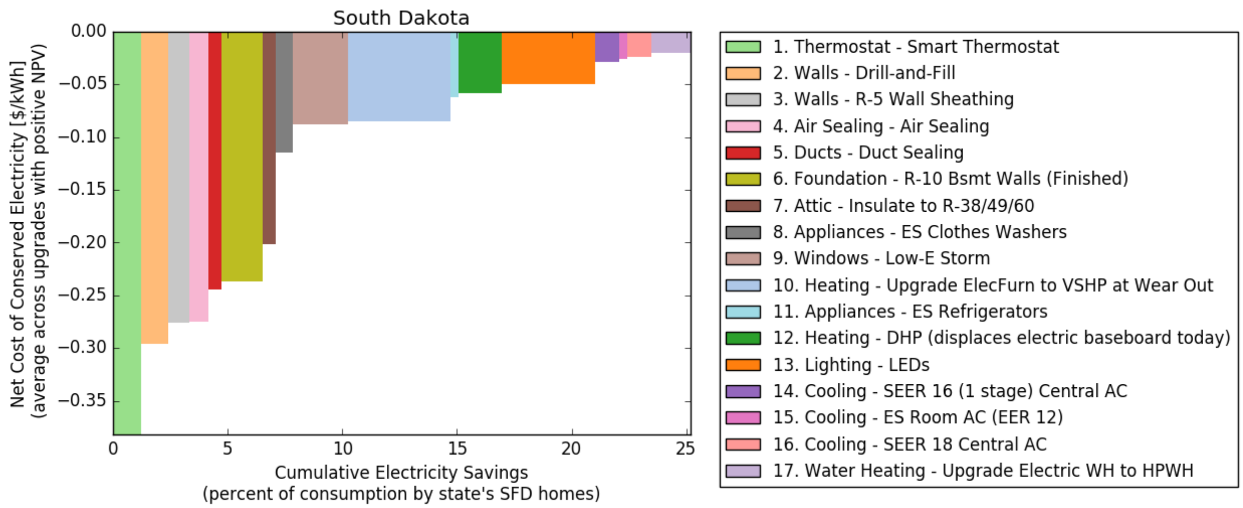


Figure C-41. Electric efficiency supply curve for Tennessee

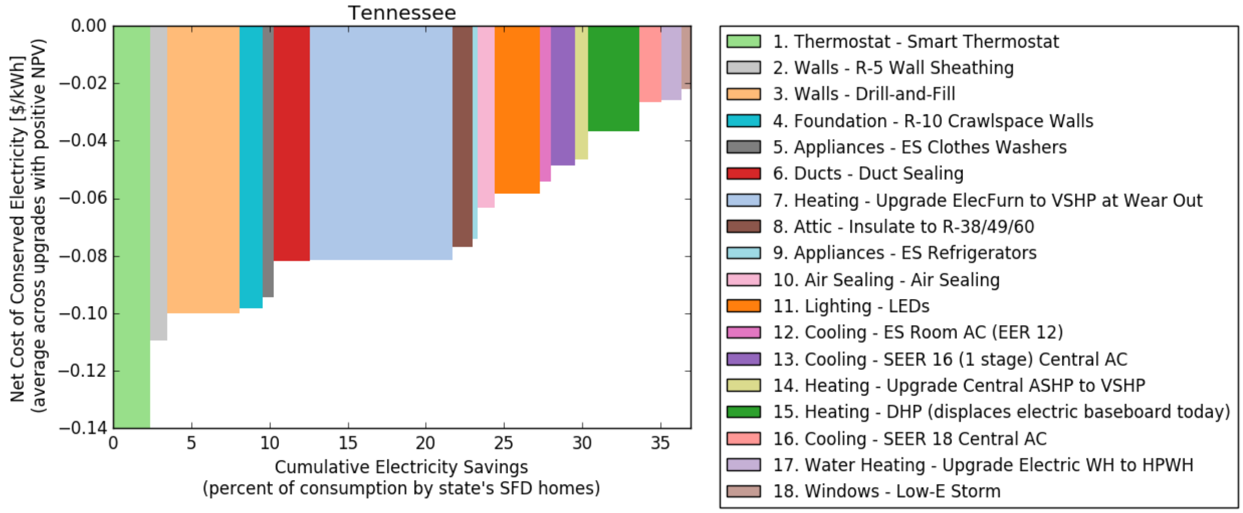


Figure C-42. Electric efficiency supply curve for Texas

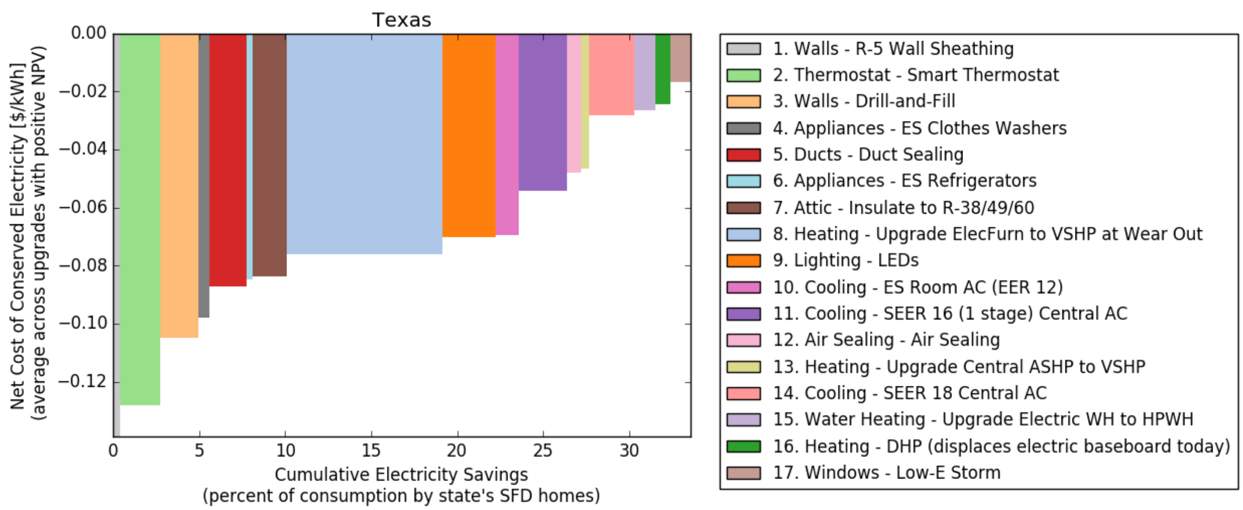


Figure C-43. Electric efficiency supply curve for Utah

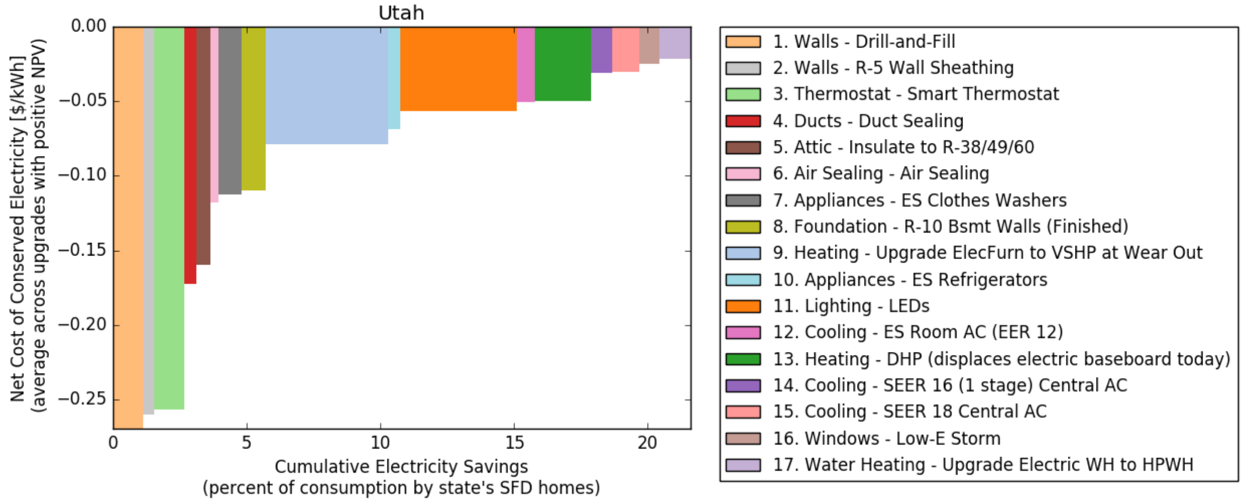


Figure C-44. Electric efficiency supply curve for Vermont

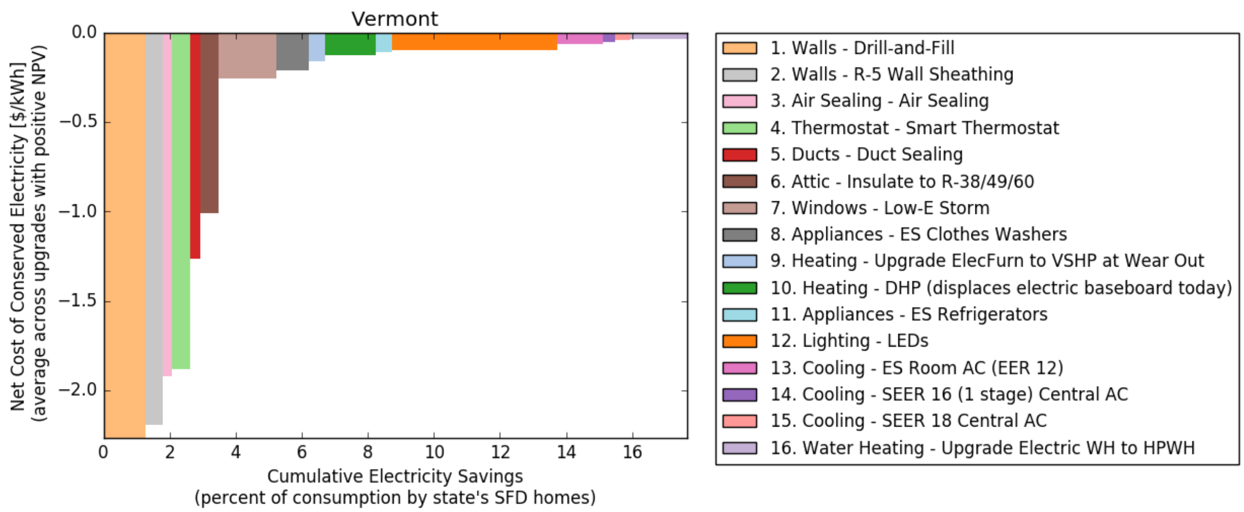


Figure C-45. Electric efficiency supply curve for Virginia

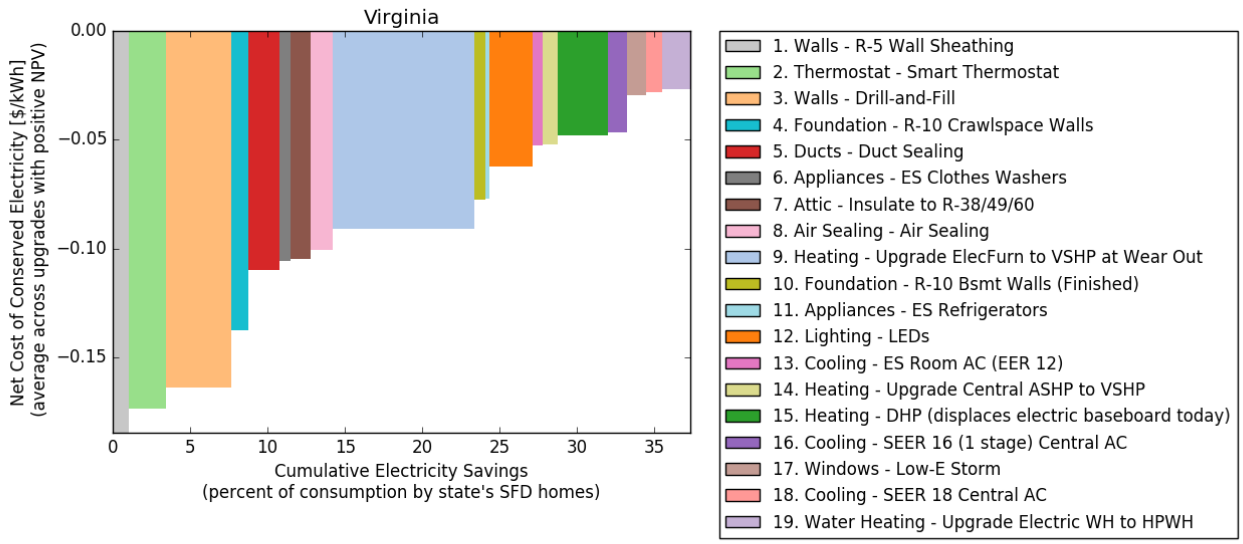


Figure C-46. Electric efficiency supply curve for Washington

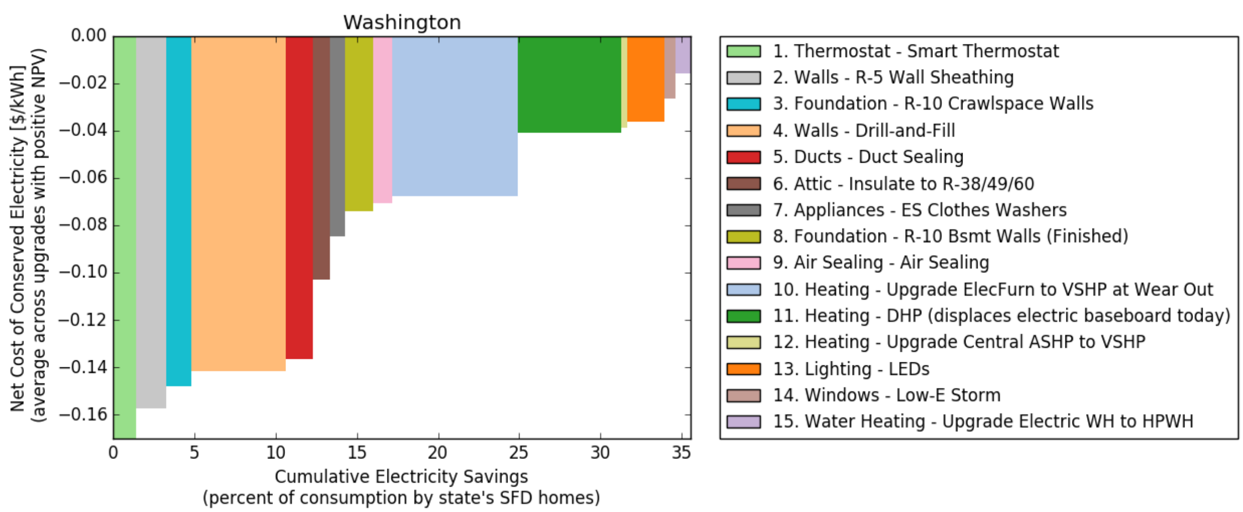


Figure C-47. Electric efficiency supply curve for West Virginia

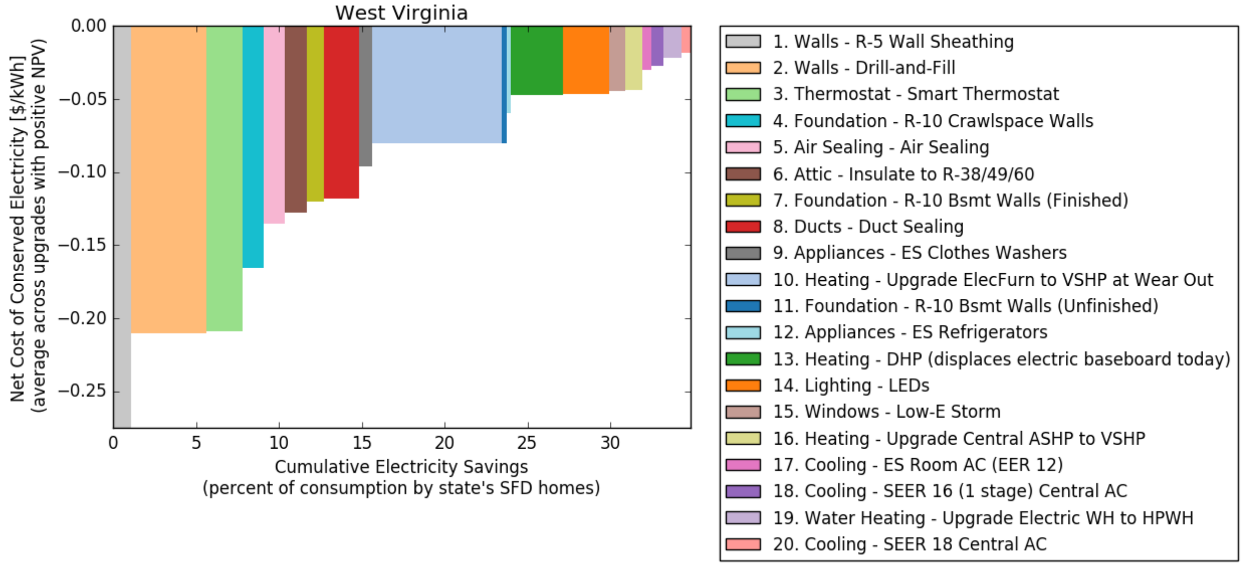


Figure C-48. Electric efficiency supply curve for Wisconsin

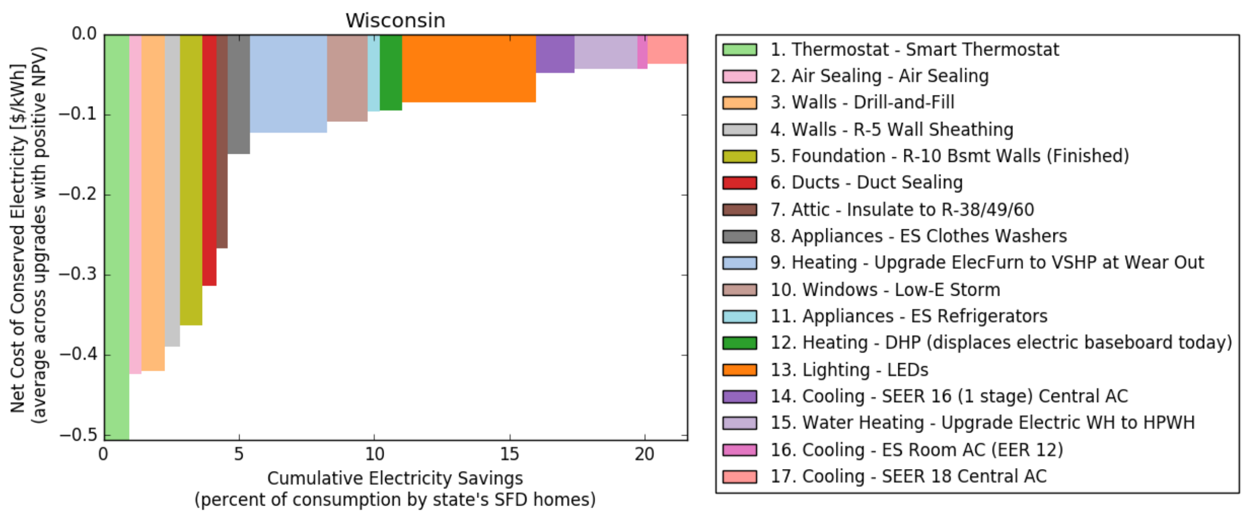
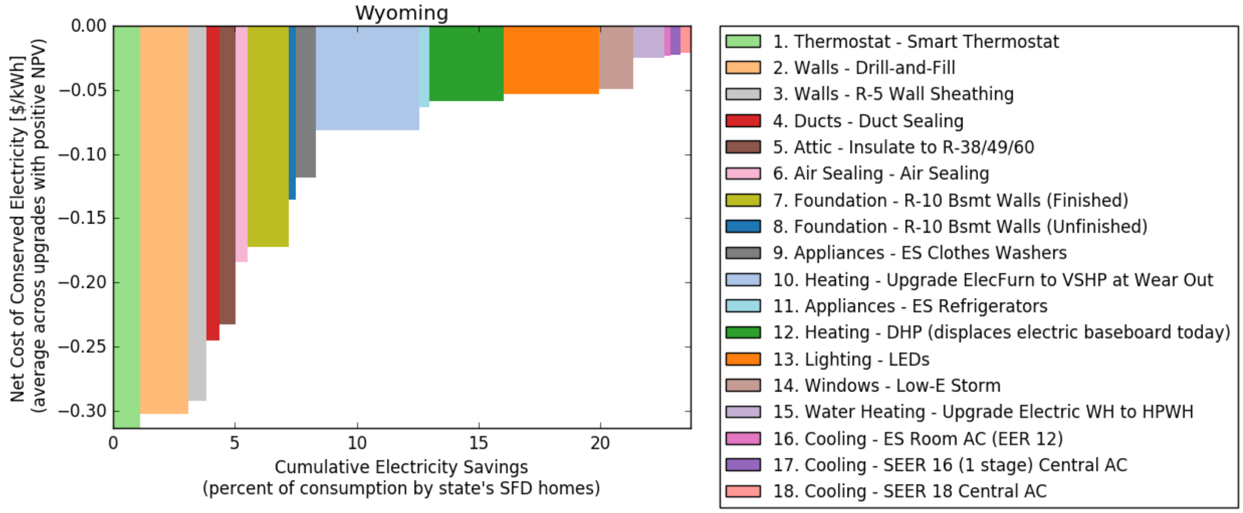


Figure C-49. Electric efficiency supply curve for Wyoming



Appendix D: Trades-Based Package Results

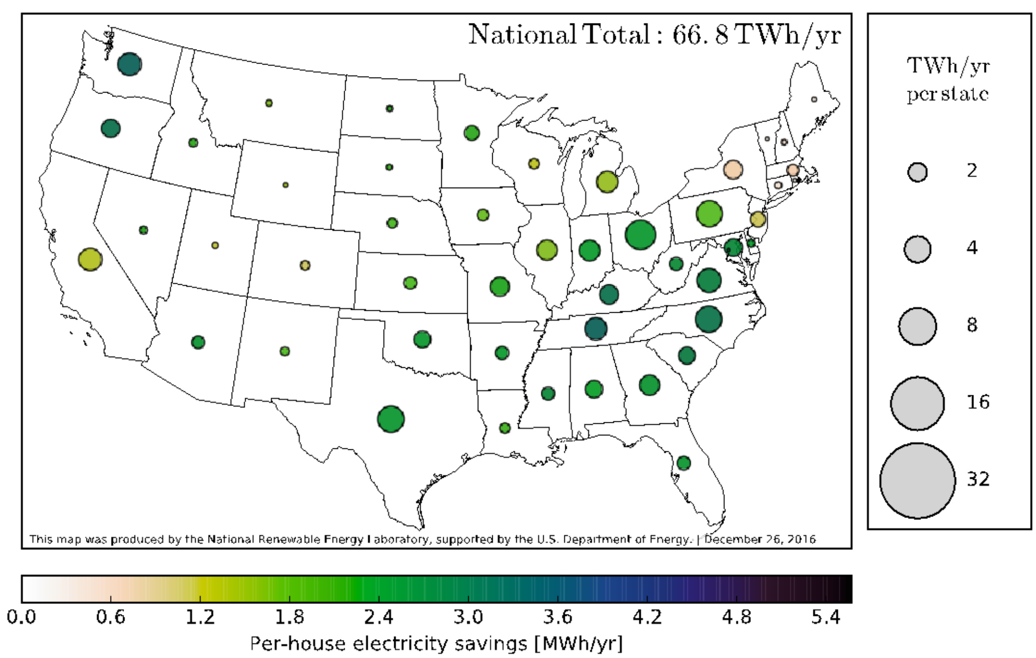
The packages of simulations described in section 2.9 allow inclusion of efficiency upgrades in all categories: enclosure, HVAC, water heating, appliances, and lighting. Alternative packages limited to a subset of those categories (organized by building trades) were also simulated. The definitions of these packages are in Table D-1. The following maps show the economic potential of these alternative packages, using the NPV > 0 threshold (Figures D-1 through D-5).

Table D-1. Package definitions

Package name	Upgrade categories considered for inclusion
Enclosure Upgrades	Air sealing, attic insulation, wall insulation, foundation insulation, low-E storm windows
HVAC Upgrades	Heating equipment, cooling equipment, duct sealing/insulation, smart thermostat
Enc.+HVAC Upgrades	All listed in above rows
Enc.+HVAC+WH Upgrades	All listed in above rows, plus water heater upgrades
All Upgrades	All listed in above rows, plus lighting and appliances (clothes washers, dishwashers, and refrigerators)

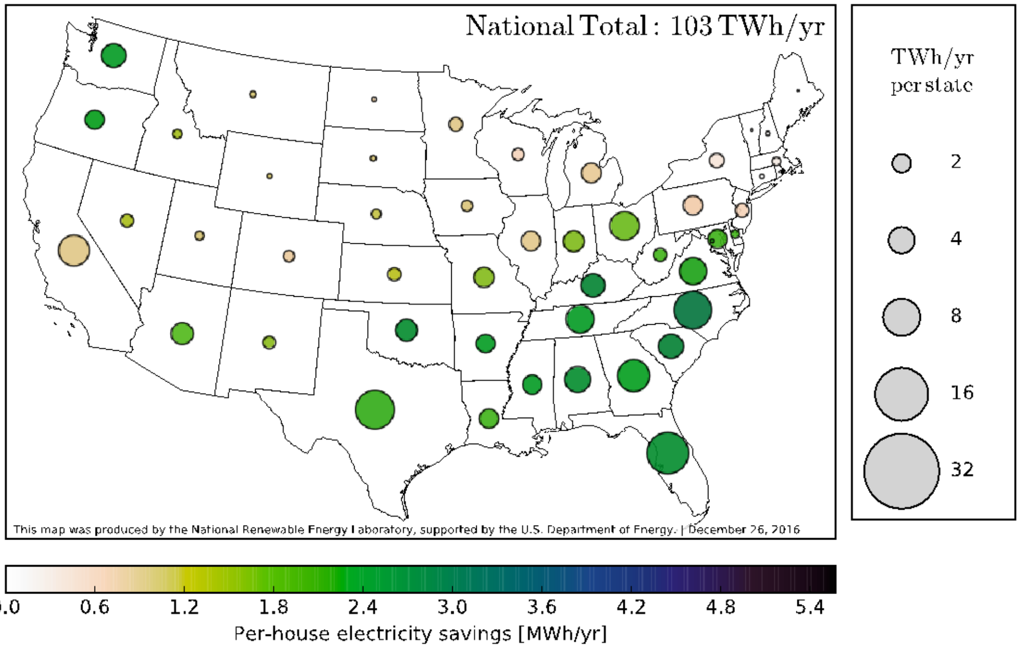
This table lists the upgrade categories included in each of the trade-specific packages.

Figure D-1. Aggregate and average electricity savings (NPV>0 economic potential) – Packages of Enclosure Upgrades



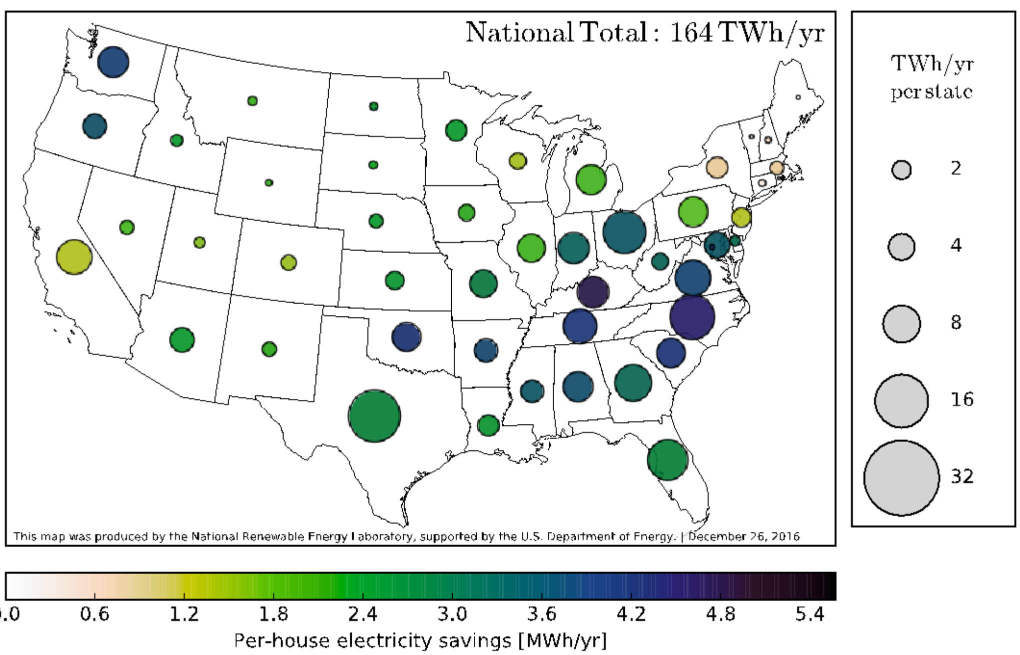
Packages of thermal enclosure upgrades result in 67 TWh/yr of economic potential electricity savings, which is fairly well distributed across the contiguous U.S.

Figure D-2. Aggregate and average electricity savings (NPV>0 economic potential) – Packages of HVAC Upgrades



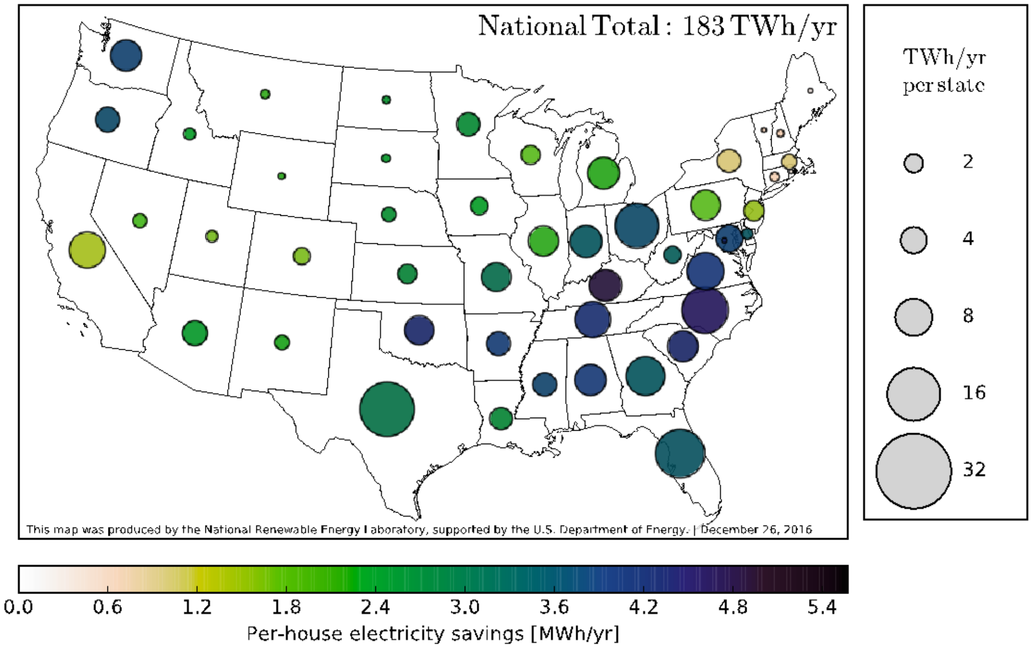
Packages of HVAC equipment upgrades result in 103 TWh/yr of economic potential electricity savings. This is larger than the enclosure-only potential, but the HVAC upgrades are considered as the equipment stock wears out over 20 years, and thus are not available immediately.

Figure D-3. Aggregate and average electricity savings (NPV>0 economic potential) – Packages of Enclosure+HVAC Upgrades



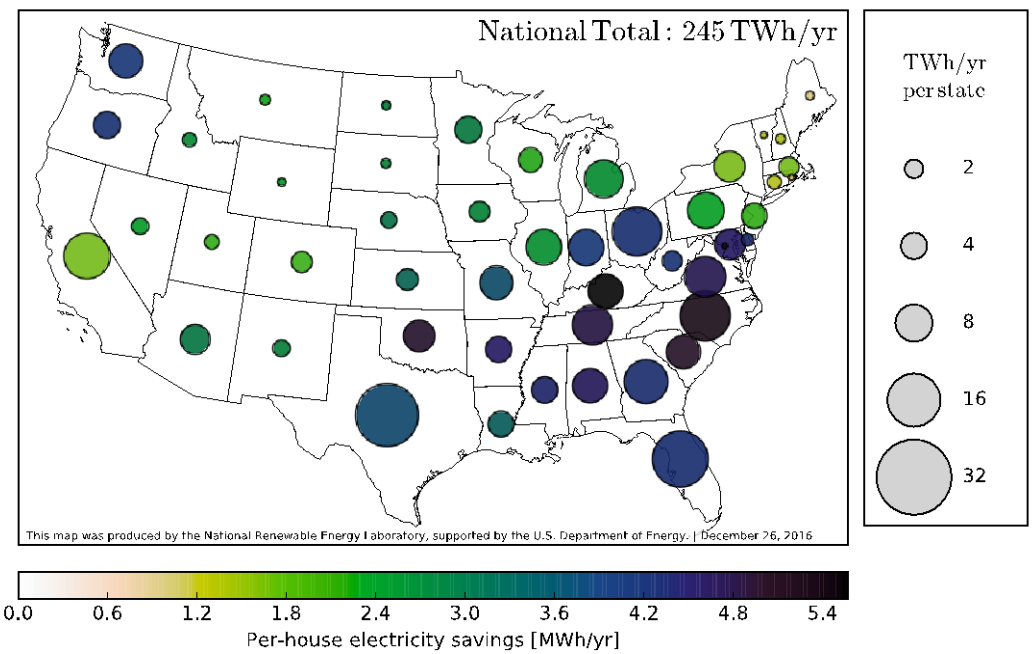
Packages of enclosure and HVAC equipment upgrades result in 164 TWh/yr of economic potential electricity savings; this is only 3.5% less than the sum of the enclosure-only and HVAC-only upgrades, suggesting that negative interaction between these categories are minimal.

Figure D-4. Aggregate and average electricity savings (NPV>0 economic potential) – Packages of Enclosure+HVAC+Water Heating Upgrades



Including water heater upgrades in the packages adds another 19 TWh/yr of economic potential.

Figure D-5. Aggregate and average electricity savings (NPV>0 economic potential) – Packages of the most cost-effective upgrades in each home across all categories



The all-inclusive packages, which add lighting and appliance upgrades to the Enc.+HVAC+WH packages, result in a total of 245 TWh/yr of economic potential.

Appendix E: Electrification Scenarios

This analysis was primarily focused on identifying the potential to reduce electricity consumption. However, studies in the literature show that increasing electrification of building end uses could help to reach deep economy-wide decarbonization.[132] [133] [134] [135] [136] A continuing shift toward both electrification of end uses and decarbonization of the electric power system would help reduce greenhouse gas (GHG) economy-wide. The level of GHG emissions reductions that can be achieved via electrification depends on a variety of factors, such as the carbon intensity of the electricity system.

This analysis includes several scenarios looking at electrification of the largest non-electric residential end uses (space heating and water heating), which would shift onsite consumption of natural gas, propane, and fuel oil to onsite electricity use. Table E-1 shows the electrification measures and packages analyzed. The packages are "synthetic" in that they were not simulated; rather, they are estimated results based on a sum of the component measures.[z]

Table E-1. Electrification Measures and Packages

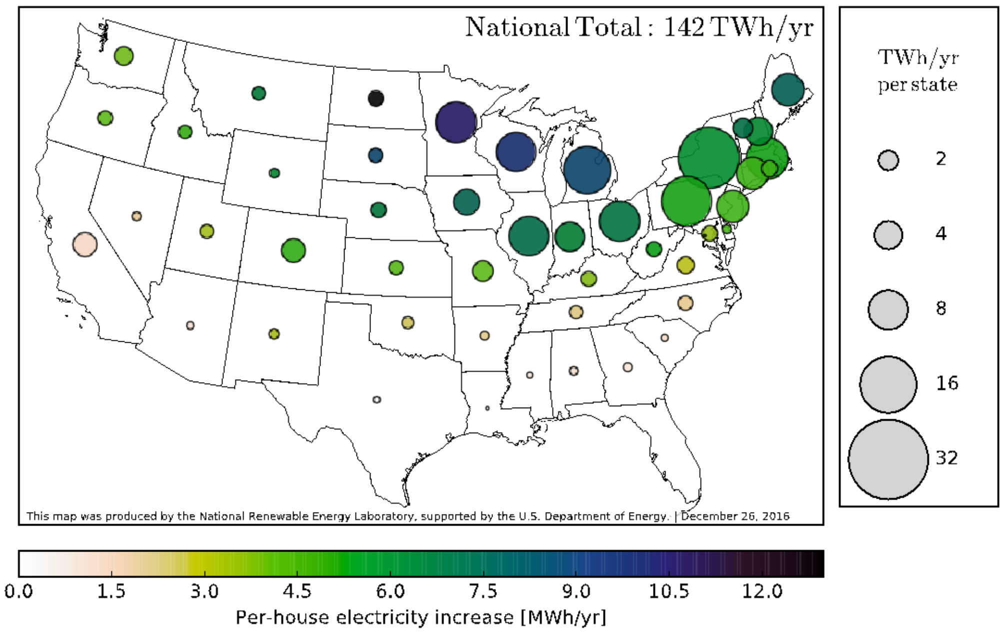
End-Use Category	Measure Short Name	Measure Description
Space heating	Replace Gas/Propane/Oil Furnace with VSHP	Replace Gas/Propane/Oil Furnace with SEER 22 HSPF 10 Variable-Speed Heat Pump (VSHP) at wear out
Space heating	DHP (replaces gas/propane/oil boiler at wear out) (60%)	Replace Gas/Propane/Oil boiler with ductless heat pump (SEER 27, HSPF 11.5) at wear out (DHP displaces 60% of space heating load)
Space heating	DHP (replaces gas/propane/oil boiler at wear out) (100%)	Replace Gas/Propane/Oil boiler with ductless heat pump (SEER 27, HSPF 11.5) at wear out (DHP displaces 100% of space heating load)
Water heating	Replace Oil/Propane Water Heater with HPWH (50 gal/80 gal)	Replace fuel water heater (<= 55 gal) with electric heat pump water heater (50 gal/80 gal) at wear out
Package	Electrification Package 1	"Synthetic" package combining upgrades related to electrification; assumes DHP displaces 60% of space heating load
Package	Electrification Package 2 (better DHP)	"Synthetic" package combining upgrades related to electrification; assumes DHP displaces 100% of space heating load (no point-source penalty)

This table describes the measures and packages included in the electrification scenarios.

[z] This simplification is reasonable because interactive effects are expected to be minor for these measures. Energy interactions between VSHPs and HPWHs are typically slightly positive (greater than the sum of the individual upgrade savings). For gas replacements, there are positive economic interactions assuming the monthly gas customer charge can be eliminated once both space and water heating are converted to electricity.

Figure E-1 shows the increase in electricity consumption resulting from Electrification Package 2 (technical potential).[aa] This technical potential increase corresponds to an overall reduction in primary energy use of 450 TBru/yr. Figure E-2 shows the increase in electricity consumption resulting from electrification package upgrades in homes in which the package would have positive net present value. Factors influencing cost-effectiveness are discussed below.

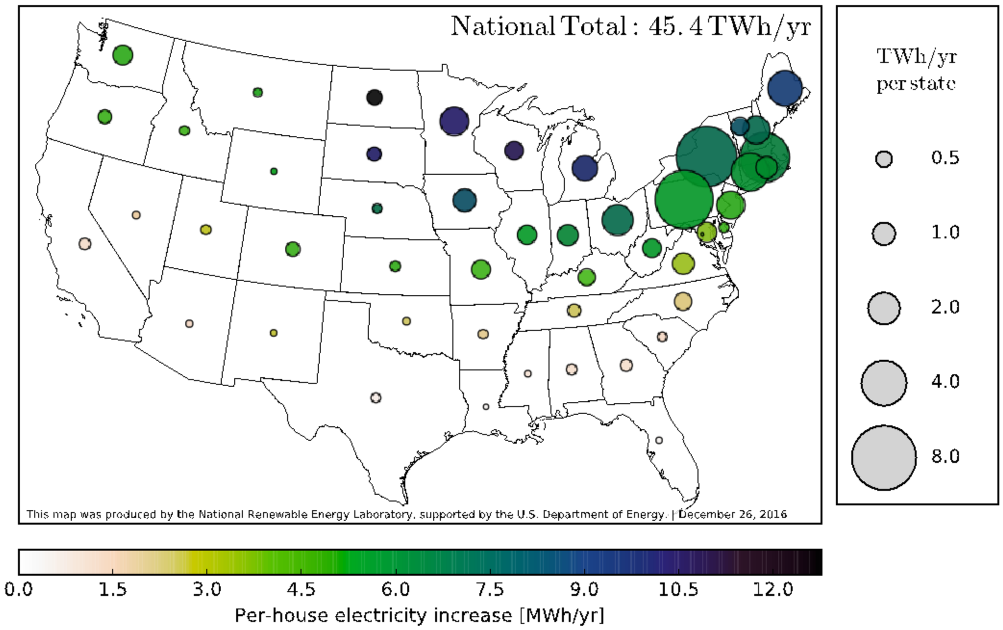
Figure E-1. Increase in electricity consumption (technical potential) – Electrification Package 2



Technical potential (i.e., ignoring cost-effectiveness) of Electrification Package 2 results in 142 TWh/yr in *increased* electricity consumption, mainly occurring in the Northeast, Great Lakes, and Upper Midwest regions.

[aa] Technical potential is a full conversion in that it includes conversions that increase primary energy use, which is only typical in the four coldest states. Economic potential filters out all the cases that increase primary energy use.

Figure E-2. Increase in electricity consumption (NPV>0 economic potential) – Electrification Package 2



Economic potential of the Electrification Package 2 results in 45 TWh/yr in *increased* electricity consumption, mainly occurring in the Northeast, Great Lakes, and Upper Midwest regions.

Factors Influencing Cost-Effectiveness

The cost-effectiveness of electrification measures depends on several factors, including: prices for fuels and electricity, climate, heating/cooling requirements of the home, and for ducted VSHP upgrades, the ages of the furnace and/or AC being replaced. VSHP measures can be triggered by either a furnace wearing out or an AC wearing out, but when triggered, both pieces of equipment are replaced by the VSHP even if one has lifetime remaining. Ideally, probability distributions of furnace and AC ages would be used to determine the incremental life cycle cost of VSHP equipment over the furnace and AC equipment in each modeled home; however, this analysis did not include that level of detail for equipment age. Instead, three different wear out scenarios for the VSHP measures were considered to bound the problem (see Table E-2).

Figure E-3 compares the cost-effectiveness of these wear-out scenarios at a national level, showing the national percent of homes in which the VSHP measure is cost-effective, for the three fuels and three wear-out scenarios. The “furnace wear out” scenario is not commonly cost-effective, especially for gas furnaces, which suggests that conversion to VSHP is usually not cost-effective for homes without AC. If the VSHP installation is triggered by an AC wearing out, then the “AC wear out” and “Furnace and AC both at end of lifetime” scenarios provide minimum and maximum bounds on cost-effectiveness. Figure E-2 and Figure E-4 use the more conservative “AC wear out” incremental cost scenario.

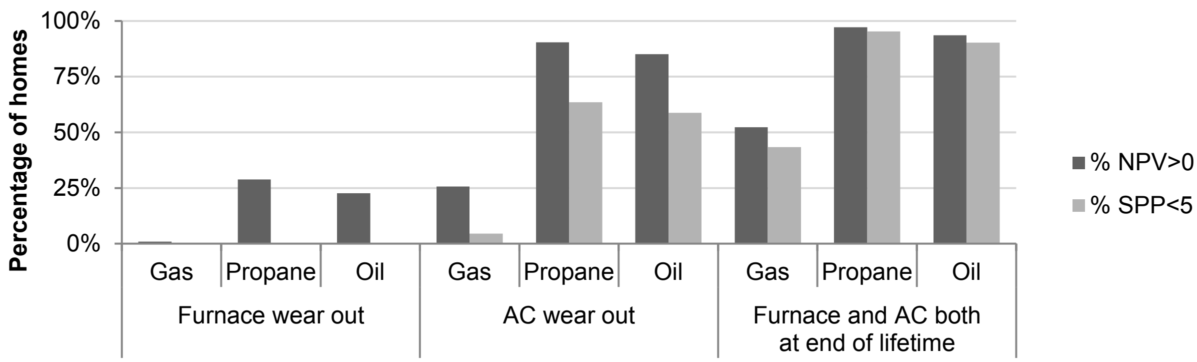
Table E-2. Variable-Speed Heat Pump Wear-Out Scenarios

Triggered by	Equipment Replaced	Cost of Variable-Speed Heat Pump Measure	Reference for Energy Savings Calculation
Furnace wear out	Gas/oil/propane furnace (and AC if present)	Incremental cost over a new furnace meeting federal standard	New furnace meeting federal standard; existing AC efficiency
AC wear out	Gas/oil/propane furnace and AC	Incremental cost over a new AC meeting federal standard	New AC meeting federal standard; existing furnace efficiency
Furnace and AC both at end of lifetime	Gas/oil/propane furnace and AC	Incremental cost over a new AC *and* furnace meeting federal standards	New AC meeting federal standard; existing furnace efficiency[i]

[i] This scenario should use "New furnace meeting federal standard" instead, but that was not within in the scope of the current analysis.

This table describes the wear-out scenarios considered for evaluating cost-effectiveness of the variable-speed heat pump upgrades.

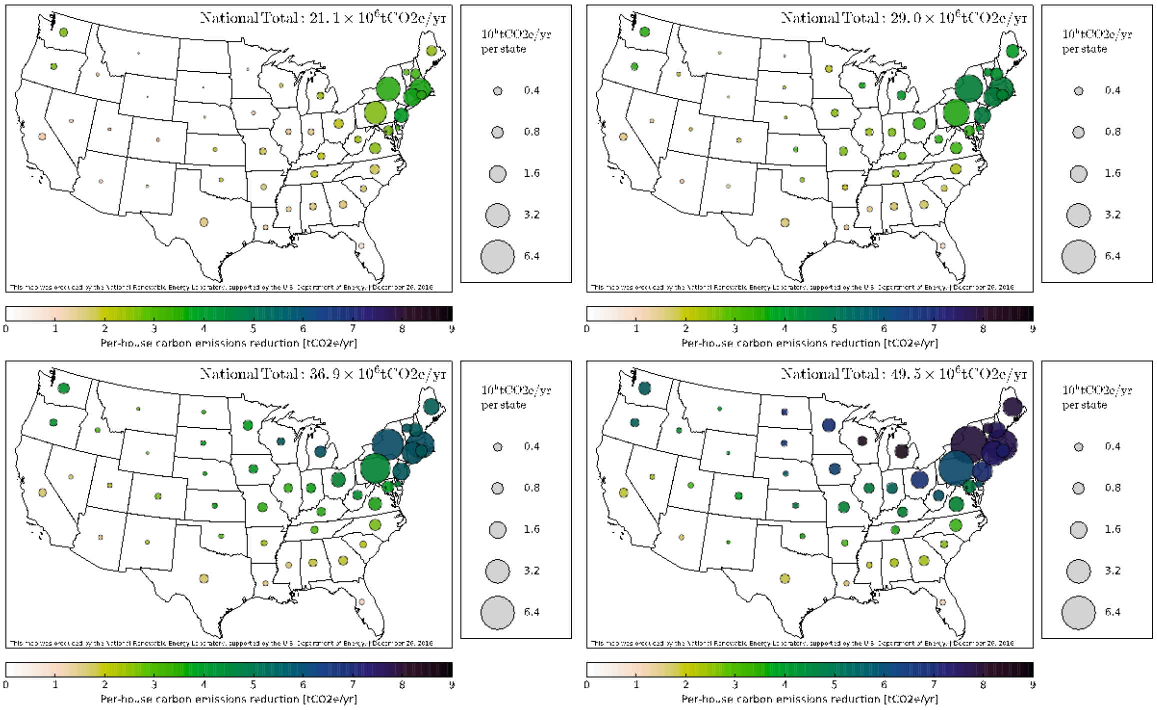
Figure E-3. National percentage of homes passing cost-effectiveness thresholds for replacement of furnace/air conditioner with variable-speed heat pump, under three wear-out scenarios



When replacing only an AC at wear out (the furnace is removed or left in place as back up), variable-speed heat pumps are cost-effective (SPP<5) in a majority of homes using propane or oil for heating.

Figure E-4 shows the reduction in equivalent carbon emissions resulting from electrification package upgrades with NPV>0, using the current electric grid carbon intensity and for three scenarios with a less carbon intensive electric grid. National average carbon emissions factors were used for this exercise.[137]

Figure E-4. Economic potential (net present value greater than zero) carbon emissions reduction resulting from Electrification Package 2 with different electric grid carbon intensities.



Figures show the potential carbon emission reductions for a set of fuel switching upgrades in Electrification Package 2: (upper left) current grid carbon intensity[138]; (upper right) 25% less carbon-intensive grid, (lower left) 50% less carbon-intensive grid; (lower right) 90% less carbon-intensive grid. With the current grid carbon intensity, Electrification Package 2 has economic potential carbon savings of 21 million metric tons of CO_2 equivalent, which would increase to 50 million metric tons if grid electricity is 90% less carbon-intensive.

Conclusions

- **Furnaces** The gas, oil, and propane furnace to VSHP scenarios have good technical potential source energy savings (498, 118, and 124 TBtu/yr respectively). Switching from a furnace and AC to VSHP is cost-effectives for oil and propane most of the time (Figure E-3). For natural gas, the switch can be cost-effective, especially in the South and if replacing a furnace and AC that are both at the end of their lifetimes.

- **Boilers** Replacing oil-fired boilers with ductless heat pumps (DHPs) can provide good technical and economic potential. Switching from a propane-fired boiler to DHP is typically cost-effective, though relatively uncommon. Replacing gas boilers is rarely cost-effective by itself, but may be cost-effective if the home also has AC. The potential carbon savings of DHPs is sensitive to how they are installed and controlled, and to the mix of fuels used for electricity generation in the region. The savings is also sensitive to the degree that DHPs provide air conditioning in homes that did not use central or room air conditioners previously, though this can be a motivation for installing DHPs for some building owners.

- **Water Heaters** Replacing oil or propane water heaters with heat pump water heaters typically does not save primary energy (and can increase primary energy use depending on the region).[bb] Approximately 50% of the propane-to-HPWH upgrades have positive NPV. Oil-to-HPWH switching was typically not cost-effective. Gas-to-HPWH switching was not analyzed because previous analysis determined that these upgrades were rarely cost-effective. However, as discussed in the footnote above, there are some synergies between space and water heating electrification, which was not accounted for in this analysis.
- **Sensitivity to fuel type** Propane costs 20–50% more per unit of heat than fuel oil (depending on the state), so the propane replacements generally have better cost-effectiveness than the fuel oil replacements. Natural gas generally costs less than half of oil and propane costs per unit of heat, so electrification of natural gas end uses is less often cost-effective (see Figure E-3).

[bb] The heat pump water heater models used for the analysis are circa 2011; HPWHs have seen modest gains in efficiency since then, which may change these results to some degree.

Endnotes

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