Insulation Industry Opportunity Study

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Submitted to:
Insulation Industry Trade Associations Coalition

Submitted by:
ICF

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Acronyms and Abbreviations

ACH	Air Changes per Hour
ANSI	American National Standards Institute
ASHRAE	American Society of Heating, Refrigeration, and Air Conditioning Engineers
BEM	Building Energy Models
BCR	Benefit to Cost Ratio
BOMA	Building Owners and Managers Association International
CASE	Codes and Standards Enhancement
CBECS	EIA’s Commercial Building Energy Consumption Survey
CRRC	Cool Roof Rating Council
DOE	U.S. Department of Energy
eGRID	Emissions and Generation Resource Integrated Database
EIA	U.S. Energy Information Administration
EPA	U.S. Environmental Protection Agency
EUI	Energy Use Index (kBtu/sf/yr)
EUL	Effective Useful Life
FEMP	U.S. DOE’s Federal Energy Management Program
FT	Feet
HR	Hour
HVAC	Heating, Ventilation, and Air Conditioning
IAC	U.S. DOE, Industrial Assessment Center
IEAD	Insulation Entirely Above Deck
IECC	International Energy Code Council
IES	Illuminating Engineering Society
IN	Inch
LF	Linear Foot
MECS	U.S. DOE, EIA, Manufacturing Energy Consumption Survey
MPH	Miles per Hour
NAICS	North American Industry Classification System
NAIMA	North American Insulation Manufacturers Association
NPS	Nominal Pipe Size
NPV	Net Present Value
NREL	National Renewable Energy Laboratory
OS	OpenStudio
PBA	Primary Building Activity (from CBECS)

RECS	EIA's Residential Energy Consumption Survey
SF	Square Foot
SPP	Simple Payback Period
YR	Year

Introduction

An Insulation Industry Trade Associations Coalition commissioned this study to assess the state- and national-level energy and emissions impacts and economic benefits that could accrue over from the installation of code-compliant insulation in the residential, commercial, and industrial building sectors.

This report documents the study's analytical approach, including its methods, data sources, assumptions, results, and findings. State- and national-level energy and emissions impacts and economic benefits are presented in tables and figures throughout the report. Supplemental data of the same types are found in appendices, which also include references to data sources, detailed intermediate and final calculations, and secondary literature research not referenced throughout the main body of the report.

Residential

This study[1] assesses the state- and national-level energy and emissions impacts and economic benefits that could accrue over a 50-year horizon from the installation of code-compliant insulation retrofits for a select number of building types and representative city/climate zone combinations. An insulation retrofit project[2] is one which involves any upgrade to a building's thermal envelope, such as replacing and/or adding insulation to the walls, ceiling, or floor, as well as air sealing the building and insulating its pipes. Often, these projects must meet the building envelope requirements of building energy codes such as the *International Energy Conservation Code (IECC)*.

Commercial

This study[3] assesses the state- and national-level energy and emissions impacts and economic benefits that could accrue over a 30-year horizon from the installation of code-compliant roof insulation (at time of a roof replacement, herein referred to as "roof upgrade") and hydronic pipe insulation in a select number of commercial buildings compared to their baseline condition[4]. It was conducted for six U.S. Department of Energy (DOE) Commercial Reference Building types within three commercial building subsectors (defined for this study) and all 16 U.S. climate zones that combined make up almost 25% of the commercial building floor area in the U.S. Department of Energy, Energy Information Administration, 2018 Commercial Building Energy Consumption Survey (CBECS).

Primary assumptions for conducting this study were two-fold. First, that roofs being replaced today were originally constructed on buildings that precede widespread adoption of building energy codes and are therefore under insulated relative to today's building energy code requirements. And second, that a substantial amount of commercial piping is uninsulated, under

[1] Opportunity that exists over a 50-year horizon if all technical potential were installed in day one.
[2] HVAC duct and pipe insulation were omitted, but its inclusion would increase the total impacts and benefits available from code-compliant insulation in the existing building stock.
[3] Opportunity that exists over a 30-year horizon if all technical potential were installed in day one.
[4] HVAC (heating, ventilation, and air conditioning) duct insulation was omitted, but its inclusion would increase the total impacts and benefits available from code-compliant insulation in the existing building stock.

insulated, or damaged due to physical or environmental factors.

Industrial

This study[5] assesses the state- and national-level energy and emissions impacts and economic benefits that could accrue over a 20-year horizon from the installation of code-compliant steam pipe insulation[6] in a select number of manufacturing sectors. It was conducted for eight manufacturing sectors found in the U.S. Department of Energy's (DOE) Industrial Assessment Center (IAC) Database and their 2018 Energy Information Administration's (EIA) Manufacturing Energy Consumption Survey (MECS) that combined make up about 61% of the pipe insulation energy savings found in the IAC database and 50% of the MECS manufacturing enclosed floor area. A primary assumption for conducting this study was that a substantial amount of industrial piping is uninsulated, under insulated, or damaged. When installed, age, maintenance, improper design, and environmental conditions are factors that contribute to the degradation of pipe insulation performance.

[5] Opportunity that exists over a 20-year horizon if all technical potential were installed in day one.
[6] Space and process cooling, industrial refrigeration, and heating, ventilation, and air conditioning (HVAC) duct insulation were omitted, but their inclusion would increase the total impacts and benefits available from code-compliant insulation in the manufacturing sector.

Residential Insulation Retrofits

This study[7] assesses the state- and national-level energy and emissions impacts and economic benefits that could accrue over a 50-year horizon from the installation of code-compliant insulation retrofits for a select number of building types and representative city/climate zone combinations. An insulation retrofit project[8] is one which involves any upgrade to a building's thermal envelope, such as replacing and/or adding insulation to the walls, ceiling, or floor, as well as air sealing the building and insulating its pipes. Often, these projects must meet the building envelope requirements of building energy codes such as the *International Energy Conservation Code (IECC)*.

Development of Energy Impacts

Within the residential sector, the scope of this analysis was only on single-family detached homes, excluding all other attached and multifamily homes. The scope was also limited to the building envelope insulation of living spaces; insulation of domestic hot/cold water and (heating, ventilating, and air conditioning) HVAC systems was neglected even though they are often addressed during retrofits. The total potential benefits from residential insulation retrofits may therefore be higher than those presented within the scope of this study. The pre-retrofit ("Baseline") and post-retrofit ("Intervention") building stock were represented by building models defined in the following two subsections.

Development of Baseline Condition

The baseline building energy models representing the current U.S. residential building stock were developed from the National Renewable Energy Laboratory's (NREL's) ResStock tool, which utilizes EnergyPlus and OpenStudio software to generate a sample set of building energy models designed to represent the current U.S. residential building stock as closely as possible. Only single-family detached homes were included in the sample set, in order to align with the scope of the analysis. The sample size of the set was selected to be 10,000, in order to obtain a representative sample for each state in the country. Since ResStock does not include models for buildings outside of the continental U.S., Hawaii and Alaska were neglected in this analysis. Table 1 summarizes the national averages of the inputs used in the baseline models. Refer to the appendices for references to the attached data files that provide a detailed breakdown of the average inputs by state.

Table 1 – National Averages of Baseline Model Inputs

Wood Frame Wall Average R-value	Unfinished Attic Average R-value	Average Infiltration ACH50	Unfinished Basement Floor Average R-value
6	25.6	17.4	2.7

[7] Opportunity that exists over a 50-year horizon if all technical potential were installed in day one.
[8] HVAC duct and pipe insulation were omitted, but its inclusion would increase the total impacts and benefits available from code-compliant insulation in the existing building stock.

Development of Intervention Condition

Intervention building energy models representing the post-retrofit U.S. residential building stock were developed by upgrading the baseline ResStock models such that they met the 2021 IECC's building envelope requirements, with some divergences from the 2021 IECC for feasibility based upon discussion with the Insulation Industry Trade Associations Coalition, as summarized in Table 2. Refer to the appendices for references to the data files that provide greater detail on these upgrades and their rationale.

Table 2 – Code Compliant Upgrades Applied to Baseline Models

Climate Zone	Wood-Framed Wall Upgraded R-value[9]	Unfinished Attic Upgraded R-value	Upgraded Air Leakage Rate (ACH50)	Floor Upgraded R-value
1	All uninsulated walls were upgraded to R-13; percentages of building stock were upgraded further	30	5	13
2		49	5	13
3		49	3	19
4		60	3	19
5		60	3	30
6		60	3	30
7[10]		60	3	38

A primary assumption is that all retrofits across the country would be required to meet the most recent 2021 edition of the IECC; while this edition has not yet been adopted as a mandatory residential building code in every state across the country, many states have adopted it and are increasingly doing so, as it is the industry standard for feasible residential building energy efficiency. Therefore, it was considered to best represent the current total potential for residential insulation retrofits across the country.

[9] 8.8% of homes with R-7 and R-11 wall insulation were upgraded to R-13, based upon American Housing Survey (AHS) estimate of 1.1% of homes undergoing gut rehabs each year over the next 8 years. In addition, R-5 continuous insulation was added to 20.8% of homes in Climate Zones 3-7, based upon NREL estimate of 2.6% of homes being re-sided each year over the next 8 years.

[10] Climate Zone 8 was neglected in this analysis, since ResStock does not include models in Alaska.

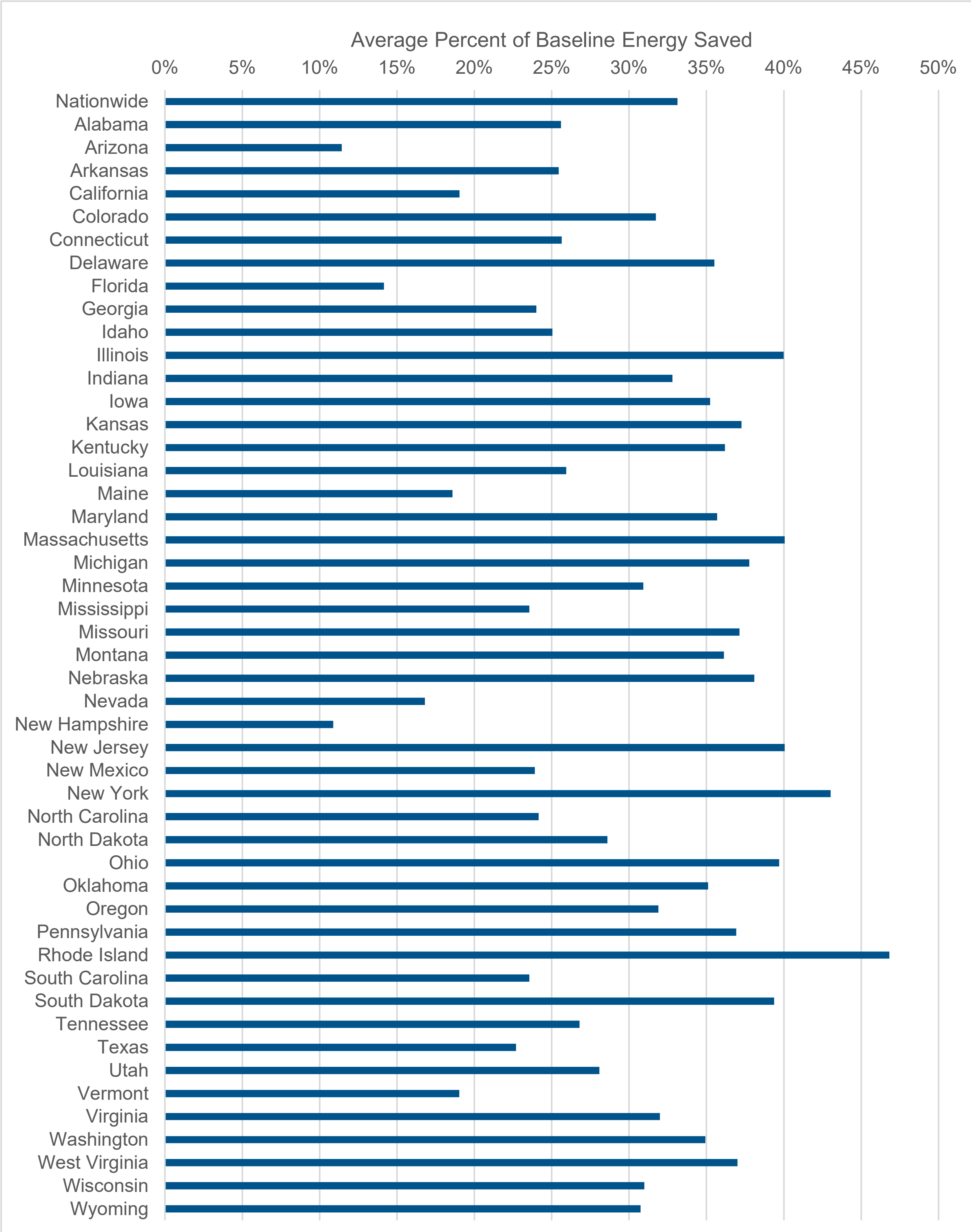
Energy Savings Results from Simulation of Building Energy Models

Incremental energy savings were calculated as the difference between the simulated whole-building energy performances of the baseline and upgrade scenario building energy models. Energy savings are the result of increased insulation and air sealing that reduces heat transfer throughout the building envelope, reduces space heating and space cooling requirements (a function of load and efficiency), and decreases the models' calculated whole-building energy use.

Raw energy performance data from the ResStock simulations in each state were post-processed to produce average relative (percent) values of whole-building energy savings, as presented in Figure 1.

Overall, the relative savings ranged from at least 10% to as high as over 45% in various states, demonstrating that insulation retrofits can significantly reduce the energy consumption of the residential building stock, depending on the location and the type of retrofits implemented. The detailed energy savings broken out into electric and natural gas savings can be found in the appendices.

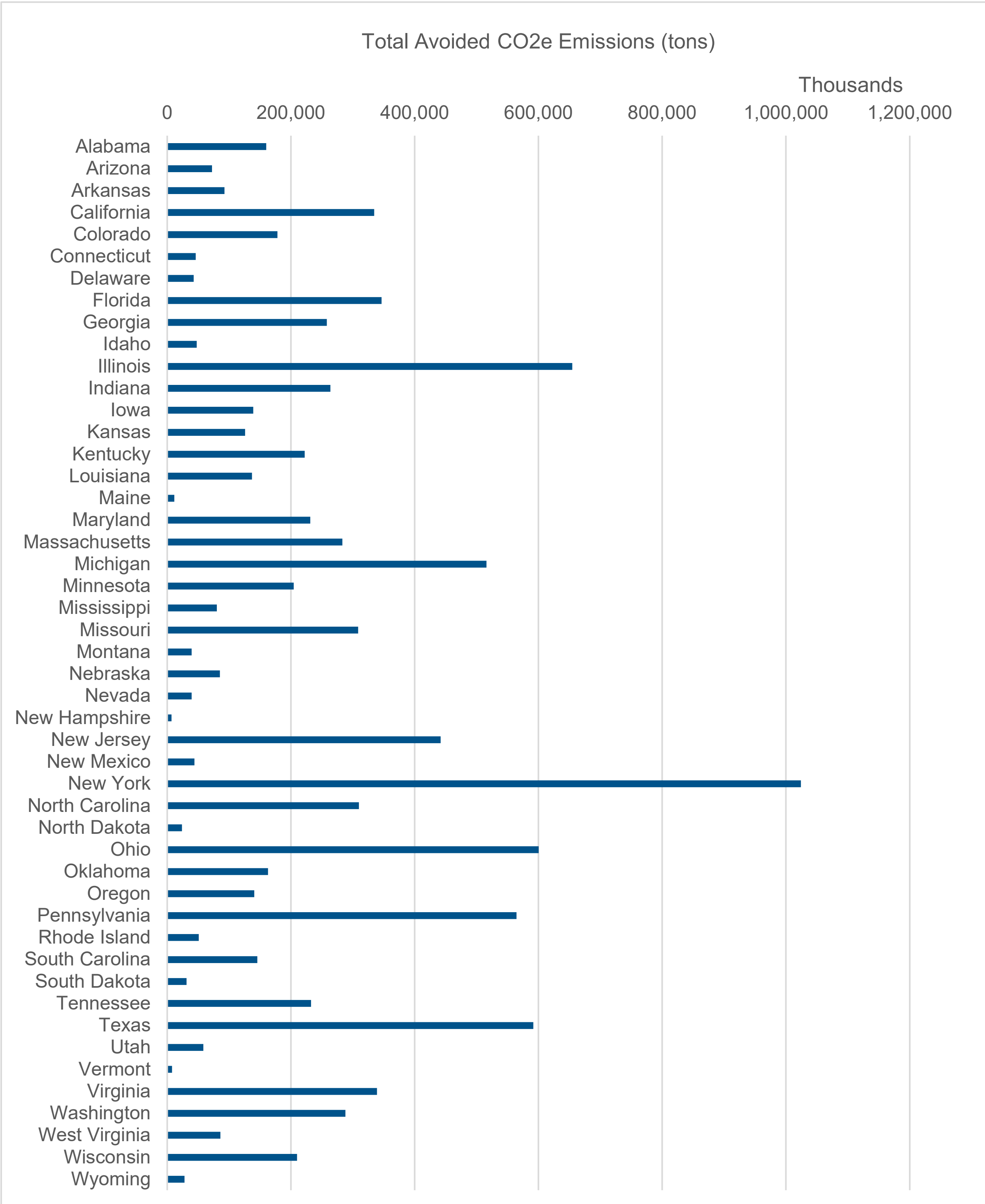
Figure 1 – Average Whole-Building Relative Energy Savings by State



Calculation of Emissions Impacts

Reductions in building emissions are the direct result of energy savings that occur from a reduction in space heating and cooling requirements and the corresponding reduction in onsite combustion of natural gas and purchased electricity. Emissions were calculated as the product of the site energy savings (derived as the difference in energy use between the baseline and upgrade scenarios), by fuel type, and the corresponding U.S. Environmental Protection Agency (EPA) national-level emissions factor for that fuel type and constituent emission source. Total carbon emissions savings data are presented in Figure 2 below by state. Combined, the retrofits across the nation were estimated to save a total of roughly 10 billion tons of carbon emissions over a 50-year period. The complete emissions data by state can be found in the appendices.

Figure 2 –Total Avoided CO2 Equivalent Emissions by State



Calculation of Economic Benefits

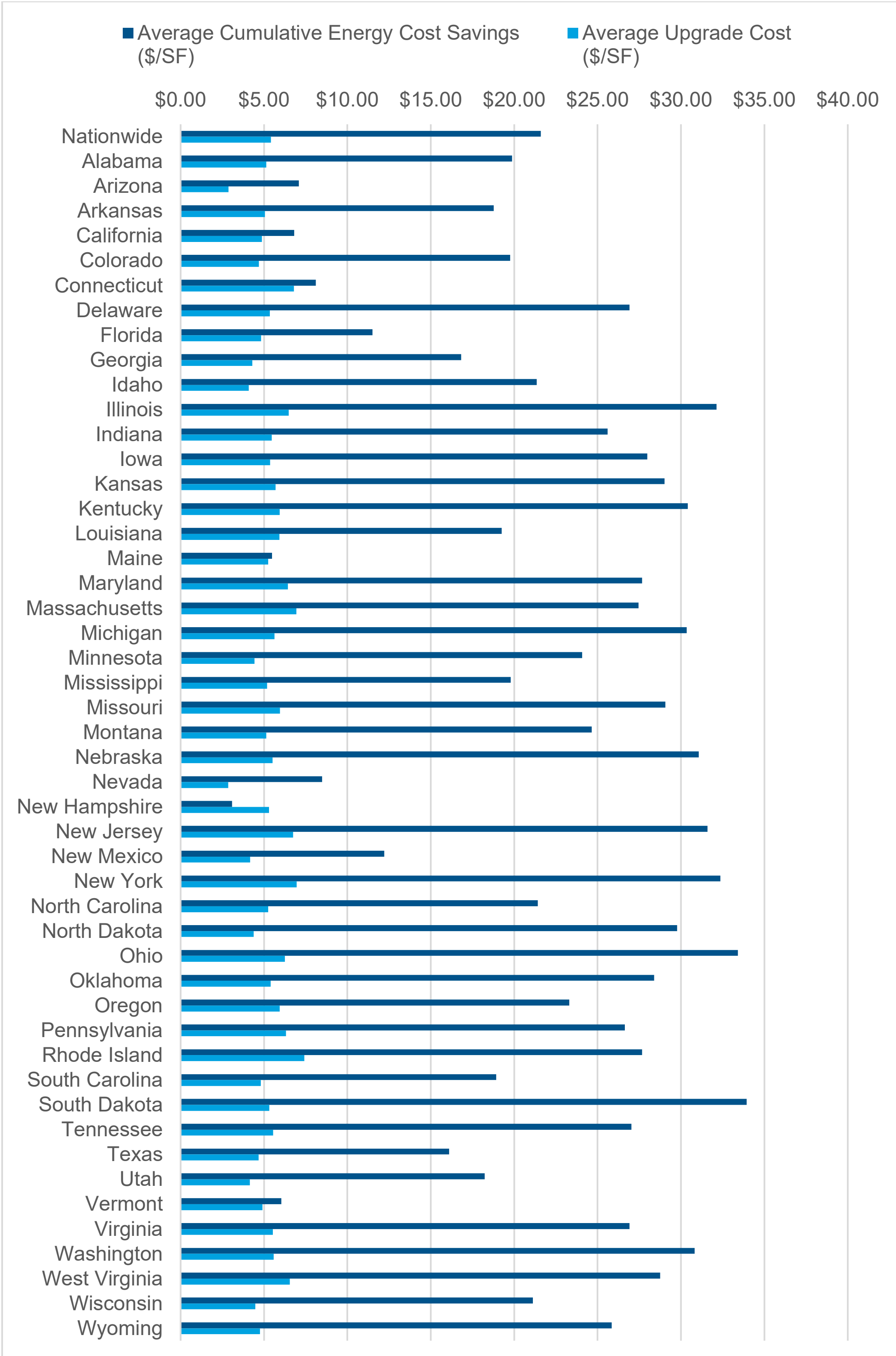
The downstream energy cost savings resulting from these energy savings were then monetized over the life of the insulation retrofits to quantify their economic benefits relative to the costs of the upgrades, as described below. As a conservative assumption, the economic benefits were limited to the energy cost savings and did not include monetized health or environmental benefits due to avoided air emissions from the energy savings.

Upgrade Costs and Energy Cost Savings

Incremental capital costs were developed using NREL's National Residential Efficiency Measures Database, with linear interpolation between entries where necessary. These costs are total (material and labor) retrofit costs.

Energy cost savings occurred from the incremental reduction in space heating and space cooling requirements and corresponding reduction in electric and natural gas usage due to the retrofit's improvement of the building envelope. Energy cost savings were calculated as the product of energy savings and energy price, by fuel type, inclusive of energy price escalation over the effective useful life of the insulation retrofit project. Figure 3 depicts the average cumulative energy cost savings and upgrade cost per square foot of conditioned building floor area by state. This graph shows that cumulative energy cost savings exceeded the retrofit cost nearly all areas of the U.S.

Figure 3 – Average Cumulative Energy Cost Savings and Upgrade Costs by State



Economic Analysis

Economic benefits associated with code-compliant insulation retrofits were quantified using two life-cycle cost analysis methods: the Net Present Value (NPV) and the Benefit-to-Cost Ratio (BCR).

NPV and BCR both use a life-cycle cost approach to account for the time value of money. This enables a comparison of the project's benefits and costs over its effective useful life and is the economic method referenced by the U.S. Department of Energy (DOE) in their *Methodology for Evaluating Cost-Effectiveness of Commercial Energy Code Changes* document and is also a method used by utility program administrators and implementers in development of cost-effective demand-side management incentive programs.

- **Benefit-to-Cost Ratio** is calculated as the ratio of the present value of benefits to the present value of costs. An insulation retrofit is cost-effective when the BCR is greater than 1.0, indicating its life-cycle benefits exceed its cost.
- **Net Present Value** is calculated by subtracting the present value of the code-compliant insulation retrofit scenario from the present value of the baseline scenario. A positive NPV indicates the project is cost-effective over its effective useful life.

For each modeled scenario, the NPV and BCR of code-compliant insulation retrofits were calculated using inputs of energy cost savings, incremental material and labor capital costs, and the modeling assumptions listed in Table 3 were used to scale up the costs and savings to represent the total current residential building stock. Details and data sources for the assumptions in Table 3 can be found in the appendices.

Table 3 – Lifecycle Cost Economic Modeling Assumptions

Input Variable	Value	Source
Discount Rate	3.00%	DOE, FEMP
Modeling Timeline (years)	50	Insulation Industry Trade Associations Coalition
Effective Useful Life (EUL, years)	50	Insulation Industry Trade Associations Coalition
Electricity Commodity Cost ($/kWh)	$0.11	DOE, EIA
Electricity Annual Escalation Rate	1.80%	DOE, EIA
Natural Gas Commodity Cost ($/therm)	$0.77	DOE, EIA
Natural Gas Annual Escalation Rate	2.90%	DOE, EIA
2022 U.S. Residential Building Stock (Billion SF)	188.6	EIA 2015 RECS

The analysis showed that the retrofits were cost-effective on average in most states, while not being cost-effective in a few states, when viewed through the lens of BCR and NPV, with BCR shown in Figure 4. The full cost-effectiveness data by state can be found in the appendices.

Figure 4 – Average Benefit-to-Cost Ratio by State

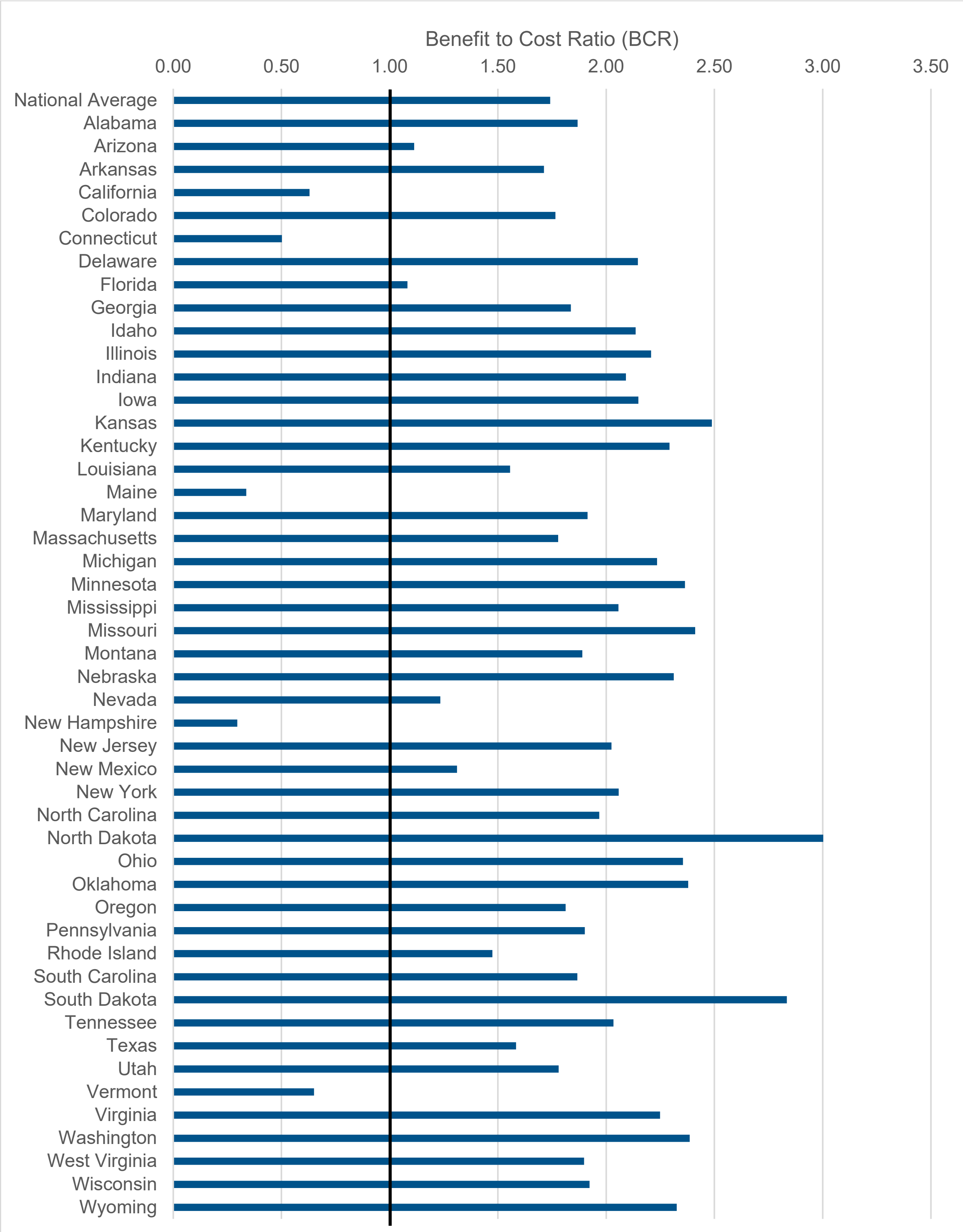


Table 4 below illustrates the number of cost-effective retrofits within the set of all retrofits considered in this study. Roughly two-thirds of the ResStock models included retrofits found to be cost-effective, but they were responsible for almost all of the total savings. This indicates that most of the energy savings (and therefore, economic benefit and avoided emissions) can be achieved by focusing on just cost-effective retrofits. The complete comparison by state of cost-effective versus all retrofits can be found in the appendices.

Table 4 – Comparison of Cost-Effective Versus All Retrofits

	All Retrofits	Only Cost-Effective Retrofits
Number of ResStock Models	9,754	6,213
Total Energy Savings (MMBtu)	2,815,590,006	2,547,899,720

The relative cost-effectiveness of the various retrofit upgrades considered in this study can be seen in Table 5. All average BCRs exceeded 1.00 indicating cost-effectiveness for all types of insulation retrofits.

Table 5 – Average Cost-Effectiveness of Upgrades within Retrofit Packages

Upgrade Type	Average BCR for Models Containing this Upgrade
Insulation Wall	2.10
Insulation Unfinished Attic	1.73
Insulation Crawlspace	2.04
Insulation Unfinished Basement	2.10
Insulation Interzonal Floor	1.77
Infiltration	1.73

Commercial Insulation Retrofits

This study[11] assesses the state- and national-level energy and emissions impacts and economic benefits that could accrue from the installation of code-compliant roof upgrade (at time of a roof replacement) and pipe insulation in a select number of commercial buildings compared to their baseline condition[12]. It was conducted for six DOE Commercial Reference Building types within three commercial building subsectors (defined for this study) and all 16 U.S. climate zones that combined make up almost 25% of the commercial building floor area in CBECS.

- **Education:** Primary School and Secondary School (7.4% of U.S. commercial floor area)
- **Federal:** Medium Office and Small Office (1.4% of U.S. commercial floor area)
- **Private:** Medium Office, Small Office, Stand-alone Retail, and Midrise Apartment (15% of U.S. commercial floor area)

These buildings are typically constructed with low-slope roofs with insulation located entirely above deck. Low-slope roof assemblies are replaced at least once during the building's life cycle presenting an opportunity to increase building envelope energy efficiency during planned maintenance and alterations.

The approaches below were used to estimate state- and national-level energy and emissions impacts and economic benefits for the building subsectors and building types listed above.

Energy Impacts: Secondary literature research, professional judgement, and consultation with the Insulation Industry Trade Associations Coalition were used to develop average building stock and roof and pipe insulation baseline conditions for comparison to an ASHRAE Standard 90.1-2019 code-compliant intervention condition. DOE's EnergyPlus building energy modeling engine and the North American Insulation Manufacturers Association's (NAIMA) 3E Plus[13] heat loss calculator were the primary software tools used to simulate the baseline and intervention performance conditions and from which building-level energy savings were developed for the roof upgrade and pipe insulation, respectively. State- and national-level estimates of energy savings were developed separately for each measure and also combined (by adding together roof upgrade and pipe insulation building-level energy savings) and energy savings were extrapolated to the state-level (using uniform allocations by US census region) and then to the national-level (using market floor area data from CBECS according to building subsector and building type).

Emissions Savings: Emissions impacts were developed directly from energy savings as the product of energy savings by fuel type and its corresponding emissions factor.

Economic Benefits: Energy cost savings were calculated as the product of energy savings by fuel type and its corresponding fuel price and then combined with secondary literature research on incremental capital costs to produce life-cycle economic metrics over a 30-year timeframe.

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[11] Opportunity that exists over a 30-year horizon if all technical potential were installed in day one.

[12] HVAC (heating, ventilation, and air conditioning) duct insulation was omitted, but its inclusion would increase the total impacts and benefits available from code-compliant insulation in the existing building stock.

[13] 3E Plus

Combined impacts and benefits of the roof upgrade and pipe insulation measures are presented in the report's main body. Individual measure impacts and benefits are separately documented in the appendices.

Development of Energy Impacts

Secondary literature research, professional judgement, and consultation with the Insulation Industry Trade Associations Coalition were used to develop average building stock and roof and pipe insulation baseline conditions for comparison to an ASHRAE Standard 90.1-2019 code-compliant intervention condition.

DOE's EnergyPlus building energy modeling engine and NAIMA's 3E Plus heat loss calculator were the primary software tools used to simulate the baseline and intervention performance conditions and from which building-level energy savings were developed for the roof upgrade and pipe insulation, respectively.

State- and national-level estimates of energy savings were developed separately by insulation measure (roof upgrade and pipe insulation) and combined (by adding together roof upgrade and pipe insulation building-level energy savings) and extrapolating the combined energy savings to the state-level (using uniform allocations by U.S. census region) and then to the national-level (using market floor area data from 2018 CBECS according to building subsector and building type).

Development of Baseline Conditions

Baseline building energy models were developed from DOE's Commercial Reference Building models.[14] A custom measure workflow was developed to create and modify the DOE building models in EnergyPlus within the OpenStudio (OS) building energy modeling environment. Building models were created for the Primary School, Secondary School, Medium Office, Small Office, Midrise Apartment, and Stand-alone Retail building types, in all U.S. climate zones and their representative DOE U.S. city locations, using the 2004 (New Construction) building energy model vintage, as depicted in Table 6.

Table 6 – Building Energy Modeling Characteristics

DOE Commercial Building Types			DOE Model Vintage	Climate Zone / City Locations	
Building Type	# Floors	Floor Area (SF)			
Primary School	1-story	73,960	New Construction (2004)	1A Very Hot Humid	Miami, FL
Secondary School	2-story	210,887		2A Hot Humid	Houston, TX
Medium Office	3-story	53,628		2B Hot Dry	Phoenix, AZ
Small Office[15]	1-story	5,500		3A Warm Humid	Atlanta, GA
Midrise Apartment	4-story	33,740		3B Warm Dry	Los Angeles, CA
Stand-alone Retail	1-story	24,962		3B Coastal	San Francisco, CA
				3C Warm Marine	Las Vegas, NV
				4A Mixed Humid	Baltimore, MD
				4B Mixed Dry	Albuquerque, NM
				4C Mixed Marine	Seattle, WA
				5A Cool Humid	Chicago, IL
				5B Cool Dry	Boulder, CO

[14] Commercial Reference Buildings | Department of Energy

[15] Small Office building model modified from attic to IEAD.

DOE Commercial Building Types			DOE Model Vintage	Climate Zone / City Locations	
Building Type	# Floors	Floor Area (SF)			
				6A Cold Humid	Minneapolis, MN
				6B Cold Dry	Helena, MT
				7 Very Cold	Duluth, MN
				8 Subarctic/Arctic	Fairbanks, AL

The 2004 vintage DOE Commercial Reference Building model was selected as the baseline condition because most commercial buildings were constructed prior to the widespread adoption of building energy codes and using the 2004-vintage models would be conservative and defensible because they include comparatively more energy efficient space heating and cooling system and lighting systems. Secondary research conducted on building characteristics such as lighting from EIA's 2015 Commercial Building Energy Consumption Survey did not yield defensible data that could be used to update building model inputs, nor did sample modeling of alternative vintage models such as pre-1980 show significant variations in energy performance that would lead to the recommended use of an alternate baseline model.

The reference building models were then modified using the measure workflow to represent the baseline roof conditions depicted in Table 7. Roof insulation R-values were modified from the DOE referenced baseline insulation values to be average roof insulation values of R-12.5 (installed as a single non-continuous insulation layer) for all building model types in all climate zones save climate zones 7 and 8, where the baseline insulation values were increased to R-15 and R-20, respectively, to account for higher roofing insulation values found in ASHRAE Standard 90.1 and the likelihood of higher existing insulation values for these two heating dominated climate zones.

Table 7 – Baseline Roof Characteristics by Climate Zone

Climate Zone	Above-deck Roof Insulation (IEAD) R-value	3-year aged solar reflectance (CRRC S100-tested)	3-year aged thermal emittance (CRRC S100-tested)
1 (A)	R-12.5	0.3	0.9
2 (A, B)	R-12.5	0.3	0.9
3 (A, B, C)	R-12.5	0.3	0.9
4 (A, B, C)	R-12.5	0.3	0.9
5 (A, B, C)	R-12.5	0.3	0.9
6 (A, B)	R-12.5	0.3	0.9
7	R-15	0.3	0.9
8	R-20	0.3	0.9

The baseline R-values were selected to represent typical roof insulation values found in commercial buildings 20-years and older with low-sloped roofs. It is based on secondary research conducted by PIMA (Polyisocyanurate Insulation Manufacturers Association) that found baseline levels of insulation to be between R-10 and R-15 for existing low-slope roofs. A primary assumption is that roofs being replaced today were originally constructed on buildings that date back prior to the widespread adoption of building energy codes and remain under insulated, where common practice was to install a single layer of 2” to 2.5” insulation.

Development of Intervention Conditions

Intervention conditions were developed separately for the roof upgrade and pipe insulation measures to be compliant with the requirements of ASHRAE Standard 90.1-2019. Roof upgrades were developed by directly modifying the baseline building energy models for compliance with the ASHRAE standard. Pipe insulation conditions on the other hand were indirectly developed by applying code-compliant upgrades to a subset of system types found in within the same baseline models.

Roof Upgrade Measure

Roof upgrades were developed by directly modifying the baseline building energy models for compliance with the ASHRAE Standard 90.1-2019. They were modified to reflect the roof insulation and cool roof requirements of the ASHRAE Standard according to climate zone, as shown in Table 8 and described below.

Table 8 –Intervention Roof Characteristics by Climate Zone

Climate Zone	Above-deck Roof Insulation (IEAD) R-value	3-year aged solar reflectance (CRRC S100-tested)	3-year aged thermal emittance (CRRC S100-tested)
1 (A)	R-20	0.55	0.75
2 (A, B)	R-25	0.55	0.75
3 (A, B, C)	R-25	0.55	0.75
4 (A, B, C)	R-30	0.3	0.9
5 (A, B, C)	R-30	0.3	0.9
6 (A, B)	R-30	0.3	0.9
7	R-35	0.3	0.9
8	R-35	0.3	0.9

- **Roof Insulation Requirements (applicable to all climate zones)** are based on ASHRAE Standard 90.1-2019 prescriptive building envelope compliance path for conditioned non-residential opaque roof (exterior) elements for insulation entirely above deck minimum rated R-value building envelop criteria. The R-values assume continuous insulation and vary according to U.S. climate zones specified by ASHRAE Standard 169. The insulation is assumed to be rigid roof insulation boards installed between a concrete, wood, or metal roof deck and an EPDM (ethylene propylene diene terpolymer membrane) water-proof roofing membrane.
- **Cool Roof Requirements (applicable to climate zones 1-3)** are based on 3-year aged solar reflectance and thermal emittance values of the ASHRAE 90.1-2019 standard for cool roofs.

These characteristics were used as inputs for modeling the performance of roof upgrades using DOE's EnergyPlus building energy modeling engine.

Pipe Insulation Measure

Pipe insulation conditions were indirectly developed by applying code-compliant upgrades to a subset of system types found within the baseline building energy models. They were developed outside of the building energy models because the DOE reference building models inherently assume no piping heat loss or heat gain and 3E Plus was identified through literature research (i.e., DOE resources, journal articles; state and regional technical reference manuals) as the primary industry tool for modeling pipe heat loss. Space heating, space cooling, and service hot-water service types (as identified in specification files previously developed by DOE) were analyzed outside of the building energy modeling environment for applicability as indicated in Table 9. Service types excluded from the study were refrigerant piping (used for refrigeration systems such as freezers and display cases as well as direct expansion heating and cooling systems), manufacturer installed piping (within terminal units and package systems) and all other listed service types that were not characteristic to the individual baseline building models.

Table 9 – Covered Service by Building Type

Service	Building Type					
	Primary School	Secondary School	Medium Office	Small Office	Stand-alone Retail	Midrise Apartment
Heating Hot Water	Yes[16]	Yes[17]	No	No	No	No
Service Hot Water	Yes	Yes	Yes	Yes	No	Yes
Steam	No	No	No	No	No	No
Steam Condensate	No	No	No	No	No	No
Chilled Water	No	Yes[18]	No	No	No	No
Refrigerant	No	No	No	No	No	No
Brine	No	No	No	No	No	No

For each covered service in Table 9, the pipe system characteristics of Table 10 were determined by examining and analyzing data from baseline building energy model output reports. System capacity and energy use were used to approximate equivalent full load hours; system capacity to approximate flow rate and then pipe size using ASHRAE's pipe sizing guidance. Professional judgement and input from the Insulation Industry Trade Associations Coalition were used to determine service insulation type and jacket material, with insulation thickness determined by ASHRAE Standard 90.1-2019.

Table 10 –Pipe System Characteristics

Process temperature (°F)	Insulation Type (according to process temperature)	Jacket material	NPS pipe size (applied to each process temperature) (inches)	Insulation Thickness (varied according to pipe size and temperature)[19] (inches)
50 (chilled water)	Mineral Fiber[20] PIPE, Types II and III, C547-15	Aluminum, in service	0.75	0.50
140 (service hot water)			1	1.00
160 (heating hot water)			2	1.50
			2.5	2.00

[16] DOE reference building model assumes "hot water from gas boiler for heating".
[17] DOE reference building model assumes "gas-fired boiler provides heating hot water and chilled water to AHU".
[18] IBID, DOE reference building model assumes "air cooled chiller".
[19] Based on ASHRAE Standard 90.1-2019. Insulation thickness varies according to service type and temperature.
[20] A.k.a. Fiberglass Insulation.

Process temperature (°F)	Insulation Type (according to process temperature)	Jacket material	NPS pipe size (applied to each process temperature) (inches)	Insulation Thickness (varied according to pipe size and temperature)[19] (inches)
			3	
			4	
			6	
			8	

Input Parameter	**Assumption**	**Source**
System Application:	Horizontal Pipe	Consultation with Insulation Industry Trade Associations Coalition
Ambient Temperature:	74°F (indoors, return air plenum)	Consultation with Insulation Industry Trade Associations Coalition
Wind Speed:	0 MPH (indoors)	Consultation with Insulation Industry Trade Associations Coalition
Base Material:	Steel	Consultation with Insulation Industry Trade Associations Coalition
Max Surface Temperature:	ASHRAE 90.1-2019 thickness	Study objective

These characteristics were used as inputs for modeling baseline and intervention pipe heat loss using 3E Plus online insulation heat flow calculator. They were intentionally tied to the DOE reference building models so that energy savings results were bound and could be directly added to the roof upgrade measure for reporting combined energy and emissions impacts and economic benefits.

Building-Level Energy Impacts

DOE's EnergyPlus building energy modeling engine and NAIMA's 3E Plus heat loss calculator were the primary software tools used to simulate the baseline and intervention performance conditions and from which building-level energy savings were developed for the roof upgrade and pipe insulation, respectively. Energy savings were developed by building type and climate zone for the roof upgrade measure and by building type and system type for the pipe insulation measure.

Roof Upgrade Measure

A custom measure workflow was used to simulate the baseline and intervention building energy models in EnergyPlus. Raw annual energy end use performance data from the EnergyPlus simulations by building type and climate zone were post-processed to produce incremental energy impacts. They were calculated as the difference between the simulated whole-building annual energy performance of the baseline and its corresponding intervention.

Energy savings are the result of increased roof insulation and thermal resistance, which reduces heat transfer through the roof assembly, reduces space heating and space cooling requirements and decreases energy use. Roof insulation measures reduce both space heating and cooling energy in all building types and climate zones modeled in this study. When paired with the cool roof requirements in climate zones 1-3, there tends to be a moderate increase in energy savings because of increased roof albedo (reflectance) and emittance that reduces the solar energy (radiation) absorbed by and transmitted as heat gain through the building's roofing assembly. Benefits not considered in the modeling associated with increased roof insulation and the addition of a second layer of continuous insulation include reduced air leakage and moisture movement (two layers of insulation with staggered joints) as well as reduced condensation potential in roof assemblies.

Pipe Insulation Measure

3E Plus was used to separately model baseline and intervention heat loss [btu/ft/hr] for the covered service types and system characteristics of Table 9 and Table 10, for the bare pipe use case. Raw heat loss data by service and system characteristic were post-processed using the assumptions of Table 11 to produce incremental building-level energy savings as the product of the difference between the baseline and intervention conditions service effective full load hours and affected piping length. They were then separately adjusted for the damaged/under insulated use case using industry standard engineering heat loss calculations to reduce insulation thermal resistance (R-value) and both use cases summed for total pipe insulation energy savings.

- **Bare (uninsulated) Pipe** is uninsulated pipe – the pipe has either never been insulated or the insulation was removed due to system maintenance or damage and not reinstalled.
- **Damaged / Under Insulated Pipe** is either under insulated or has under-performing pipe insulation - the pipe insulation is less than required by ASHRAE 90.1-2019 or its insulating value has been reduced due to physical or environmental damage.

Table 11 – Insulation Assumptions[21] [22]

Insulation Modeling Assumptions		
Parameter	**Assumption**	**Source**
Uninsulated Piping:	10% of total pipe length; based on range of 5-15%.	Consultation with Insulation Industry Trade Associations Coalition

[21] Secondary literature research (i.e., DOE energy code compliance studies, journal articles, and internet research) generally lacked mention of pipe insulation conditions but some studies observed that despite code requirements having been in effect for many years, pipe insulation tended to have a low compliance level compared to equipment efficiency; and with respect to water heaters that "pipe insulation is present for only 26% of the water heaters surveyed". There are several studies; however, that make anecdotal reference to 30% of installed piping is uninsulated; however, the source of that data could not be corroborated nor was any quantitative information available for the split of uninsulated and under insulated or damaged piping; however, the Consultation with Insulation Industry Trade Associations Coalition indicated they understand the amount of uninsulated piping is greater than 30%. The sum of uninsulated and under insulated and damaged piping used herein is thus considered to be conservative.

[22] Older commercial buildings tend to have a larger percentage of uninsulated or damaged insulation compared to newer commercial buildings.

Insulation Modeling Assumptions		
Under or Damaged Piping:	15% of total pipe length; based on range of 10-30%	Consultation with Insulation Industry Trade Associations Coalition
Distribution System Length and Pipe Size	Equal pipe length for max pipe size and smaller sized distribution piping.	Consultation with Insulation Industry Trade Associations Coalition
Pipe Length (LF pipe/SF building):	Various	Insulation Outlook, Mechanical Insulation in Hospitals and Schools Update, Figure 3, July 2021[23]
System Efficiencies:	Various	Technical Reference Manuals

Energy savings are the result of increased pipe insulation and thermal resistance, which reduces the temperature difference between the system's working fluid and its ambient conditions, reduces heat transfer, and thus reduces space heating, space cooling, and service hot water system energy input requirements.

State- and National-Level Energy Impacts

Macro-level estimates of energy savings were developed separately by measure and combined by adding together roof upgrade and pipe insulation measure building-level energy savings and extrapolating each to the state-level (using uniform allocations by U.S. census region) and then to the national-level (using market floor area data from CBECS according to building subsector and building type).

First, state/county climate zone data from ASHRAE Standard 90.1-2019 Annex 1 were used to derive the percentage of counties within each state and within each ASHRAE Standard 169 climate zone as a proxy for the distribution of the commercial building stock and allocation of building-level energy savings to the state level by climate zone.

Second, EIA's 2018 CBECS[24] Primary Building Activity (PBA) types were mapped to the study's six commercial building types as shown in Table 12, allowing definition of interested commercial subsectors for analysis. Professional judgement was used in the mapping of building types and determining the size of small and medium office building types from data within CBECS.

Table 12 – Building Type Mapping to EIA CBECS Primary Building Activity

Commercial Subsector	Building Type	EIA CBECS PBA (i.e., Building Type)
Educational	Primary School	28=Elementary school
	Secondary School	54=Middle/junior high school
	Primary School/Secondary School (50%/50%)[25]	55=Multi-grade school (any K-12)

[23] Mechanical Insulation in Hospitals and Schools - Insulation Outlook Magazine
[24] Energy Information Administration (EIA)- Commercial Buildings Energy Consumption Survey (CBECS) Data
[25] Professional judgment used in relative allocation of CBECS building types to study's educational building type.

Commercial Subsector	Building Type	EIA CBECS PBA (i.e., Building Type)
Federal	Medium Office (0-100,000 sf)[26]	4=Government office
	Small Office (0-10,000 sf)[27]	4=Government office
Private	Medium Office (0-100,000 sf)[28]	2=Administrative/professional office
		3=Bank/other financial
		5=Medical office (non-diagnostic)
		6=Mixed-use office
		7=Other office
	Small Office (0-10,000 sf)[29]	2=Administrative/professional office
		3=Bank/other financial
		5=Medical office (non-diagnostic)
		6=Mixed-use office
		7=Other office
	Midrise Apartment	37=Dormitory/fraternity/sorority
		40=Other lodging
	Stand-alone Retail	42=Retail store
		43=Other retail

Third, floor area data for each building type, from CBECS, were summed for each U.S. Census Region as shown in Table 13, and then divided equally by the number of states[30] in the corresponding region to uniformly allocate floor area by U.S. Census Region[31] into its constituent states as shown in Table 14.

Table 13 – Commercial Floor Area (SF) by Building Type and U.S. Census Region (x1000)

Commercial Subsector	Building Type	U.S. Census Region				Total
		Northeast	Midwest	South	West	
Educational	Primary School	800,658	1,288,633	1,680,071	723,893	4,493,255
	Secondary School	583,215	833,205	761,400	482,392	2,660,212
Federal	Medium Office	146,918	236,059	492,755	158,284	1,034,016
	Small Office	29,199	100,230	94,446	91,342	315,217
Private	Medium Office	722,884	1,701,132	1,817,740	1,190,862	5,432,617
	Small Office	396,266	715,818	907,198	491,399	2,510,681
	Stand-alone Retail	605,540	1,469,150	2,175,798	942,311	5,192,799
	Midrise Apartment	325,747	300,182	431,014	278,026	1,334,968
Total		**3,610,426**	**6,644,408**	**8,360,422**	**4,358,509**	**22,973,765**

[26] Professional judgement used to determine gross floor area range.
[27] IBID.
[28] IBID.
[29] IBID.
[30] 2018 EIA CBECS includes the most recent and statistically robust set of publicly available data for the commercial building stock. Data is provided at the Census rather than state level.
[31] U.S. Energy Information Administration - EIA - Independent Statistics and Analysis

Table 14 – Commercial Floor Area (SF) per State Located within each U.S. Census Region

Commercial Subsector	Building Type	U.S. Census Region			
		Northeast	Midwest	South	West
Educational	Primary School	88,962,045	107,386,054	98,827,704	55,684,101
	Secondary School	64,801,668	69,433,725	44,788,261	37,107,075
Federal	Medium Office	16,324,193	19,671,579	28,985,604	12,175,708
	Small Office	3,244,343	8,352,511	5,555,622	7,026,306
Private	Medium Office	80,320,395	141,760,985	106,925,888	91,604,743
	Small Office	44,029,587	59,651,473	53,364,592	37,799,925
	Stand-alone Retail	67,282,171	122,429,200	127,988,135	72,485,444
	Midrise Apartment	36,194,066	25,015,137	25,353,741	21,386,618

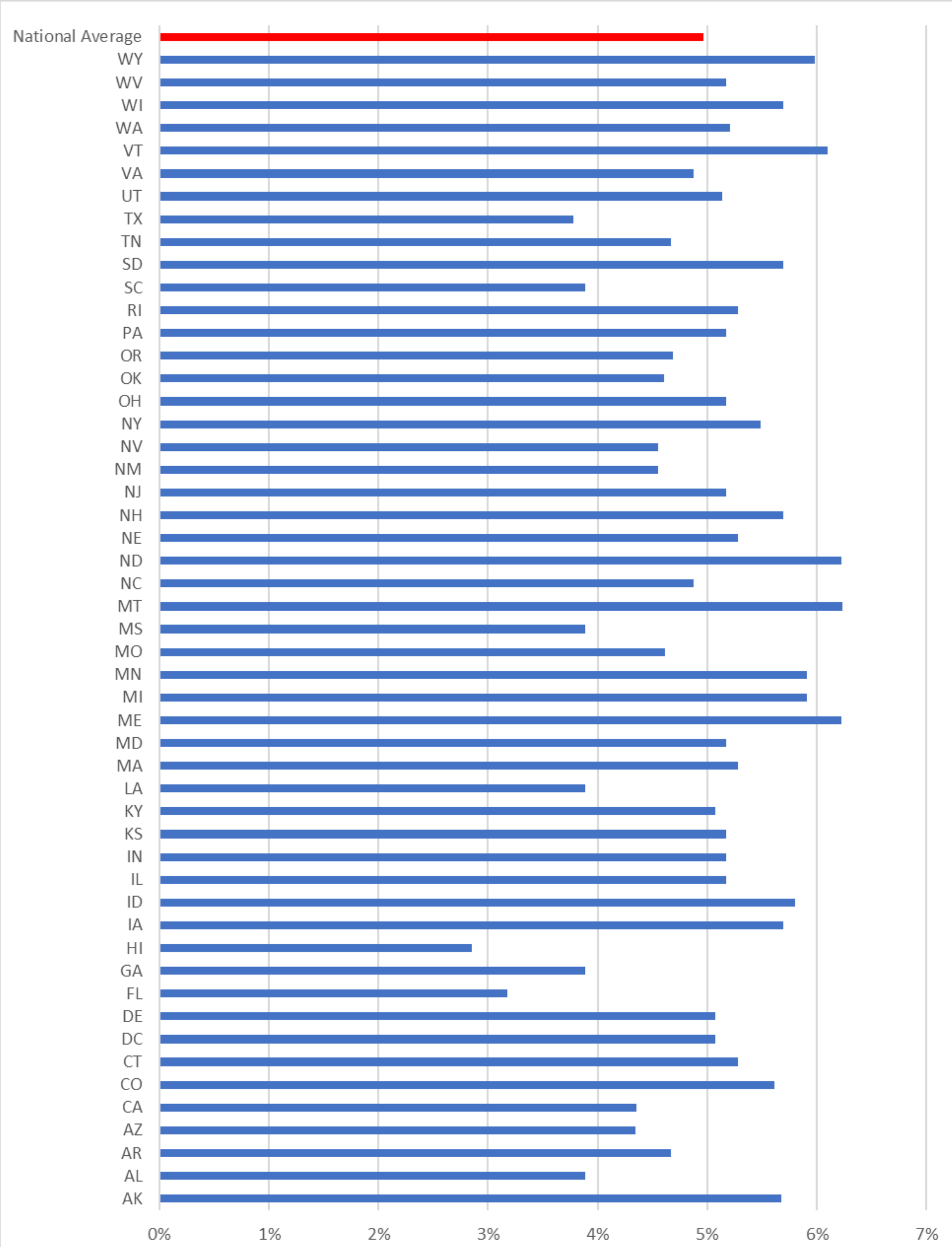
Finally, the state-level floor areas of Table 14 were used to scale building-level energy savings first to the state- and then national-level, the latter shown in Table 15.

Table 15 – Combined National-Level Energy Savings by Building and Fuel Type

Commercial Subsector	Building Type	Annual		Cumulative	
		Electric Savings (kWh)	Natural Gas Savings (Therms)	Electric Savings (kWh)	Natural Gas Savings (Therms)
Educational	Primary School	2,315,027,715	323,503,953	69,450,831,456	9,705,118,601
	Secondary School	1,204,771,430	172,640,019	36,143,142,905	5,179,200,565
Federal	Medium Office	227,905,300	992,398	6,837,158,987	29,771,926
	Small Office	196,310,536	2,818,932	5,889,316,087	84,567,966
Private	Medium Office	1,250,036,619	5,936,108	37,501,098,555	178,083,236
	Midrise Apartment	327,526,820	20,542,599	9,825,804,587	616,277,973
	Stand-alone Retail	2,448,749,201	159,422,166	73,462,476,021	4,782,664,987
	Small Office	1,554,541,035	21,064,733	46,636,231,042	631,941,989
Total		**9,524,868,655**	**706,920,908**	**285,746,059,641**	**21,207,627,244**

From absolute savings, relative energy savings were developed as the ratio of total energy saved to the baseline energy use (in MMBtu) for each modeled condition. Weighted average relative energy savings for all building types and climate zones are shown in Figure 5.

Figure 5 – Combined Weighted Average Relative Energy Savings by State



National-level relative energy savings by commercial subsector and building type are presented in Table 16 with the building types and their corresponding roof-to-floor area ratios - calculated as the quotient of the building's roof and floor areas. From this perspective, it can be seen that while the magnitude of relative savings is similar at the state-level (Figure 1), there are greater variances at the building-level with, generally, greater relative energy savings for buildings that have greater roof-to-floor area ratios compared to buildings with smaller ratios.

Table 16 – Combined Average Relative Energy Savings by Building Type, Climate Zone, and Scenario

Commercial Subsector	Building Type	Relative Energy Savings (%)	Floor Area	Roof Area	Roof-to-Floor Area Ratio
Educational	Primary School	8.7%	73,960	73,960	1.00
	Secondary School	7.1%	210,887	105,444	0.50
Federal	Medium Office	1.6%	53,628	17,876	0.33
	Small Office	5.7%	5,500	5,500	1.00
Private	Medium Office	1.6%	53,628	17,876	0.33
	Midrise Apartment	3.6%	33,740	8,435	0.25
	Stand-alone Retail	5.6%	24,962	24,962	1.00
	Small Office	5.7%	5,500	5,500	1.00

At the national-level, more than two-thirds of the total energy savings (in MMBtu) are from natural gas energy savings as shown in Table 17.

Table 17 – Combined Weighted Average Relative Savings by Building Type

Commercial Subsector	Building Type	Relative Savings[32]	Relative Savings by Fuel Type[33]	
			Electric	Natural Gas
Educational	Primary School	39%	20%	80%
	Secondary School	21%	19%	81%
Federal	Medium Office	1%	89%	11%
	Small Office	1%	70%	30%
Private	Medium Office	5%	88%	12%
	Midrise Apartment	3%	35%	65%
	Stand-alone Retail	24%	34%	66%
	Small Office	7%	72%	28%
Total/Average		**100%**	**31%**	**69%**

[32] Relative energy savings is for all buildings covered in this study. Column sums to 100%.
[33] Relative energy savings is for individual building types. Rows sum to 100%.

Calculation of Emissions Impacts

Reductions in building emissions are the direct result of energy savings that occur from a reduction in space heating, space cooling, and service hot water requirements and the corresponding reduction in onsite combustion of natural gas and purchased electricity. Scope 1 direct and Scope 2 indirect emissions were calculated as the product of the site energy savings (derived as the difference in energy use between the baseline and intervention (or code-compliant scenarios), by fuel type, and the corresponding U.S. Environmental Protection Agency (EPA) Emissions & Generation Resource Integrated Database (eGRID) for electric and Center for Corporate Climate Leadership for natural gas national-level emissions factors, for the corresponding fuel type and its constituent emissions. State- and national-level weighted average CO2e emissions savings are presented in Figure 6 and Table 18, respectively.

Figure 6 – Combined Cumulative CO2e Emissions Savings (tons) by State

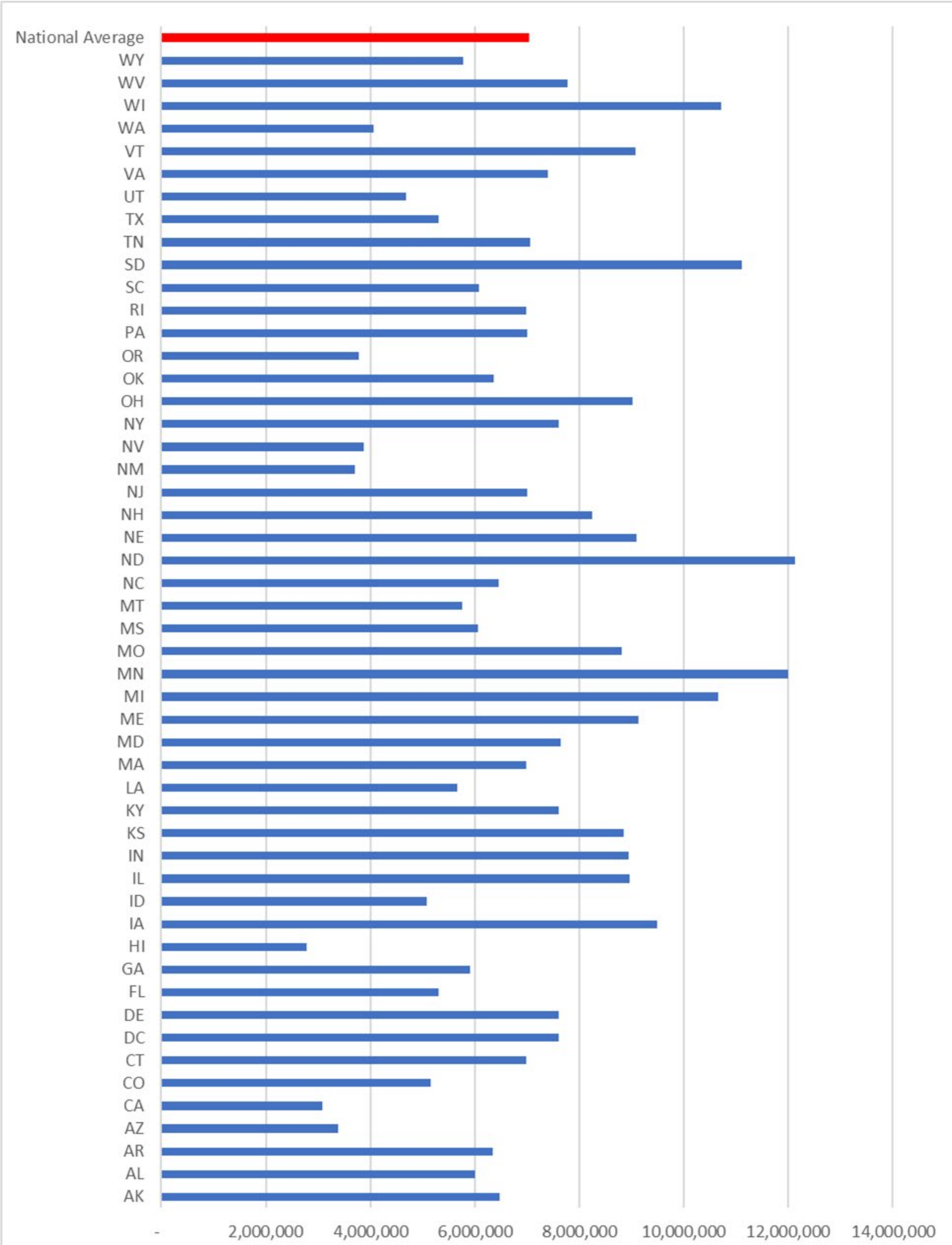


Table 18 – Combined CO2e Emissions Savings (tons) by Building Type

Commercial Subsector	Building Type	Annual CO2e (tons)	Cumulative CO2e (tons)
Educational	Primary School	4,541,099	136,232,975
	Secondary School	2,409,458	72,283,734
Federal	Medium Office	114,253	3,427,598
	Small Office	119,599	3,587,964
Private	Medium Office	631,984	18,959,509
	Midrise Apartment	370,382	11,111,454
	Stand-alone Retail	2,832,263	84,967,901
	Small Office	933,511	28,005,327
Total		**11,952,549**	**358,576,461**

Calculation of Economic Benefits

Installation of roof upgrades (at the time of roof replacement) and pipe insulation projects directly result in energy savings and downstream operational savings (e.g., energy cost savings), the latter which can be monetized along with incremental measure costs over the project's life to quantify the economic benefits of the proposed interventions, compared to the baseline conditions. As a conservative assumption, the economic benefits were limited to the energy cost savings and did not include monetized health or environmental benefits due to avoided air emissions from the energy savings.

This section presents development of economic benefits that flow from energy cost savings combined with incremental project capital costs and are presented using the Benefit-to-Cost Ratio (BCR) metric.

Energy Cost Savings and Upgrade Project Costs

Energy cost savings accrue from the incremental reduction in space heating, space cooling, and service hot water requirements and corresponding reduction in natural gas and electric usage. Energy cost savings were calculated as the product of energy savings and national-level energy price from EIA, by fuel type, inclusive of energy price escalation over the effective useful life of the intervention.

Incremental project capital costs were developed using a combination of industry accepted resources and secondary literature research.

- **Insulation capital costs** were developed using 2019 RSMeans national average material and labor costs per square foot for Polyiso insulation. Incremental costs were used to isolate the incremental benefit of code-compliant insulation compared to the baseline scenario. 2019 RSMeans was selected as the most recent year for which to base the representative analysis. It provides cost details for insulation thicknesses ranging from 0.75 to 4.4 inches but is exclusive of cost data for the baseline (R-12.5: 2.2 inches at R-5.7/inch) and code-compliant (R-25: 4.4 inches at R-5.7/inch; and R-30: 3.1 inches at R-5.7/inch) scenarios evaluated in this analysis. For the baseline and intervention scenarios, capital costs were developed as the sum of the material and labor costs, inclusive of overhead and profit. Material costs are generally linear with respect to installed insulation thickness and were therefore estimated as the product of the average material unit cost, with overhead and profit, and the installed insulation thickness. In contrast, labor costs, are generally not linear with installed insulation thickness and were therefore developed from a logarithmic expression of insulation R-value and costs per square foot.
- **Cool roof costs** were developed by averaging multiple sources of cost data obtained from literature research and product internet research. Generalized unit costs for warmer and cooler roof options obtained from EPA's Heat Island Compendium, Chapter 4: Cool Roofs[34], were converted to current dollars using the U.S. Bureau of Labor Statistics

[34] Heat Island Compendium | US EPA

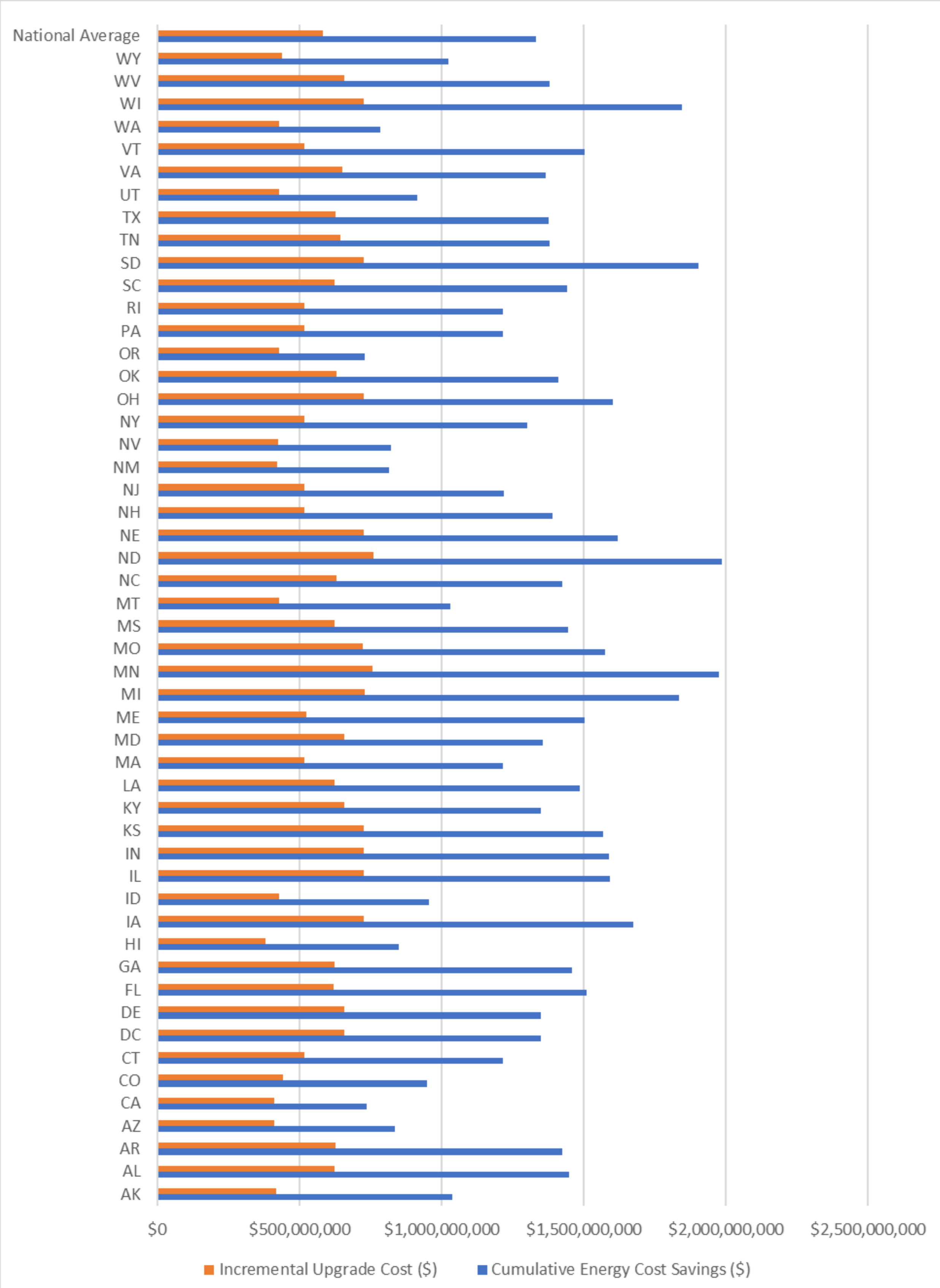
Consumer Price Index[35]. Product specific unit costs were obtained through internet research of products listed on the CRRC Roof Products Directory. Incremental costs of each were averaged to define a single unit cost for cool roof exclusive of labor costs (assumed to be same for black and cool roofs) and maintenance costs for cleaning, which were omitted to be consistent with the modeling 3-year aged solar reflectance and thermal emittance.

- **Pipe insulation costs** were derived from 3E Plus for the bare pipe use case and RSMeans for the damaged/under-insulated use case.

Weighted average state energy cost savings and incremental project capital costs are presented side-by-side in Figure 7 for comparison, and show that, on average, the cumulative energy savings over the project life exceed the incremental upgrade costs.

[35] https://www.bls.gov/data/inflation_calculator.htm

Figure 7 – Combined Cumulative Energy Cost Savings and Incremental Upgrade Costs by State



The same data by commercial subsector and building type are shown in Table 19, with similar results – that on average, the cumulative energy savings over the project life exceed the incremental upgrade costs.

Table 19 – Combined Cumulative Energy Cost Savings and Upgrade Costs, by Building Type

Commercial Subsector	Building Type	Cumulative Energy Cost Savings ($)	Incremental Upgrade Cost ($)
Educational	Primary School	22,247,893,698	8,175,312,874
	Secondary School	11,739,842,923	2,858,790,305
Federal	Medium Office	1,025,347,626	722,702,549
	Small Office	957,353,014	559,695,532
Private	Medium Office	5,642,532,712	3,810,910,318
	Midrise Apartment	2,195,240,938	746,716,566
	Stand-alone Retail	16,632,999,742	8,434,411,298
	Small Office	7,533,588,407	4,453,809,023
Total		**67,974,799,062**	**29,762,348,466**

Economic Benefits

Economic benefits associated with each intervention were quantified using the BCR metric to determine cost effectiveness at the macro-level.

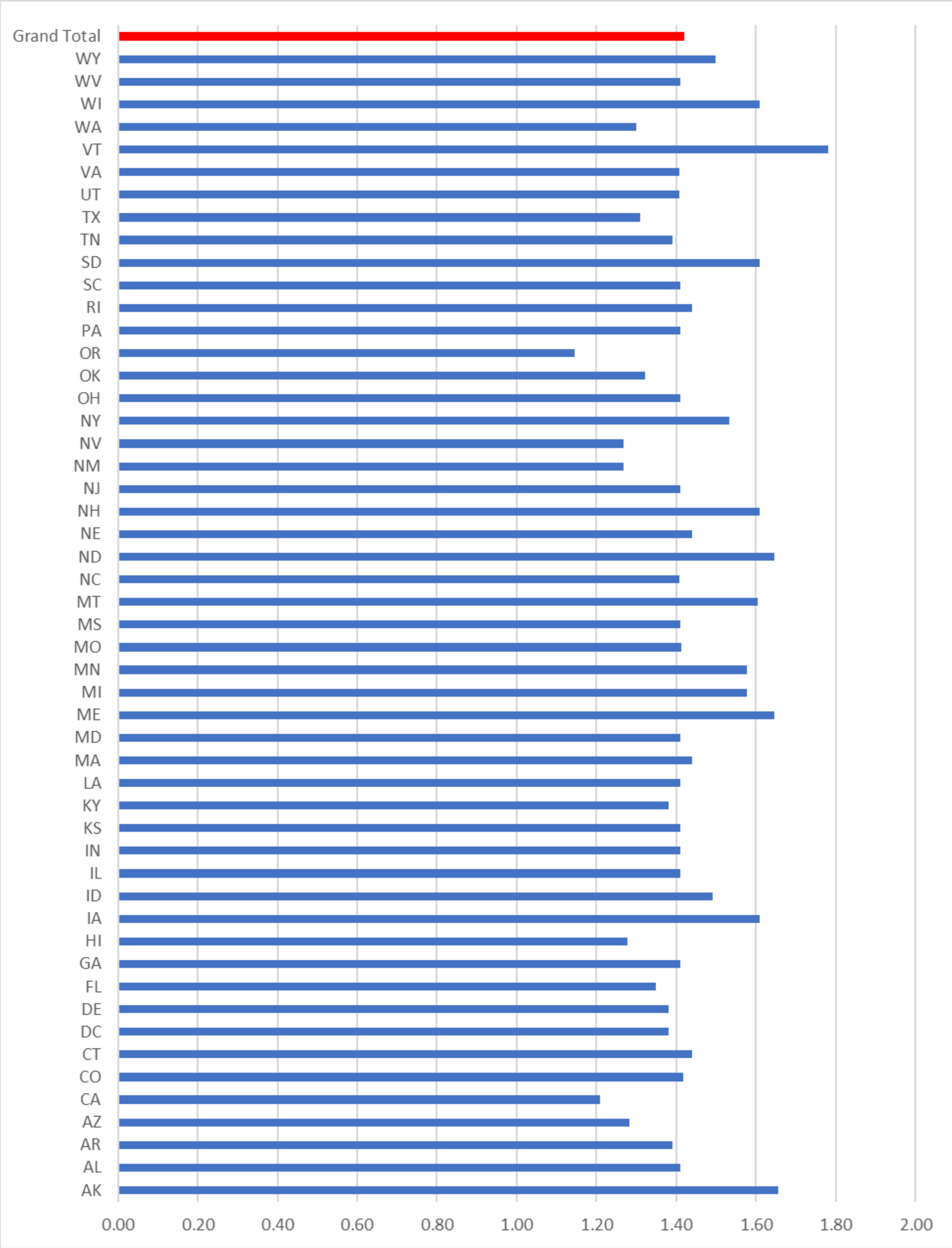
BCR uses a life-cycle cost approach to account for the time value of money. This enables a comparison of the project's benefits and costs over its effective useful life and is the economic method referenced by DOE in their *Methodology for Evaluating Cost-Effectiveness of Commercial Energy Code Changes* document and is also a method used by utility program administrators and implementers in development of cost-effective demand-side management incentive programs. BCR is calculated as the ratio of the present value of benefits to the present value of costs. The intervention is cost-effective when the BCR is greater than 1.0, indicating its life-cycle benefits exceed its cost. The BCR of each intervention was calculated using inputs of energy cost savings, incremental capital costs, and the modeling assumptions listed in Table 20. Details and data sources for the assumptions in Table 20 can be found in the appendices.

Table 20 – Lifecycle Cost Economic Modeling Assumptions

Input Variable		Value	Source
Discount Rate		3.00%	DOE, FEMP
Modeling Timeline (years)		30	DOE, FEMP
Effective Useful Life (EUL)	Roof Insulation	30	Insulation Industry Trade Associations Coalition
	Pipe Insulation	30	
Electricity Commodity Cost ($/kWh)		$0.11	DOE, EIA
Electricity Annual Escalation Rate		1.80%	DOE, EIA
Natural Gas Commodity Cost ($/therm)		$0.77	DOE, EIA
Natural Gas Annual Escalation Rate		2.90%	DOE, EIA

The weighted average BCR for each state is depicted in Figure 8 and shows that on average, the cumulative benefits of roof upgrades and pipe insulation measures exceed their investment capital costs and are therefore cost-effective based on the assumptions listed in Table 20.

Figure 8 – Combined Weighted Average Benefit-to-Cost Ratio (BCR) by State



The same BCR results by commercial subsector and building type are shown in Table 21. As with the findings above, on average, project economics are cost effective with the cumulative energy savings exceeding the incremental project upgrade costs.

Table 21 – Combined Weighted Average Economics by Building Type

Commercial Subsector	Building Type	Average BCR (Benefit-to-Cost Ratio)
Educational	Primary School	1.64
	Secondary School	2.49
Federal	Medium Office	0.92
	Small Office	1.09
Private	Medium Office	0.92
	Midrise Apartment	1.88
	Stand-alone Retail	1.31
	Small Office	1.09
Total/Average		**1.42**

Industrial Insulation Retrofits

This study[36] assesses the state- and national-level energy and emissions impacts and economic benefits that could accrue over a 20-year horizon from the installation of code-compliant steam pipe insulation[37] in a select number of manufacturing sectors. It was conducted for eight manufacturing sectors found in the U.S. Department of Energy's (DOE) Industrial Assessment Center (IAC) Database and their 2018 Energy Information Administration's (EIA) Manufacturing Energy Consumption Survey (MECS) that combined make up about 61% of the pipe insulation energy savings found in the IAC database and 50% of the MECS manufacturing enclosed floor area. A primary assumption for conducting this study was that a substantial amount of industrial piping is uninsulated, under insulated, or damaged. When installed, age, maintenance, improper design, and environmental conditions are factors that contribute to the degradation of pipe insulation performance.

State- and national-level energy and emissions impacts and economic benefits from pipe insulation for the industrial sector were assessed using the following approach.

Energy Impacts Secondary literature research was conducted using publicly available resources to identify manufacturing sectors and their systems with the greatest opportunity for pipe insulation, their corresponding market potential, and system characteristics. Findings from analysis of DOE's IAC Database[38] and EIA's MECS[39] were supported by relevant DOE publications, journal articles, state- and utility-program energy efficiency technical reference manuals (TRMs), and white papers identified through internet research.

Secondary literature research, professional judgement, and consultation with the Insulation Industry Trade Association Coalition were used to develop average pipe insulation baseline conditions for the covered industrial sectors and systems for comparison to an ASHRAE Standard 90.1-2019 code-compliant intervention condition. The North American Insulation Manufacturers Association's (NAIMA) 3E Plus[40] heat loss calculator was used to calculate the baseline and intervention performance conditions [Btu/ft/hr] from which energy savings by climate zone were developed by industrial sector, pipe location, and system temperature. Savings were then extrapolated to the state-level by allocating state counties to climate zones and MECS manufacturing enclosed floor area from U.S. Census Regions to states, and then to the national-level by aggregating state-level results.

Emissions Savings Emissions impacts were developed directly from energy savings as the product of energy savings by fuel type and its corresponding U.S. Environmental Protection Agency (EPA) emissions factor.

Economic Benefits Energy cost savings were calculated as the product of energy savings by fuel type and its corresponding fuel price and then combined with secondary literature research

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[36] Opportunity that exists over a 20-year horizon if all technical potential were installed in day one.
[37] Space and process cooling, industrial refrigeration, and heating, ventilation, and air conditioning (HVAC) duct insulation were omitted, but their inclusion would increase the total impacts and benefits available from code-compliant insulation in the manufacturing sector.
[38] IAC: Search IAC Assessments
[39] Manufacturing Energy Consumption Survey (MECS) - Data - U.S. Energy Information Administration (EIA)
[40] 3E Plus

on incremental capital costs and economic inputs to produce life-cycle economic metrics over a 20-year timeframe.

Development of Energy Impacts

Secondary literature research was conducted using publicly available resources to identify manufacturing sectors and their systems with the greatest opportunity for pipe insulation, their corresponding market potential, and system characteristics. Findings from analysis of DOE's IAC database and MECS were supported by relevant DOE publications, journal articles, state- and utility-program energy efficiency TRMs, and white papers identified through internet research.

Secondary literature research, professional judgement, and consultation with the Consultation with Insulation Industry Trade Association Coalition were used to develop average pipe insulation baseline conditions for the covered industrial sectors and systems for comparison to an ASHRAE Standard 90.1-2019 code-compliant intervention condition. NAIMA's 3E Plus heat loss calculator was used to calculate the baseline and intervention performance conditions [Btu/ft/hr] from which energy savings by climate zone were developed by industrial sector, pipe location, and system temperature. Savings were then extrapolated to the state-level by allocating state counties to climate zones and MECS manufacturing enclosed floor area from U.S. Census Regions to states, and then to the national-level by aggregating state-level results.

Market Assessment

IAC's database contains energy conservation measure data from nearly 20,000 energy audits conducted by DOE funded IACs since the 1980s. Although the data is for small-to-medium manufacturers, it was used in this study as a proxy for the broader insulation opportunity that exists across the manufacturing sector because it is inclusive of industrial sectors with significant thermal processing energy use[41] and therefore have high potential for energy savings. According to DOE, pipe insulation is one of the top 10 recommended IAC measures and has installation rates of nearly 70% due to generally low initial cost and high return on investment.

The database includes three insulation measures that were relevant to this study:

- Thermal systems; steam; condensate: Install / Repair Insulation on Condensate Lines.
- Thermal systems; steam; condensate: Install / Repair Insulation on Steam Lines.
- Space conditioning; maintenance: Install / Upgrade Insulation on HVAC Distribution Systems.

In contrast to the steam and steam condensate thermal system measures, the space conditioning measure is unspecific and is an amalgamation of piping and ductwork measures and cannot be used to discern savings for process chilled water piping insulation, for example.

For each measure, energy savings and total facility energy use by fuel type, facility hours of production, economic payback period, and whether the measure was installed were analyzed to calculate average characteristics for those same fields as well as calculate the prevalence of each measure in the database and its relative energy savings. The prevalence of each insulation measure is shown in Table 22 by total number of instances in the IAC database and

[41] Session 1 High Temperature Metals (energy.gov)

the percentage of instances relative to each other. Steam and steam condensate measures account for more than 95% of the IAC's instances of relevant insulation recommendations.

Table 22: Prevalence of Insulation Measures in IAC Database

Measure	Count	Percent
Install / Repair Insulation on Steam Lines	1,533	81%
Install / Repair Insulation on Condensate Lines.	313	16%
Install / Upgrade Insulation on HVAC Distribution	52	3%
Total	**1,898**	**100%**

Similarly, Table 23 shows the percentage of total energy savings for the three insulation measures relative to each other. Again, steam and steam condensate measures account for more than 95% of the IAC's energy savings for relevant insulation recommendations.

Table 23: Relative Energy Savings of Insulation Measures in IAC Database

Measure	Count	Percent
Install / Repair Insulation on Steam Lines	1,533	90%
Install / Repair Insulation on Condensate Lines.	313	8%
Install / Upgrade Insulation on HVAC Distribution	52	2%
Total	**1,898**	**100%**

Table 24 shows the breakout of total and relative energy savings by measure and fuel type with the greatest energy savings for natural gas (62%) and insulation of steam lines (90%). Natural gas savings for insulation of steam lines accounts for 57% of the total IAC insulation savings while relative savings from steam condensate are marginal and (heating, ventilation, and air conditioning) HVAC distribution systems minimal.

Table 24: Absolute and Relative Energy Savings of Insulation Measures in IAC Database by Fuel Type

Measure	Natural Gas		Electricity		All Other Fuels[42]	
	Savings (MMBtu)	Relative Savings	Savings (MMBtu)	Relative Savings	Savings (MMBtu)	Relative Savings
Install / Repair Insulation on Steam Lines	188,492,131	57%	48,834,931	15%	59,124,581	18%
Install / Repair Insulation on Condensate Lines.	12,142,184	4%	6,196,898	2%	7,292,597	2%
Install / Upgrade Insulation on HVAC Distribution	3,663,459	1%	2,858,249	1%	483,664	0%
Total	**204,297,774**	**62%**	**57,890,077**	**18%**	**66,900,841**	**20%**

Accordingly, the analysis was limited to natural gas savings from steam and steam condensate pipe insulation measures, which account for about 61% of the insulation energy savings identified by IAC assessments. This study boundary was corroborated by secondary literature research that indicated the largest industrial insulation energy savings potential to be for natural gas steam boilers and their distribution systems.

[42] All Other Fuels include LPG, Fuel Oil, Coal, Wood, Other Gas Consumption, and Other Energy Consumption.

Rough estimates for proxying market potential were developed, by manufacturing sector and its North American Insulation Manufacturers Association (NAICS) Code, by extrapolating the relative natural gas steam and steam condensate measure energy savings from the IAC database to that sector's total thermal process energy use from MECS, as shown in Table 25.

Table 25: Steam and Steam Condensate Market Potential by Industrial Sector

NAICS Code	Industrial Sector	Total Thermal Process Energy Use (Trillion Btu)	Relative Natural Gas Savings from Steam and Steam Condensate	Insulation Market for Steam and Steam Condensate (MMBtu)
325	Chemicals	2,257	7.37%	166,249,129
311	Food	587	4.41%	25,883,488
322	Paper	544	1.63%	8,849,212
324	Petroleum and Coal Products	1,038	0.75%	7,781,154
331	Primary Metals	592	0.85%	5,058,323
327	Nonmetallic Mineral Products	329	1.19%	3,913,206
336	Transportation Equipment	94	3.17%	2,978,799
326	Plastics and Rubber Products	62	3.28%	2,032,539
332	Fabricated Metal Products	87	1.33%	1,153,875
321	Wood Products	59	1.53%	904,629
339	Miscellaneous	16	2.50%	399,735
313	Textile Mills	20	1.96%	392,402
335	Electrical Eq., Appliances, Components	25	1.23%	307,164
323	Printing and Related Support	15	1.74%	261,317
312	Beverage and Tobacco Products	49	0.37%	179,374
334	Computer and Electronic Products	14	0.89%	124,709
333	Machinery	32	0.29%	92,424
314	Textile Product Mills	10	0.91%	91,457
315	Apparel	2	1.73%	34,547
337	Furniture and Related Products	8	0.19%	15,530

The Chemicals sector accounts for roughly 75% of the market share. It is followed by the Food, Paper, Petroleum and Coal Products, Primary Meals, Nonmetallic Mineral Product Transportation Equipment, and Plastics and Rubber Products sectors that combined make up 98% of the market potential and are the basis for estimating impacts and benefits in this study.

The eight topmost industrial sectors having significant thermal processing energy use and market potential, discussed in the preceding section, were crosswalked in Table 26 with their thermal process temperature ranges[43] according to DOE to determine the range of fluid temperatures to be used in the analysis. Fluid temperatures within these ranges were determined in consultation with the Insulation Industry Trade Association Coalition and a uniform percentage of total piping, by sector, was allocated to each temperature bin as shown in Table 27 for the ensuing energy savings analysis.

[43] Session 1 High Temperature Metals (energy.gov)

Table 26: Typical Range of Temperatures Used in Thermal Processes by Industrial Sector

NAICS Code	Industrial Sector	< 800°F	800 – 1400°F	> 1400°F
325	Chemicals	Yes	Yes	Yes
311	Food	Yes	Yes	No
322	Paper	Yes	Yes	Yes
324	Petroleum and Coal Products	No	Yes	No
331	Primary Metals	No	Yes	Yes
327	Nonmetallic Mineral Products	No	Yes	Yes
336	Transportation Equipment	Yes	No	No
326	Plastics and Rubber Products	Yes	Yes	Yes

Table 27: Allocation of Thermal Process Temperatures by Industrial Sector

Industrial Sector	125 °F	175 °F	225 °F	300 °F	400 °F	600 °F	800 °F	1000 °F	1200 °F
Chemicals	11%	11%	11%	11%	11%	11%	11%	11%	11%
Food	11%	11%	11%	11%	11%	11%	11%	11%	11%
Paper	11%	11%	11%	11%	11%	11%	11%	11%	11%
Petroleum and Coal Products	0%	0%	0%	0%	0%	0%	33%	33%	33%
Primary Metals	0%	0%	0%	0%	0%	0%	33%	33%	33%
Nonmetallic Mineral Products	0%	0%	0%	0%	0%	0%	33%	33%	33%
Transportation Equipment	17%	17%	17%	17%	17%	17%	0%	0%	0%
Plastics and Rubber Products	11%	11%	11%	11%	11%	11%	11%	11%	11%

Average annual hours of steam and steam condensate system production were derived from the IAC database by industrial sector and are presented in Table 28. They were used in the energy savings analysis to convert energy savings per linear foot of pipe per hour [Btu/ft/hr] derived from NAIMA's 3E Plus to energy savings per linear foot [Btu/ft].

Table 28: Average Production Hours from IAC Database by Industrial Sector

NAICS Code	Industrial Sector	Average Annual hours of Production
325	Chemical	6,844
311	Food Manufacturing	6,117
327	Nonmetallic Mineral Product	5,388
322	Paper	6,804
324	Petroleum and Coal Products	5,183
326	Plastics and Rubber Products	6,186
331	Primary Metal	5,951
336	Transportation Equipment	6,077

Development of Baseline Conditions

Constructs of the analysis were informed by the preceding market assessment, which identified natural gas steam and steam condensate systems within eight industrial sectors as having the greatest opportunity and potential for energy savings based on the prevalence of their energy savings identified through review of IAC assessment database and their process temperature requirements as indicated by DOE.

A primary assumption for conducting this study was that a substantial amount of industrial piping is uninsulated, under insulated, or damaged. When installed, age, maintenance, improper design, and environmental conditions are factors that contribute to the degradation of pipe insulation performance.

- **Bare (uninsulated) Pipe** is uninsulated pipe – the pipe has either never been insulated or the insulation was removed due to system maintenance or damage and not reinstalled.
- **Damaged / Under Insulated Pipe** is either under insulated or has under-performing pipe insulation - the pipe insulation is less than required by ASHRAE 90.1-2019 or its insulating value has been reduced due to physical or environmental damage.

While secondary literature research conducted supported this hypothesis there is no repository (database or meta-analysis) of information on installed insulation conditions and performance that could be used to support developing reasonable characteristic assumptions for this analysis. Information pertaining to the total and relative amount of uninsulated, under insulated, and damaged pipe length[44] and corresponding characteristics could not be identified nor quantified through review of publicly available resources. Consequently, reasonable assumptions and approximations that served as both inputs to 3E Plus and for post-processing and extrapolating 3E Plus results to the sector-, state-, and national-levels were determined in consultation with the Insulation Industry Trade Association Coalition. They are summarized in Table 29.

[44] Information on piping distribution system lengths was likely unavailable because distribution system design is a discretionary process based on site specific conditions, design preference, and is not directly regulated by code.

Table 29 – Baseline Assumptions[45]

Parameter	Assumption	Source
System Application	Horizontal pipe	Consultation with Insulation Industry Trade Association Coalition
Base Material	Steel pipe	Consultation with Insulation Industry Trade Association Coalition
Ambient Temperature	Indoors - 68°F	Consultation with Insulation Industry Trade Association Coalition
	Outdoors - temperature varied by climate zone according to average ambient dry bulb temperature	
Wind Speed	Indoors - 0 MPH	Consultation with Insulation Industry Trade Association Coalition
	Outdoors - 6.5 MPH	
Uninsulated Piping:	10% of total pipe length	Consultation with Insulation Industry Trade Association Coalition
Under or Damaged Piping:	15% of total pipe length	Consultation with Insulation Industry Trade Association Coalition
Distribution System Length and Pipe Size	8" maximum pipe size. All pipe sizes evaluated assumed to be of equal pipe length.	Consultation with Insulation Industry Trade Association Coalition
Pipe Length (LF pipe/SF building):	Various	Insulation Outlook, Mechanical Insulation in Hospitals and Schools Update, Figure 3, July 2021[46]
Relative Length of Indoor/Outdoor Pipe	Varies by industrial sector	Consultation with Insulation Industry Trade Association Coalition
Equivalent Full Load Hours	Varies by industrial sector	Calculated from IAC Database for steam and steam condensate insulation measures
System Efficiencies:	Various	Technical Reference Manuals

A detailed breakout of total and affected system piping lengths by sector and pipe location are presented in Table 30. They are based on the uninsulated piping; under or damaged piping; and distribution system length and pipe size assumptions listed in Table 29 and the relative allocations of pipe length for given process temperature shown in Table 27.

[45] Secondary literature research (DOE energy code compliance studies, journal articles, and internet research) generally lacked mention of pipe insulation conditions but some studies observed that despite code requirements having been in effect for many years, pipe insulation tended to have a low compliance level compared to equipment efficiency; and with respect to water heaters that "pipe insulation is present for only 26% of the water heaters surveyed". There are several studies; however, that make anecdotal reference to 30% of installed piping is uninsulated; however, the source of that data could not be corroborated nor was any quantitative information available for the split of uninsulated and under insulated or damaged piping; however, the Consultation with Insulation Industry Trade Association Coalition indicated they understand the amount of uninsulated piping is greater than 30%. The sum of uninsulated and under insulated and damaged piping used herein is thus considered to be conservative.

[46] Mechanical Insulation in Hospitals and Schools - Insulation Outlook Magazine

Table 30 – Piping Assumptions

Industrial Sector	Pipe Location	Total Pipe Length (lf) [x1000] [47]	Percent of Piping Located Indoors	Percent of Piping Located Outdoors	Uninsulated Pipe		Damaged Pipe	
					Uninsulated Percent of Total Pipe Length	Pipe Length (lf) [x1000]	Damaged/ Under insulated Percent of Total Pipe Length	Pipe Length (lf) [x1000]
Chemicals	Indoor	28,170	20%	0%	10%	563	15%	845
	Outdoor	28,170	0%	80%	10%	2,253	15%	3,380
Food	Indoor	8,107	100%	0%	10%	810	15%	1,216
	Outdoor	8,107	0%	0%	10%	0	15%	0
Nonmetallic Mineral Products	Indoor	7,305	100%	0%	10%	730	15%	1,095
	Outdoor	7,305	0%	0%	10%	0	15%	0
Paper	Indoor	8,850	20%	0%	10%	177	15%	265
	Outdoor	8,850	0%	80%	10%	708	15%	1,062
Petroleum and Coal Products	Indoor	3,660	20%	0%	10%	73	15%	109
	Outdoor	3,660	0%	80%	10%	292	15%	439
Plastics and Rubber Products	Indoor	12,660	100%	0%	10%	1,266	15%	1,899
	Outdoor	12,660	0%	0%	10%	0	15%	0
Primary Metals	Indoor	18,060	50%	0%	10%	903	15%	1,354
	Outdoor	18,060	0%	50%	10%	903	15%	1,354
Transportation Equipment	Indoor	17,535	100%	0%	10%	1,753	15%	2,630
	Outdoor	17,535	0%	0%	10%	0	15%	0
Total		**208,695**	**62%**	**38%**	**10%**	**10,434**	**15%**	**15,652**

Development of Intervention Conditions

Intervention conditions were developed by applying pipe insulation upgrades compliant with ASHRAE 90.1-2019 along with a protective insulation jacket to the baseline conditions. Intervention conditions were developed for each relevant instance of process temperature, pipe size, and insulation thickness listed in Table 31, for both the bare pipe and damaged / under insulated pipe use cases.

- **Bare (uninsulated) Pipe** The intervention condition is defined as pipe that has been insulated (with protective jacket) in compliance with the thickness requirements of ASHRAE 90.1-2019.
- **Damaged / Under Insulated Pipe** The intervention condition is defined as pipe that has had its extant insulation removed and replaced with insulation (with protective jacket) in compliance with the thickness requirements of ASHRAE 90.1-2019.

[47] Industrial piping systems can be on the order of thousands of linear feet in length and consist of various pipe configurations and sizes. One case study stated the referenced facility had more than 5 miles of total piping and more than 5,000 linear feet of piping in the mechanical room alone.

Table 31 –Pipe System Characteristics

Process temperature (°F)	Insulation Type (according to process temperature)	Jacket material	Nominal Pipe Size (applied to each process temperature)	Insulation Thickness (varies according to pipe size and temperature)[48]
125	Mineral Fiber[49] PIPE, Types II and III, C547-15	Aluminum, in service	0.75	0.5
175			1	1
225			2	1.5
300			2.5	2
400			3	3
600			4	4
800			6	4.5
1,000			8	5
1,200				

The characteristics of Table 31 and relevant assumptions of Table 29 were used as inputs for modeling baseline and intervention pipe heat loss using the 3E Plus online insulation heat flow calculator.

Industrial Sector-Level Energy Impacts

NAIMA's 3E Plus heat loss calculator was the primary software tool used to calculate the baseline and intervention performance conditions and from which industrial sector-level energy savings were developed for pipe insulation. It was chosen because secondary literature research found it to be the calculation tool of choice for calculating pipe heat loss by many state and utility program administrators and was frequently referenced in relevant DOE resources.

Raw energy savings were developed by industrial sector, process temperature, pipe location, and U.S. climate zone, for the pipe sizes and insulation thicknesses in Table 10, and for both the bare pipe and under insulated / damaged pipe use cases. 3E Plus was used to separately model baseline and intervention heat loss [btu/ft/hr] for each parameter and condition for U.S. climate zones 1A and 8A. Interpolation was used to derive baseline and intervention heat loss for the remaining climate zones based on average annual dry bulb temperatures derived from DOE's representative city typical meteorological year (TMY3) weather files.

Heat loss data were post-processed using the assumptions of Table 8 and Table 9 to produce incremental industrial sector-level energy savings as the product of the difference between the baseline and intervention conditions, annual production hours, and affected piping length. They

[48] Based on ASHRAE Standard 90.1-2019. Insulation thickness varies according to service type and temperature.
[49] A.k.a. Fiberglass Insulation.

were then separately adjusted for the damaged/under insulated use case using industry standard engineering heat loss calculations to reduce insulation thermal resistance (R-value) and both use cases summed for total pipe insulation energy savings.

Energy savings from code-compliant pipe insulation are due to increased thermal resistance, which reduces the temperature difference between the system's working fluid and its ambient conditions, reduces heat transfer, and thus reduces space and process heating energy input requirements.

State- and National-Level Energy Impacts

Macro-level estimates of energy savings were developed by extrapolating the industrial sector-level energy savings to state- and then the national-level. First, state county climate zone data from ASHRAE Standard 90.1-2019 Annex 1 were used to derive the percentage of counties within each state within each ASHRAE Standard 169 climate zone as a proxy for the relative distribution of industrial floor area by state and climate zone. Second, MECS enclosed floor area, by industrial sector, were summed for each U.S. Census Region[50], as shown in Table 32, and then divided equally by the number of states in that corresponding region to uniformly allocate regional floor area to its constituent states (not shown).

Table 32 – EIA MECS Enclosed Floor Space (sf) by Region and Industrial Sector

Industrial Sector	Northeast Census Region	Midwest Census Region	South Census Region	West Census Region
Chemicals	61,158,101	247,478,096	553,955,701	76,408,102
Food	133,135,009	395,295,465	245,018,768	307,550,757
Paper	96,111,871	59,827,146	336,969,130	97,091,853
Petroleum and Coal Products	15,736,345	20,247,305	43,352,002	42,664,348
Primary Metals	93,719,553	267,703,035	154,812,641	85,764,771
Nonmetallic Mineral Products	72,403,112	116,742,320	140,006,108	157,848,461
Transportation Equipment	341,786,615	409,630,938	270,479,539	147,102,907
Plastics and Rubber Products	202,855,015	240,565,653	257,625,228	142,954,103
Total	**1,016,905,620**	**1,757,489,959**	**2,002,219,117**	**1,057,385,303**

Third, applicable floor area by industrial sector, state, and climate zone were calculated as the product of the relative distribution of floor area by state and climate zone and the corresponding state-level floor area by industrial sector. Finally, for each industrial sector, state, climate zone, and system type, energy savings were calculated as the product of the corresponding applicable floor area, linear foot of pipe per floor area by industrial sector, and sum of energy savings per linear foot, for both the bare pipe and damaged / under insulated use cases.

[50] U.S. Energy Information Administration - EIA - Independent Statistics and Analysis

Table 33 – National-Level Energy Savings by Industrial Sector

Industrial Sector	Total Linear Feet of Pipe (Uninsulated, Damaged)	Annual Energy Savings (MMBtu)	Cumulative Energy Savings (MMBtu)
Chemicals	7,042,500	132,171,794	2,643,435,886
Food	2,026,875	38,729,011	774,580,214
Nonmetallic Mineral Products	1,826,250	76,730,817	1,534,616,347
Paper	2,212,500	41,278,002	825,560,049
Petroleum and Coal Products	,915,000	30,945,906	618,918,130
Plastics and Rubber Products	3,165,000	61,160,599	1,223,211,985
Primary Metals	4,515,000	188,233,856	3,764,677,118
Transportation Equipment	4,383,750	20,952,360	419,047,200
Total	**26,086,875**	**590,202,346**	**11,804,046,928**

Table 33 summarizes the total linear foot of affected pipe and corresponding annual and cumulative energy savings that accrue over a 20-year period by industrial sector. On average, the annual energy savings equate to approximately 10% of the total thermal process energy use presented in Table 25, and on a percentage-basis is greater than the relative energy savings from steam and steam condensate measures documented in the IAC database. Aside from the multitude of governing assumptions, these energy savings could be explained as the total technical potential in contrast to the achievable potential identified in IAC assessments, which tend to focus on the most cost-effective measures and therefore may omit less cost-effective insulation opportunities that are likely to not pass an industrial organizations economic test for simple payback.

In this analysis, energy savings are driven by code-compliant pipe insulation that significantly reduces heat transfer from high process temperature distribution pipe, the affected pipe length (proxied to enclosed floor area), and long annual hours of operation that allow energy savings to swiftly accrue.

Figure 9 and Figure 10 provide national-level energy savings by industrial sector and state-level energy savings, respectively.

Figure 9 – National-Level Energy Savings by Industrial Sector (MMBtu)

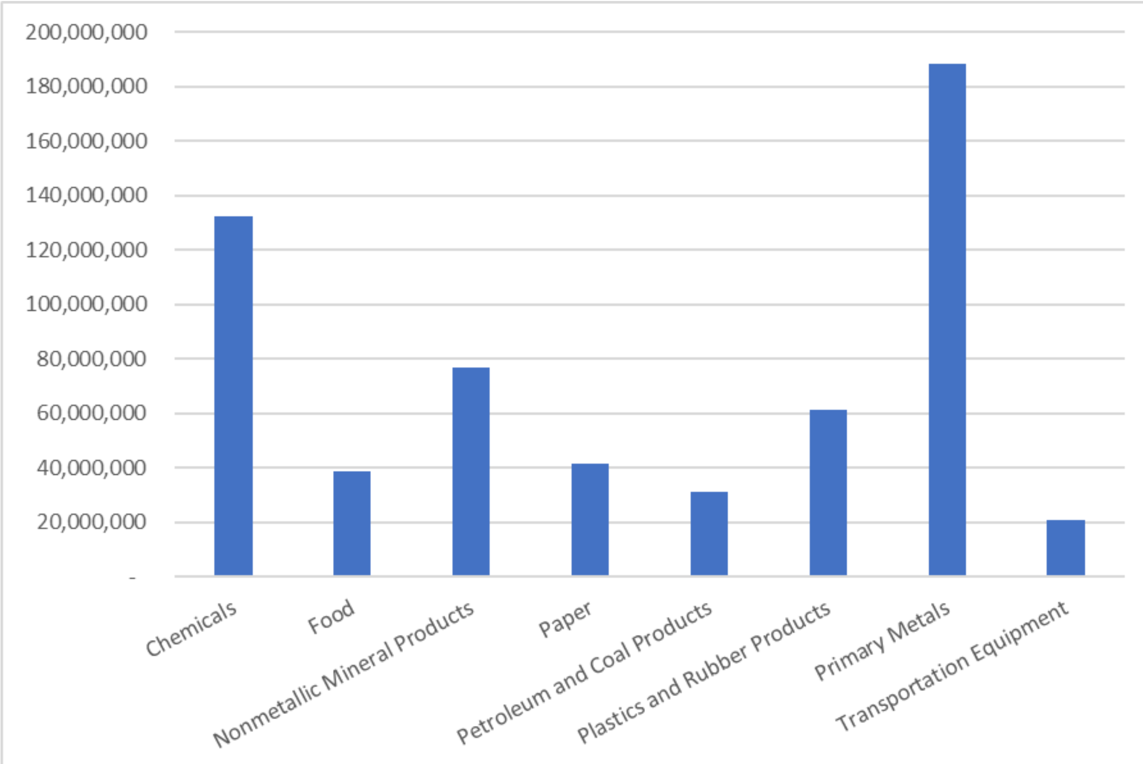
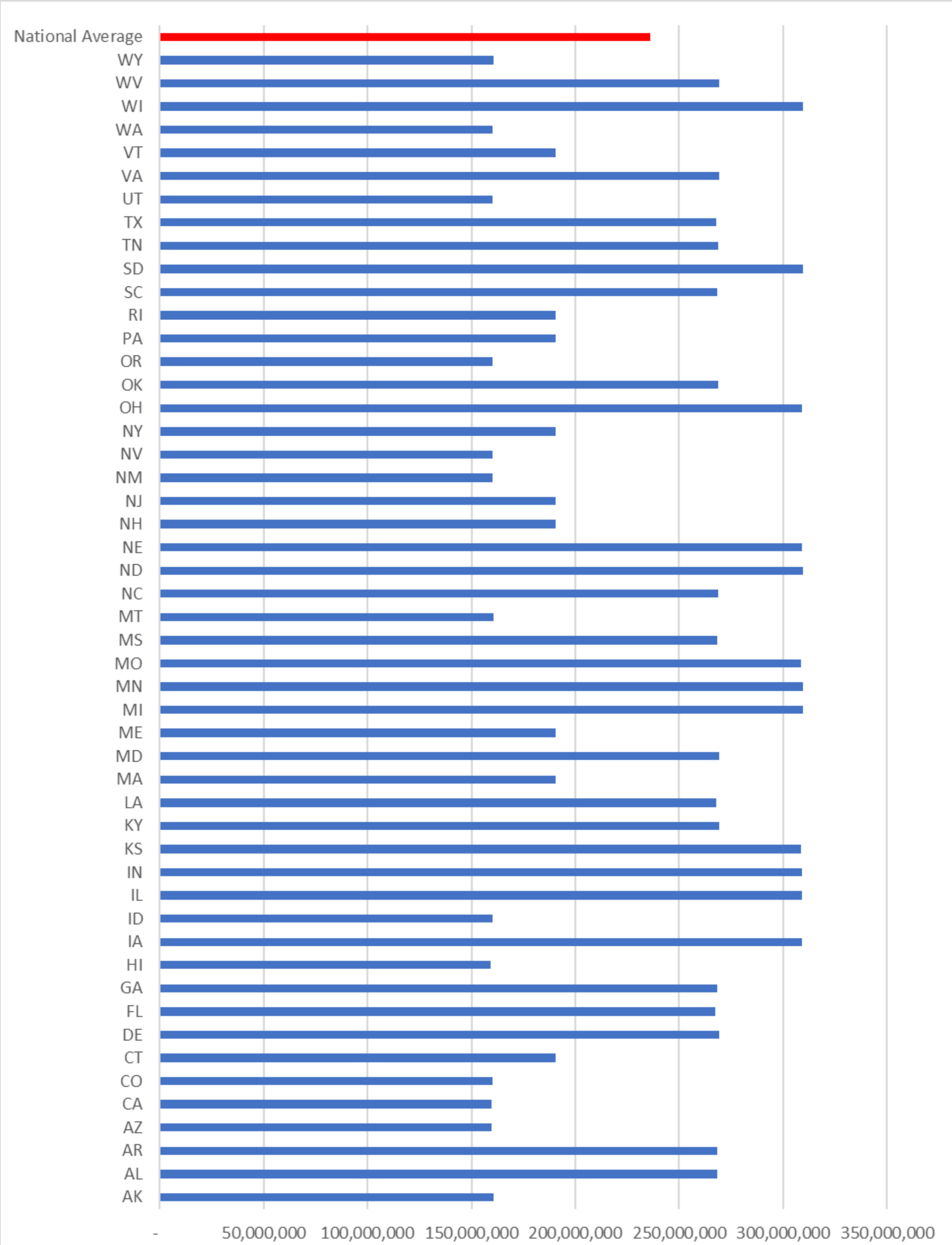


Figure 10 – Energy Savings by State (MMBtu)



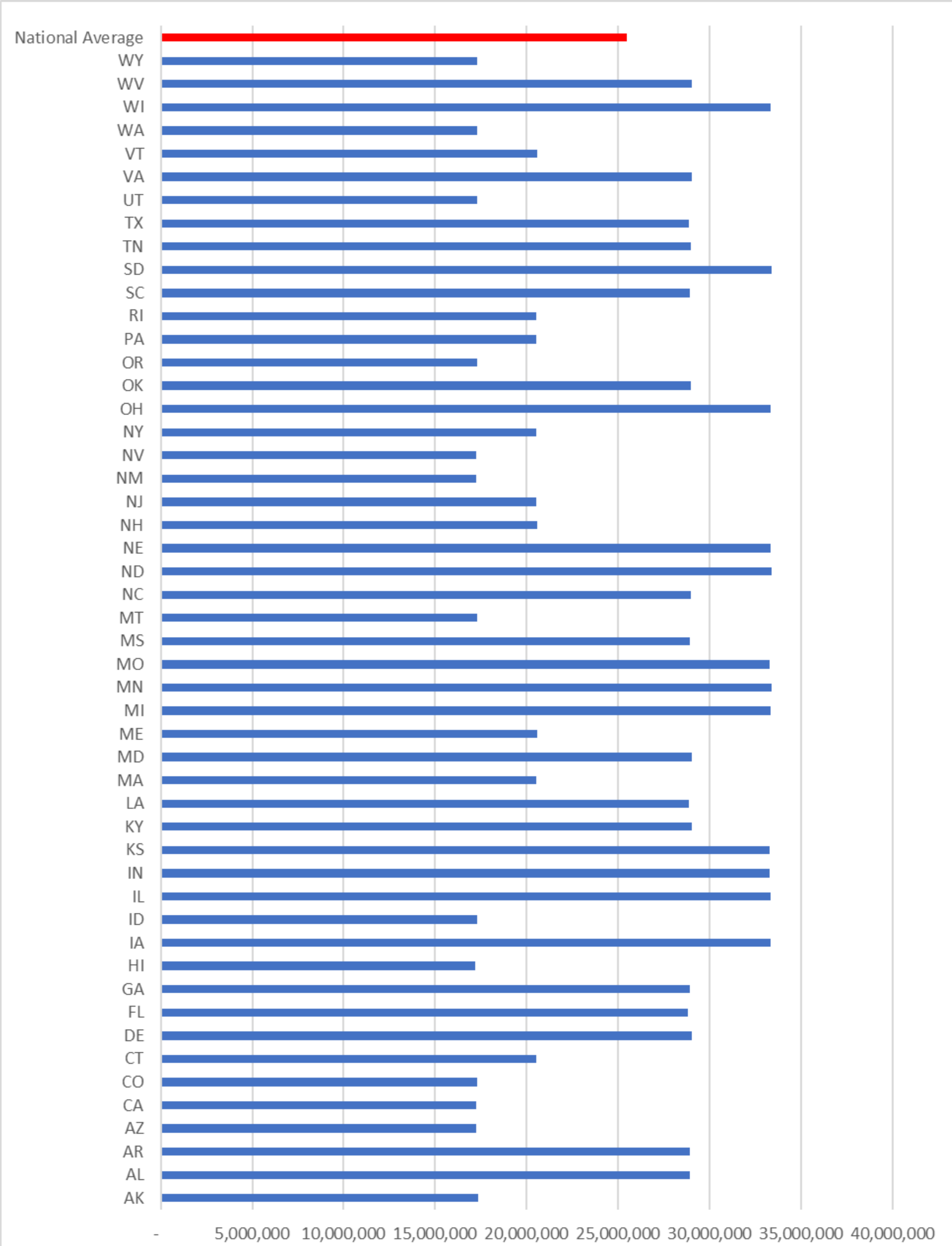
Calculation of Emissions Impacts

Reductions in emissions are the direct result of energy savings that occur and accrue from a reduction in space heating and process heating loads and the corresponding reduction in onsite combustion of natural gas. Scope 1 direct emissions were calculated as the product of the site energy savings derived as the difference in energy use between the baseline and intervention conditions for natural gas and its corresponding EPA Center for Corporate Climate Leadership national-level emissions factor. Total CO2e emissions reductions by industrial sector and by state are presented in Table 34 and Figure 11, respectively.

Table 34 – National-Level CO2e Emissions Savings (tons) by Industrial Sector

Industrial Sector	Annual CO2e (tons)	Cumulative CO2e (tons)
Chemicals	14,255,829	285,116,579
Food	4,177,246	83,544,928
Nonmetallic Mineral Products	8,276,058	165,521,156
Paper	4,452,176	89,043,528
Petroleum and Coal Products	3,337,774	66,755,476
Plastics and Rubber Products	6,596,680	131,933,602
Primary Metals	20,302,589	406,051,786
Transportation Equipment	2,259,887	45,197,731
Total	**63,658,239**	**1,273,164,785**

Figure 11 – Cumulative CO2e Emissions Savings (tons) by State



Calculation of Economic Benefits

Installation of pipe insulation projects directly results in energy savings and downstream operational savings (e.g., energy cost savings), the latter which can be monetized along with incremental measure costs over the project's life to quantify the economic benefits of the proposed interventions, compared to the baseline conditions. As a conservative assumption, the economic benefits were limited to the energy cost savings and did not include monetized health or environmental benefits due to avoided air emissions from the energy savings.

This section presents development of economic benefits that flow from energy cost savings combined with incremental project capital costs. They are presented as Benefit-to-Cost ratio (BCR) and Simple Payback Period (SPP) metrics.

Energy Cost Savings and Upgrade Project Costs

Energy cost savings accrue from the incremental reduction of service process heating requirements and the corresponding reduction in natural gas usage. Energy cost savings were calculated as the product of energy savings and national-level energy price from EIA, inclusive of energy price escalation over the effective useful life of the intervention.

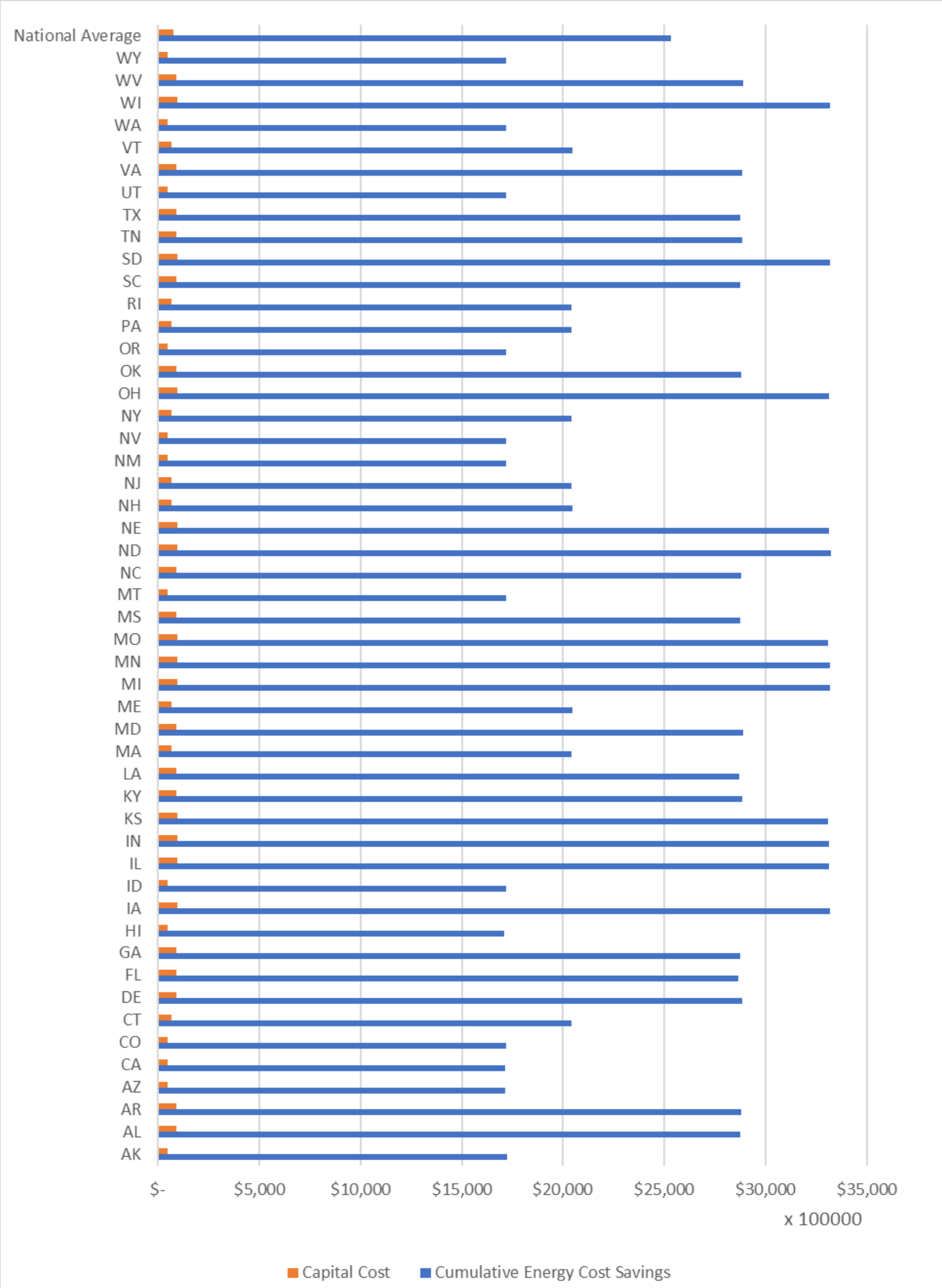
Incremental project capital costs were developed from a combination of industry accepted resources and secondary literature research. Pipe insulation costs per linear foot were derived from 3E Plus for the bare pipe use case and RSMeans for the damaged/under-insulated use case and were supplemented by internet research for pipe insulation jacket costs. RSMeans was used to estimate lift equipment rental costs based on our Labor Hours to install new insulation and remove damaged insulation, as applicable. These cost metrics were then applied to each relevant instance of pipe size and insulation thickness for each service temperature, manufacturing sector, and U.S. climate zone.

Cumulative energy cost savings and insulation capital cost by industrial sector and by state are presented in Table 35 and Figure 12, respectively, and show that on average the cumulative energy cost savings over the project life far exceeds the incremental upgrade costs.

Table 35 – Cumulative Energy Cost Savings and Incremental Upgrade Costs by Industrial Sector

Industrial Sector	Cumulative Energy Cost Savings ($)	Insulation Capital Cost ($)
Chemicals	28,352,323,897	968,834,177
Food	8,307,804,709	278,836,461
Nonmetallic Mineral Products	16,459,616,045	316,845,560
Paper	8,854,591,875	304,372,825
Petroleum and Coal Products	6,638,242,059	158,748,083
Plastics and Rubber Products	13,119,630,623	435,407,905
Primary Metals	40,378,261,337	783,330,706
Transportation Equipment	4,494,514,890	524,326,620
Total	**126,604,985,434**	**3,770,702,336**

Figure 12 – Cumulative Energy Cost Savings and Incremental Upgrade Costs by State



Economic Benefits

The BCR and SPP metrics were used to quantify economic benefits and determine cost effectiveness at the macro-level.

SPP is the ratio of the investment capital cost to annual energy cost savings and is the predominate economic metric used by the industrial sector. The intervention is considered cost effective when the SPP is less than the intervention's effective useful life (EUL), although many industrial facilities require energy projects to have SPPs of less than 3-years.

BCR, on the other hand, uses a life-cycle cost approach to account for the time value of money. This enables a comparison of the project's benefits and costs over its effective useful life and is the economic method referenced by DOE in their *Methodology for Evaluating Cost-Effectiveness of Commercial Energy Code Changes* document and is also a method used by utility program administrators and implementers in development of cost-effective demand-side management incentive programs. BCR is calculated as the ratio of the present value of benefits to the present value of costs. The intervention is cost-effective when the BCR is greater than 1.0, indicating its life-cycle benefits exceed its cost. For this analysis, the BCR was calculated using inputs of energy cost savings, incremental capital costs, and the modeling assumptions listed in Table 36. Details and data sources for the assumptions in Table 36 can be found in the appendices.

Table 36 – Lifecycle Cost Economic Modeling Assumptions

Input Variable	Value	Source
Discount Rate	3.00%	DOE, FEMP
Modeling Timeline (years)	20[51]	Various
Effective Useful Life (EUL)	20[52]	Various
Electricity Commodity Cost ($/kWh)	$0.11	DOE, EIA
Electricity Annual Escalation Rate	1.80%	DOE, EIA
Natural Gas Commodity Cost ($/therm)	$0.77	DOE, EIA
Natural Gas Annual Escalation Rate	2.90%	DOE, EIA

Average SPP and BCR results by industrial sector are shown in Table 37 and are generally consistent with industrial insulation payback periods found in secondary literature research and IAC's database. Consistent with findings of the preceding section, the project economics are cost effective with the cumulative energy savings exceeding the incremental project upgrade costs.

Table 37 –Average Economics by Industrial Sector

Industrial Sector	Average Simple Payback Period (Years)	Average BCR (Benefit-to-Cost Ratio)
Chemicals	0.90	21.84
Food	0.89	22.19

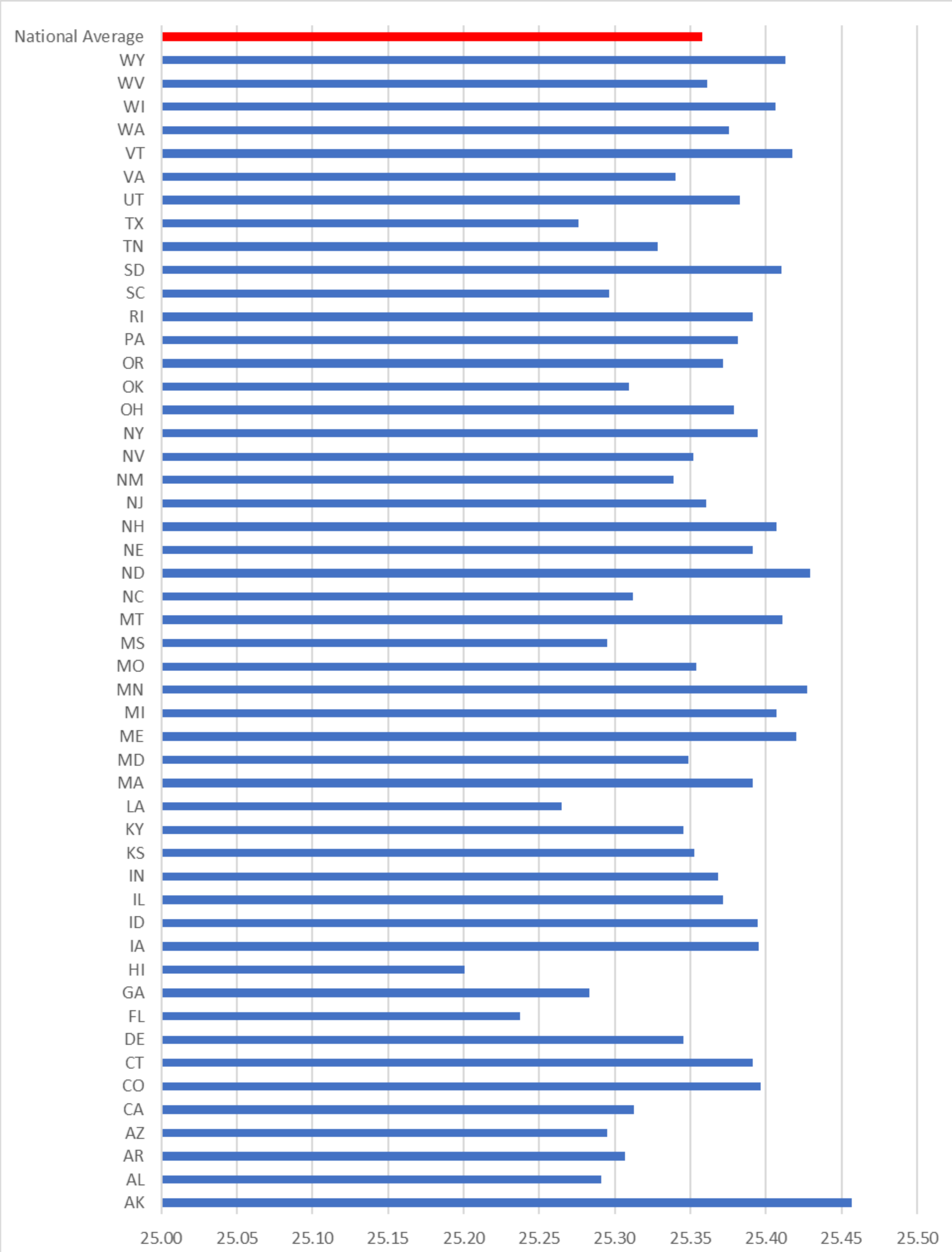
[51] Secondary literature research found that the effective useful life of pipe insulation can be 20 or more years when properly designed, maintained, and serviced.
[52] IBID

Industrial Sector	Average Simple Payback Period (Years)	Average BCR (Benefit-to-Cost Ratio)
Nonmetallic Mineral Products	0.51	38.70
Paper	0.91	21.72
Petroleum and Coal Products	0.63	31.16
Plastics and Rubber Products	0.88	22.44
Primary Metals	0.51	38.39
Transportation Equipment	3.10	6.38
Average	**1.04**	**25.35**

Similar to energy savings, favorable economics are determined by each industry's thermal processes and its corresponding process temperatures and annual hours of operation that allow energy savings accrue over the analysis horizon.

Figure 13 provides average the BCR economics by state.

Figure 13 – Weighted Average Benefit-to-Cost Ratio (BCR) by State



Conclusion

Incremental energy savings from insulation projects analyzed in this study accrue when they produce a reduction in the input energy used for space heating, space cooling, space process heating, and/or service hot water service, depending upon building sector. The energy, emissions, and economic analyses produced first year and cumulative estimates of whole-building energy savings by electric and natural gas fuel types that were extrapolated and aggregated to the state- and national-levels. Downstream impacts of those energy savings were developed and include carbon emissions reduction, energy costs savings, and economic benefits.

Insulation retrofits support a transition to building electrification and support building performance standards and carbon reduction goals. Insulation retrofits can be a cost-effective tool to help building owners reduce their carbon footprint to meet corporate carbon reduction goals and local building performance standards, as they can reduce emissions in advance of the transition to electrification and can be implemented fairly reliably and quickly.

Residential

- Insulation retrofits are economical under most conditions. Economic results showed the incremental benefit of insulation retrofits to be cost-effective in nearly all areas of the U.S.. These few instances of cost-ineffectiveness could be resolved through the addition of public or utility incentives for common insulation retrofits in those states. Overall, the vast majority of retrofit energy savings were generated by only the cost-effective retrofits; therefore, cost-effectiveness should not be a major barrier to achieving energy savings through insulation retrofits.
- Energy savings from insulation retrofits has the potential to reduce natural gas fossil fuel use by roughly 23 billion therms across the U.S. residential building stock, along with reducing HVAC sizing requirements and the demand on the electric grid. Therefore, retrofits can support a cost-effective transition to electric heating solutions desired for decarbonization.
- Across the nation, residential insulation retrofits could save over 10 billion tons of greenhouse gas emissions over their lifetime, which would be a significant step for the nation's decarbonization goals to mitigate climate change.

Commercial

- Roof insulation upgrade relative energy savings, on average, tend to be correlated with the building's roof-to-floor area ratio, where greater energy savings accrue for buildings that have greater roof-to-floor area ratios compared to buildings with smaller ratios.
- Pipe insulation relative energy savings, on average, tend to be small when compared to roof insulation savings. However, in addition to energy savings and emissions reductions, pipe insulation promotes reduction of mold development and improved indoor air quality.
- Projects that combine roof and pipe insulation measures, on average, are cost effective, with the cumulative energy cost savings greater than the project capital investment costs, across all U.S. states and for all modeled building types save the Medium Office

building type.

- Simple payback period for combined roof and pipe insulation measures, on average, are significantly less than the evaluated 30-year insulation lifetime. However, the payback periods are longer than a 5-year time horizon typically used by Energy Service Companies (ESCOs) or other forms of third-party financing that demand short payback periods, which signals the opportunity for federal or state policies that incentivize investment in these types of efficiency improvements. (Note: Simple payback period as a costing method does not fully evaluate the costs and benefits of energy efficiency upgrades and is mentioned here for information purposes only.)
- At the national-level, more than two-thirds of the total energy savings (in MMBtu) are from natural gas energy savings.
- Energy savings from insulation upgrades have the potential to reduce natural gas fossil fuel use by roughly 21 billion therms across the evaluated U.S. commercial building stock, along with reducing heating, ventilation, and air conditioning (HVAC) sizing requirements and demand on the electric grid.
- Across the nation, commercial insulation retrofits could save over 350 million tons of emissions over their lifetime, which would be a positive step towards meeting the nation's decarbonization goals to mitigate climate change.

Industrial

- Energy savings and economics are heavily determined by industry thermal process requirements (and their high system temperatures) and relatively long annual hours of operation. Higher process temperatures result in greater energy savings for given insulation requirement, thus shorter paybacks, and stronger economics.
- On average, industrial pipe insulation measures are cost effective for all evaluated industrial sectors in all U.S. states with simple payback periods generally consistent with that found in secondary literature research and the IAC database. Long system annual hours of operation allow swift recovery of capital costs.
- On a percentage-basis, the total technical potential identified in this study is greater than that document in the IAC database and thus may represent the upper limit of technical potential, whereas the IACs may omit pipe insulation measures that are more difficult to access or expensive to insulate due to their lower cost-effectiveness.
- Secondary literature research conducted found limited to no information pertaining to the total and relative amount of uninsulated, under insulated, and damaged pipe length and corresponding characteristics. However, research suggested that insulation maintenance audits be frequently performed to maintain system performance.
- Energy savings from insulation upgrades has the potential to reduce natural gas fossil fuel use by roughly 118 billion therms across the U.S. industrial sector while helping to reduce demand on the electric grid.
- Across the nation, industrial insulation retrofits could save over 1.27 billion tons of emissions over their lifetime, which would be positive step towards meeting the nation's decarbonization goals to mitigate climate change.

Appendix A – Residential

Table 38 – Residential Energy Impacts

State	Number of Homes	Total Annual Energy Savings			Total Cumulative Energy Savings			Average Annual EUI Savings (kBtu/SF)	Average Annual Energy Savings (%)
		Total Annual Electric Savings (kWh)	Total Annual Natural Gas Savings (Therms)	Total Annual Energy Savings (MMBtu)	Total Cumulative Electric Savings (kWh)	Total Cumulative Natural Gas Savings (Therms)	Total Cumulative Energy Savings (MMBtu)		
Alabama	1,264,424	4,965,379,776	122,296,930	29,172,272	248,268,988,800	6,114,846,500	1,458,613,600	9.25	26%
Arizona	1,628,556	2,152,879,407	63,031,235	13,649,053	107,643,970,350	3,151,561,750	682,452,650	3.34	11%
Arkansas	784,910	1,960,785,956	148,064,993	21,496,979	98,039,297,800	7,403,249,650	1,074,848,950	10.73	25%
California	7,088,020	1,698,863,039	997,148,398	105,511,601	84,943,151,950	49,857,419,900	5,275,580,050	6.04	19%
Colorado	1,352,000	430,330,266	571,251,572	58,593,505	21,516,513,300	28,562,578,600	2,929,675,250	17.08	32%
Connecticut	862,148	454,112,616	117,956,769	13,345,173	22,705,630,800	5,897,838,450	667,258,650	6.18	26%
Delaware	267,820	619,116,066	92,389,613	11,351,473	30,955,803,300	4,619,480,650	567,573,650	16.61	36%
Florida	5,014,036	13,799,570,788	2,151,055	47,301,195	689,978,539,400	107,552,750	2,365,059,750	3.73	14%
Georgia	2,430,080	5,544,591,500	406,374,772	59,556,409	277,229,575,000	20,318,738,600	2,977,820,450	9.67	24%
Idaho	417,275	675,136,750	104,769,494	12,780,612	33,756,837,500	5,238,474,700	639,030,600	12.22	25%
Illinois	3,009,992	2,559,212,531	2,016,941,527	210,426,548	127,960,626,550	100,847,076,350	10,521,327,400	27.93	40%
Indiana	1,594,797	2,084,477,837	722,824,855	79,395,019	104,223,891,850	36,141,242,750	3,969,750,950	19.51	33%
Iowa	871,903	481,968,464	434,086,113	45,053,156	24,098,423,200	21,704,305,650	2,252,657,800	20.89	35%
Kansas	679,886	795,559,865	362,456,300	38,960,193	39,777,993,250	18,122,815,000	1,948,009,650	22.45	37%
Kentucky	1,141,534	5,378,256,314	298,946,991	48,246,071	268,912,815,700	14,947,349,550	2,412,303,550	16.56	36%
Louisiana	1,124,250	4,094,756,385	117,275,576	25,699,446	204,737,819,250	5,863,778,800	1,284,972,300	8.96	26%
Maine	530,438	170,749,624	24,694,981	3,052,120	8,537,481,200	1,234,749,050	152,606,000	2.5	19%
Maryland	1,353,713	3,243,467,358	512,351,760	62,302,346	162,173,367,900	25,617,588,000	3,115,117,300	18.37	36%
Massachusetts	1,568,086	1,043,034,643	877,406,663	91,299,648	52,151,732,150	43,870,333,150	4,564,982,400	23.25	40%
Michigan	2,686,589	1,248,191,239	1,655,076,170	169,766,622	62,409,561,950	82,753,808,500	8,488,331,100	25.06	38%
Minnesota	1,211,706	762,866,676	633,072,875	65,910,297	38,143,333,800	31,653,643,750	3,295,514,850	21.99	31%
Mississippi	604,787	2,512,148,691	58,850,218	14,456,829	125,607,434,550	2,942,510,900	722,841,450	9.55	24%
Missouri	1,652,891	4,800,555,874	643,636,923	80,743,869	240,027,793,700	32,181,846,150	4,037,193,450	19.23	37%
Montana	258,714	103,544,205	125,769,872	12,930,295	5,177,210,250	6,288,493,600	646,514,750	20.04	36%
Nebraska	414,390	460,035,401	250,958,221	26,665,528	23,001,770,050	12,547,911,050	1,333,276,400	25.21	38%
Nevada	771,684	521,581,156	89,584,247	10,738,133	26,079,057,800	4,479,212,350	536,906,650	5.45	17%
New Hampshire	338,467	159,568,642	9,657,677	1,510,239	7,978,432,100	482,883,850	75,511,950	1.95	11%
New Jersey	2,168,079	1,470,696,887	1,383,177,732	143,335,999	73,534,844,350	69,158,886,600	7,166,799,950	25.96	40%
New Mexico	559,714	272,614,801	126,666,567	13,596,857	13,630,740,050	6,333,328,350	679,842,850	10.11	24%
New York	4,586,246	4,266,905,349	3,132,606,212	327,819,907	213,345,267,450	156,630,310,600	16,390,995,350	28.5	43%
North Carolina	2,366,610	9,978,659,297	204,490,096	54,497,608	498,932,964,850	10,224,504,800	2,724,880,400	9.11	24%
North Dakota	151,709	283,141,305	57,273,635	6,693,482	14,157,065,250	2,863,681,750	334,674,100	22.7	29%
Ohio	2,638,624	3,551,994,451	1,747,014,535	186,821,362	177,599,722,550	87,350,726,750	9,341,068,100	28.09	40%
Oklahoma	802,302	2,290,736,318	360,926,955	43,909,012	114,536,815,900	18,046,347,750	2,195,450,600	21.44	35%
Oregon	894,127	3,110,235,336	214,536,446	32,066,208	155,511,766,800	10,726,822,300	1,603,310,400	14.17	32%
Pennsylvania	3,141,800	5,308,249,103	1,473,665,880	165,479,086	265,412,455,150	73,683,294,000	8,273,954,300	20.77	37%
Rhode Island	270,876	125,226,500	163,738,161	16,801,107	6,261,325,000	8,186,908,050	840,055,350	26.9	47%

State	Number of Homes	Total Annual Energy Savings			Total Cumulative Energy Savings			Average Annual EUI Savings (kBtu/SF)	Average Annual Energy Savings (%)
		Total Annual Electric Savings (kWh)	Total Annual Natural Gas Savings (Therms)	Total Annual Energy Savings (MMBtu)	Total Cumulative Electric Savings (kWh)	Total Cumulative Natural Gas Savings (Therms)	Total Cumulative Energy Savings (MMBtu)		
South Carolina	1,171,423	4,742,902,460	92,189,437	25,402,399	237,145,123,000	4,609,471,850	1,270,119,950	8.65	24%
South Dakota	127,499	98,604,047	98,595,709	10,196,022	4,930,202,350	4,929,785,450	509,801,100	33.32	39%
Tennessee	1,613,449	7,161,411,734	180,774,146	42,513,166	358,070,586,700	9,038,707,300	2,125,658,300	10.35	27%
Texas	5,802,125	14,922,470,069	744,744,453	125,392,027	746,123,503,450	37,237,222,650	6,269,601,350	8.47	23%
Utah	565,087	203,057,677	182,209,380	18,913,800	10,152,883,850	9,110,469,000	945,690,000	13.35	28%
Vermont	208,599	61,658,941	21,401,259	2,350,515	3,082,947,050	1,070,062,950	117,525,750	4.83	19%
Virginia	1,998,602	8,313,587,639	446,736,066	73,040,745	415,679,381,950	22,336,803,300	3,652,037,250	14.45	32%
Washington	1,624,757	6,240,142,981	450,433,757	66,335,627	312,007,149,050	22,521,687,850	3,316,781,350	16.35	35%
West Virginia	453,675	1,372,461,895	176,409,335	22,323,968	68,623,094,750	8,820,466,750	1,116,198,400	19.28	37%
Wisconsin	1,490,290	480,613,060	675,132,090	69,153,129	24,030,653,000	33,756,604,500	3,457,656,450	18.75	31%
Wyoming	170,134	102,223,899	86,845,471	9,033,350	5,111,194,950	4,342,273,550	451,667,500	20.8	31%
National Total/Average	73,728,823	137,078,334,817	23,478,593,123	2,815,590,006	6,853,916,740,850	1,173,929,656,150	140,779,500,300	14.93	33%

Table 39 – Residential Emissions Impacts

State	Annual CO2e Emissions (tons)		Cumulative CO2e Emissions (tons)		
	Electricity	Natural Gas	Electricity	Natural Gas	Total
Alabama	716,029	2,486,866	35,801,475	124,343,277	160,144,752
Arizona	369,038	1,078,250	18,451,904	53,912,509	72,364,413
Arkansas	866,897	982,042	43,344,875	49,102,095	92,446,970
California	5,838,149	850,860	291,907,436	42,543,009	334,450,445
Colorado	3,344,589	215,527	167,229,453	10,776,351	178,005,804
Connecticut	690,619	227,438	34,530,926	11,371,910	45,902,836
Delaware	540,927	310,079	27,046,341	15,503,934	42,550,275
Florida	12,594	6,911,390	629,705	345,569,510	346,199,215
Georgia	2,379,261	2,776,958	118,963,053	138,847,925	257,810,978
Idaho	613,409	338,136	30,670,454	16,906,807	47,577,261
Illinois	11,808,879	1,281,758	590,443,941	64,087,922	654,531,863
Indiana	4,232,027	1,043,992	211,601,353	52,199,593	263,800,946
Iowa	2,541,507	241,390	127,075,333	12,069,477	139,144,810
Kansas	2,122,125	398,449	106,106,262	19,922,448	126,028,710
Kentucky	1,750,288	2,693,651	87,514,406	134,682,551	222,196,957
Louisiana	686,630	2,050,822	34,331,512	102,541,085	136,872,597
Maine	144,585	85,518	7,229,264	4,275,920	11,505,184
Maryland	2,999,740	1,624,461	149,986,992	81,223,064	231,210,056
Massachusetts	5,137,079	522,394	256,853,975	26,119,723	282,973,698
Michigan	9,690,213	625,145	484,510,673	31,257,265	515,767,937
Minnesota	3,706,543	382,075	185,327,159	19,103,744	204,430,903
Mississippi	344,559	1,258,187	17,227,944	62,909,347	80,137,291
Missouri	3,768,394	2,404,315	188,419,702	120,215,749	308,635,451
Montana	736,363	51,859	36,818,152	2,592,959	39,411,111
Nebraska	1,469,321	230,405	73,466,067	11,520,228	84,986,295
Nevada	524,502	261,229	26,225,091	13,061,460	39,286,552
New	56,544	79,919	2,827,210	3,995,926	6,823,135
New Jersey	8,098,290	736,585	404,914,520	36,829,262	441,743,782
New Mexico	741,613	136,537	37,080,652	6,826,833	43,907,485
New York	18,340,922	2,137,041	917,046,097	106,852,047	1,023,898,145
North Carolina	1,197,258	4,997,721	59,862,885	249,886,062	309,748,947
North Dakota	335,328	141,809	16,766,411	7,090,438	23,856,849
Ohio	10,228,498	1,778,984	511,424,914	88,949,215	600,374,128
Oklahoma	2,113,171	1,147,295	105,658,558	57,364,728	163,023,286
Oregon	1,256,078	1,557,733	62,803,876	77,886,662	140,690,537
Pennsylvania	8,628,084	2,658,589	431,404,222	132,929,427	564,333,649
Rhode Island	958,661	62,719	47,933,073	3,135,928	51,069,001
South Carolina	539,755	2,375,440	26,987,740	118,771,990	145,759,730
South Dakota	577,263	49,385	28,863,127	2,469,247	31,332,374
Tennessee	1,058,404	3,586,728	52,920,225	179,336,414	232,256,639

State	Annual CO2e Emissions (tons)		Cumulative CO2e Emissions (tons)		
	Electricity	Natural Gas	Electricity	Natural Gas	Total
Texas	4,360,363	7,473,784	218,018,145	373,689,208	591,707,352
Utah	1,066,808	101,700	53,340,379	5,084,980	58,425,359
Vermont	125,301	30,881	6,265,052	1,544,066	7,809,118
Virginia	2,615,570	4,163,785	130,778,508	208,189,258	338,967,766
Washington	2,637,220	3,125,319	131,860,978	156,265,958	288,126,936
West Virginia	1,032,849	687,385	51,642,460	34,369,256	86,011,717
Wisconsin	3,952,793	240,711	197,639,667	12,035,535	209,675,202
Wyoming	508,467	51,198	25,423,336	2,559,896	27,983,232
National Total	137,463,510	68,654,444	6,873,175,478	3,432,722,202	10,305,897,680

Table 40 – Residential Energy Cost Savings and Upgrade Costs

State	Total Annual Energy Cost Savings ($)	Total Cumulative Energy Cost Savings ($)	Average Cumulative Energy Cost Savings ($/SF)	Average Upgrade Cost ($/SF)	Total Upgrade Cost ($)
Alabama	$645,990,108	$54,590,577,234	$19.86	$5.14	$14,903,325,127
Arizona	$288,156,636	$24,553,048,834	$7.10	$2.87	$10,800,786,888
Arkansas	$335,558,457	$30,369,601,967	$18.77	$5.06	$8,675,161,315
California	$991,447,162	$103,054,862,020	$6.81	$4.87	$75,796,983,632
Colorado	$508,136,008	$54,250,671,004	$19.76	$4.68	$13,822,896,145
Connecticut	$145,188,146	$14,423,237,704	$8.10	$6.79	$13,728,081,254
Delaware	$142,758,190	$13,620,157,878	$26.91	$5.35	$3,193,436,041
Florida	$1,522,937,209	$121,885,747,102	$11.50	$4.82	$54,138,473,379
Georgia	$938,940,594	$84,789,647,700	$16.82	$4.30	$23,027,054,057
Idaho	$158,917,683	$15,207,643,739	$21.36	$4.08	$3,400,062,085
Illinois	$1,908,722,712	$200,715,125,564	$32.14	$6.49	$44,690,452,600
Indiana	$812,721,369	$82,225,957,066	$25.61	$5.47	$19,692,687,266
Iowa	$403,208,282	$42,590,948,934	$27.99	$5.36	$9,102,697,715
Kansas	$380,009,752	$39,029,763,293	$29.00	$5.69	$8,322,175,120
Kentucky	$833,967,067	$73,834,234,303	$30.40	$5.94	$15,148,444,738
Louisiana	$545,966,932	$46,469,207,347	$19.26	$5.92	$15,363,603,216
Maine	$38,738,477	$3,686,986,906	$5.49	$5.25	$5,541,457,989
Maryland	$770,742,510	$73,856,871,852	$27.66	$6.44	$18,954,351,520
Massachusetts	$822,583,253	$86,695,074,945	$27.46	$6.94	$24,884,800,862
Michigan	$1,472,367,396	$157,191,802,115	$30.35	$5.62	$32,352,434,869
Minnesota	$594,650,466	$62,643,598,697	$24.07	$4.44	$12,040,973,965
Mississippi	$324,388,989	$27,352,088,006	$19.78	$5.19	$7,561,480,166
Missouri	$1,048,266,719	$99,184,268,941	$29.06	$5.96	$22,511,046,859
Montana	$112,844,114	$12,021,733,125	$24.65	$5.13	$3,143,706,610
Nebraska	$253,102,981	$26,222,794,023	$31.07	$5.51	$5,044,319,019
Nevada	$129,743,932	$12,512,232,917	$8.48	$2.86	$4,747,453,170
New Hampshire	$25,378,773	$2,260,217,338	$3.09	$5.30	$3,879,764,890
New Jersey	$1,277,616,965	$135,138,665,976	$31.59	$6.74	$32,226,790,821
New Mexico	$132,204,853	$13,591,934,486	$12.20	$4.16	$4,859,407,765
New York	$2,996,723,284	$314,315,780,999	$32.35	$6.96	$73,259,951,375
North Carolina	$1,264,917,910	$106,061,416,932	$21.41	$5.25	$29,089,463,365
North Dakota	$77,401,798	$7,555,650,023	$29.76	$4.38	$1,175,403,552
Ohio	$1,800,473,979	$185,629,034,878	$33.42	$6.26	$38,044,641,954
Oklahoma	$543,597,887	$52,080,357,237	$28.39	$5.40	$10,163,126,161
Oregon	$515,875,931	$46,377,451,206	$23.31	$5.93	$12,094,532,194
Pennsylvania	$1,773,627,562	$176,973,645,540	$26.63	$6.32	$46,432,422,764
Rhode Island	$145,854,630	$15,566,485,961	$27.67	$7.41	$4,424,968,900

State	Total Annual Energy Cost Savings ($)	Total Cumulative Energy Cost Savings ($)	Average Cumulative Energy Cost Savings ($/SF)	Average Upgrade Cost ($/SF)	Total Upgrade Cost ($)
South Carolina	$597,184,365	$49,969,354,857	$18.93	$4.81	$12,908,355,661
South Dakota	$90,384,334	$9,578,014,747	$33.94	$5.31	$1,439,412,034
Tennessee	$935,230,998	$79,121,947,354	$27.02	$5.54	$19,254,835,909
Texas	$2,245,601,269	$197,377,780,488	$16.10	$4.68	$60,516,822,332
Utah	$169,330,908	$17,884,330,564	$18.23	$4.15	$5,201,262,000
Vermont	$24,056,517	$2,434,019,855	$6.04	$4.90	$1,915,055,297
Virginia	$1,276,732,488	$112,773,793,617	$26.91	$5.54	$24,803,612,085
Washington	$1,051,147,385	$94,815,082,489	$30.81	$5.58	$19,727,721,402
West Virginia	$293,563,180	$27,684,793,261	$28.75	$6.54	$6,917,027,375
Wisconsin	$597,455,675	$63,869,329,548	$21.12	$4.48	$14,435,632,671
Wyoming	$81,307,134	$8,572,100,321	$25.85	$4.75	$1,703,197,692
National Total/Average	$34,045,722,969	$3,282,609,070,894	$21.59	$5.42	$895,061,753,805

Table 41 – Residential Economic Benefits

State Averages	Total Present Value of Lifetime Benefits ($)	Total Upgrade Cost ($)	BCR (Benefit to Cost Ratio)
Alabama	$17,045	$9,904	1.87
Arizona	$6,071	$5,695	1.11
Arkansas	$15,478	$9,552	1.71
California	$5,205	$8,504	0.63
Colorado	$16,149	$9,186	1.76
Connecticut	$6,749	$14,145	0.5
Delaware	$21,885	$11,208	2.15
Florida	$9,647	$9,008	1.08
Georgia	$14,506	$8,507	1.84
Idaho	$15,630	$7,637	2.14
Illinois	$25,506	$12,643	2.21
Indiana	$19,437	$10,287	2.09
Iowa	$21,907	$10,432	2.15
Kansas	$24,418	$11,539	2.49
Kentucky	$27,157	$11,981	2.29
Louisiana	$16,654	$11,738	1.56
Maine	$3,579	$11,742	0.34
Maryland	$21,558	$12,095	1.91
Massachusetts	$21,120	$13,501	1.78
Michigan	$23,122	$10,624	2.24
Minnesota	$18,368	$7,862	2.36
Mississippi	$14,887	$8,755	2.06
Missouri	$25,416	$12,578	2.41
Montana	$18,334	$10,699	1.89
Nebraska	$26,533	$11,330	2.31
Nevada	$7,133	$5,924	1.23
New Hampshire	$2,742	$10,133	0.3
New Jersey	$25,699	$13,658	2.02
New Mexico	$10,127	$8,026	1.31
New York	$26,530	$13,759	2.06
North Carolina	$16,685	$9,723	1.97
North Dakota	$20,353	$6,948	3
Ohio	$24,543	$11,156	2.35
Oklahoma	$21,931	$9,356	2.38
Oregon	$19,315	$10,867	1.81
Pennsylvania	$21,524	$12,446	1.9
Rhode Island	$23,732	$15,059	1.47
South Carolina	$16,312	$8,949	1.87
South Dakota	$24,126	$8,083	2.83

State Averages	Total Present Value of Lifetime Benefits ($)	Total Upgrade Cost ($)	BCR (Benefit to Cost Ratio)
Tennessee	$19,596	$10,152	2.03
Texas	$13,357	$8,792	1.58
Utah	$12,350	$8,002	1.78
Vermont	$5,891	$10,242	0.65
Virginia	$23,110	$10,924	2.25
Washington	$22,730	$10,210	2.39
West Virginia	$21,620	$11,770	1.9
Wisconsin	$16,389	$8,272	1.92
Wyoming	$19,648	$8,695	2.33
National Average	$17,268	$10,306	1.74

Table 42 – Residential Cost-Effective Retrofit Comparison

State	Total Number of ResStock Models	Number of Cost-Effective ResStock Models	Total Energy Savings from All Upgrades (MMBtu)	Total Energy Savings from Cost-Effective Upgrades (MMBtu)
Alabama	169	123	29,172,272	25,421,492
Arizona	213	75	13,649,053	9,441,165
Arkansas	102	76	21,496,979	18,887,223
California	1,001	190	105,511,601	46,542,229
Colorado	169	116	58,593,505	52,762,918
Connecticut	109	18	13,345,173	11,367,568
Delaware	32	25	11,351,473	10,590,057
Florida	675	294	47,301,195	32,723,088
Georgia	304	222	59,556,409	53,565,274
Idaho	50	40	12,780,612	11,799,821
Illinois	397	332	210,426,548	197,268,569
Indiana	215	177	79,395,019	73,741,194
Iowa	98	72	45,053,156	41,866,732
Kansas	81	72	38,960,193	36,983,882
Kentucky	142	114	48,246,071	45,021,072
Louisiana	147	95	25,699,446	20,298,731
Maine	53	1	3,052,120	2,471,020
Maryland	176	132	62,302,346	58,256,158
Massachusetts	207	113	91,299,648	86,672,476
Michigan	342	276	169,766,622	162,025,393
Minnesota	172	127	65,910,297	62,104,580
Mississippi	97	75	14,456,829	12,764,368
Missouri	201	163	80,743,869	76,151,449
Montana	33	20	12,930,295	11,462,857
Nebraska	50	40	26,665,528	25,556,558
Nevada	90	42	10,738,133	7,986,832
New Hampshire	43	2	1,510,239	702,267
New Jersey	265	211	143,335,999	133,336,297
New Mexico	68	43	13,596,857	11,466,398
New York	598	425	327,819,907	317,497,134
North Carolina	336	237	54,497,608	46,674,838
North Dakota	19	18	6,693,482	6,609,050
Ohio	383	317	186,821,362	177,587,641
Oklahoma	122	115	43,909,012	42,896,073
Oregon	125	79	32,066,208	27,652,066
Pennsylvania	419	279	165,479,086	156,403,578
Rhode Island	33	19	16,801,107	16,649,475

State	Total Number of ResStock Models	Number of Cost-Effective ResStock Models	Total Energy Savings from All Upgrades (MMBtu)	Total Energy Savings from Cost-Effective Upgrades (MMBtu)
South Carolina	162	122	25,402,399	23,101,471
South Dakota	20	17	10,196,022	10,058,032
Tennessee	213	155	42,513,166	37,670,011
Texas	773	513	125,392,027	106,898,875
Utah	73	52	18,913,800	16,542,948
Vermont	21	6	2,350,515	2,193,204
Virginia	255	202	73,040,745	69,112,245
Washington	217	168	66,335,627	59,113,242
West Virginia	66	49	22,323,968	20,066,483
Wisconsin	196	137	69,153,129	63,441,624
Wyoming	22	17	9,033,350	8,494,064
National Total	9,754	6,213	2,815,590,006	2,547,899,720

Table 43 – Residential Data Sources

Model Input	Data Source	Description of Data Source and Use	Data Location
Baseline U.S. Residential Building Stock	ResStock Building Models	ResStock software used to generate a sample set of 10,000 building energy models designed to represent the current U.S. residential building stock as closely as possible. ResStock's models were last updated in 2018, so variation between 2018 and 2022 was neglected in this analysis.	https://resstock.nrel.gov/
Upgraded Insulation R-Values	2021 IECC	Baseline building energy models' thermal envelopes upgraded to meet 2021 IECC.	https://codes.iccsafe.org/content/IECC2021P1
Economics: Energy Rates	EIA's Annual Energy Outlook 2021	Obtained from DOE's EIA Annual Energy Outlook 2021 – national average.	https://www.eia.gov/outlooks/aeo/data/browser/#/?id=3-AEO2021&region=1-0&cases=ref2021&start=2019&end=2050&f=A&linechart=~ref2021-d113020a.79-3-AEO2021.1-0~ref2021-d113020a.80-3-AEO2021.1-0&map=ref2021-d113020a.4-3-AEO2021.1-0&ctype=linechart&chartindexed=0&maptype=0&sid=~~~~&sourcekey=0
Economics: Energy Escalation Rates	EIA's Annual Energy Outlook 2021	Obtained from DOE's EIA Annual Energy Outlook 2021 – national average, escalated annually.	https://www.eia.gov/outlooks/aeo/data/browser/#/?id=3-AEO2021&region=1-0&cases=ref2021&start=2019&end=2050&f=A&linechart=~ref2021-d113020a.79-3-AEO2021.1-0~ref2021-d113020a.80-3-AEO2021.1-0&map=ref2021-d113020a.4-3-AEO2021.1-0&ctype=linechart&chartindexed=0&maptype=0&sid=~~~~&sourcekey=0
Economics: Capital Costs	NREL National Residential Efficiency Measures Database	Upgrade costs taken from total (materials and labor) retrofit cost entries in database, with linear interpolation and extrapolation from entries where necessary.	https://remdb.nrel.gov/
Economics: Discount Rate	DOE, Energy Efficiency & Renewable Energy, Federal Energy Management Program	2021 nominal discount rate.	https://www.energy.gov/eere/femp/articles/2021-discount-rates

Model Input	Data Source	Description of Data Source and Use	Data Location
Economics: Effective Useful Life	Insulation Effective Useful Life (EUL)	Value taken from Table 5, cellulose fibre measure, after discussion with the Insulation Industry Trade Associations Coalition.	(PDF) Factors for Eco-Efficiency Improvement of Thermal Insulation Materials (researchgate.net)
Emission Factors: Electric	EPA Emissions and Generation Resource Integrated Database (eGRID)	National-level emission factors obtained from Table 1: Subregion Output Emission Rates (eGRID2018).	https://www.epa.gov/sites/default/files/2020-01/documents/egrid2018_summary_tables.pdf
Emission Factors: Natural Gas	EPA Emission Factors for Greenhouse Gas Inventories	National-level emission factors obtained from Table 1: Stationary Combustion for natural gas.	https://www.epa.gov/sites/default/files/2021-04/documents/emission-factors_mar2020.pdf

Table 44 – Residential Attachments

File Name	File Description
Insulation Industry Residential Energy Economic Emissions Analysis 08_10_2022	Contains raw energy performance data from simulation of building energy models and all subsequent calculations conducted in the study. Raw energy performance data was used to calculate whole-building energy savings and emissions impacts that were scaled to derive estimates of state- and national-level impacts and downstream energy and economic benefits. Data are presented in a series of two-way tables for inclusion in the final report, and pivot tables for assessing data trends, for quality control.
Residential Upgrades 08_10_2022	Contains list of the insulation retrofit upgrades (based upon 2021 IECC, with input from the Insulation Industry Trade Associations Coalition on feasibility) which were applied to the baseline models, along with their rationale.
Baseline Residential Building Stock Summary 08_10_2022	Contains state- and national-level averages of the key building insulation and infiltration inputs used in the baseline models representing the current U.S. residential single-family building stock.

Appendix B – Commercial

Table 45 – Commercial Combined Energy Impacts

State	Annual Energy Savings			Cumulative Energy Savings			Average Savings	
	Annual Electric Savings (kWh)	Annual Natural Gas Savings (Therms)	Annual Total Savings (MMBtu)	Cumulative Electric Savings (kWh)	Cumulative Natural Gas Savings (Therms)	Cumulative Total Savings (MMBtu)	Average Relative Energy Savings (%)	Average Energy Savings per SF (EUI)
Alabama	272,676,711	7,075,306	1,637,904	8,180,301,330	212,259,169	49,137,105	$0.04	2.72
Arizona	160,604,413	3,697,476	917,730	4,818,132,384	110,924,272	27,531,895	$0.04	2.72
Arkansas	350,910,380	24,862,136	3,683,520	10,527,311,389	745,864,069	110,505,593	$0.05	4.59
California	137,309,306	3,743,308	842,830	4,119,279,195	112,299,235	25,284,904	$0.04	2.82
Colorado	126,288,556	10,608,504	1,491,747	3,788,656,667	318,255,116	44,752,408	$0.06	4.32
Connecticut	145,639,879	15,473,400	2,044,263	4,369,196,385	464,201,987	61,327,897	$0.05	4.17
DC	168,619,208	16,383,394	2,213,668	5,058,576,247	491,501,809	66,410,043	$0.05	3.99
Delaware	168,619,208	16,383,394	2,213,668	5,058,576,247	491,501,809	66,410,043	$0.05	3.99
Florida	325,034,962	2,683,172	1,377,336	9,751,048,848	80,495,160	41,320,095	$0.03	2.19
Georgia	280,748,119	6,434,297	1,601,342	8,422,443,557	193,028,917	48,040,269	$0.04	2.72
Hawaii	190,887,116	536,171	704,924	5,726,613,483	16,085,132	21,147,718	$0.03	1.93
Idaho	132,277,709	10,127,764	1,464,108	3,968,331,271	303,832,932	43,923,240	$0.06	4.20
Illinois	199,145,184	19,324,904	2,611,974	5,974,355,528	579,747,127	78,359,214	$0.05	4.08
Indiana	198,590,992	19,292,408	2,606,833	5,957,729,745	578,772,253	78,204,999	$0.05	4.08
Iowa	206,663,596	20,633,789	2,768,515	6,199,907,883	619,013,667	83,055,452	$0.06	4.88
Kansas	195,242,639	19,096,074	2,575,775	5,857,279,170	572,882,207	77,273,257	$0.05	4.08
Kentucky	168,619,208	16,383,394	2,213,668	5,058,576,247	491,501,809	66,410,043	$0.05	3.99
Louisiana	300,268,702	4,884,028	1,512,920	9,008,061,054	146,520,828	45,387,587	$0.04	2.72
Maine	159,449,925	21,487,252	2,692,768	4,783,497,754	644,617,565	80,783,051	$0.06	5.89
Maryland	169,656,519	16,465,057	2,225,374	5,089,695,556	493,951,706	66,761,212	$0.05	4.08
Massachusetts	145,639,879	15,473,400	2,044,263	4,369,196,385	464,201,987	61,327,897	$0.05	4.17
Michigan	215,041,542	23,870,569	3,120,779	6,451,246,271	716,117,068	93,623,359	$0.06	5.31
Minnesota	210,045,762	28,212,699	3,537,946	6,301,372,870	846,380,966	106,138,381	$0.06	5.31
Mississippi	268,874,382	7,377,276	1,655,127	8,066,231,472	221,318,275	49,653,809	$0.04	2.72
Missouri	198,859,429	18,858,720	2,564,380	5,965,782,881	565,761,610	76,931,412	$0.05	3.54
Montana	131,260,023	12,258,855	1,673,745	3,937,800,677	367,765,660	50,212,342	$0.06	4.79
Nebraska	203,284,247	19,567,603	2,650,366	6,098,527,422	587,028,103	79,510,986	$0.05	4.17
Nevada	134,444,928	6,332,948	1,092,021	4,033,347,852	189,988,434	32,760,626	$0.05	2.86
New Hampshire	155,487,292	18,935,378	2,424,060	4,664,618,760	568,061,336	72,721,813	$0.06	4.88
New Jersey	146,201,502	15,455,628	2,044,402	4,386,045,047	463,668,837	61,332,069	$0.05	4.08
New Mexico	139,710,839	5,556,519	1,032,345	4,191,325,185	166,695,567	30,970,358	$0.05	2.86
New York	150,486,282	17,145,971	2,228,056	4,514,588,469	514,379,118	66,841,688	$0.05	4.59
North Carolina	244,016,720	9,699,222	1,802,507	7,320,501,603	290,976,666	54,075,218	$0.05	3.72
North Dakota	208,554,900	28,666,489	3,578,238	6,256,647,010	859,994,658	107,347,145	$0.06	5.89
Ohio	200,667,402	19,414,161	2,626,093	6,020,022,051	582,424,841	78,782,799	$0.05	4.08

State	Annual Energy Savings			Cumulative Energy Savings			Average Savings	
	Annual Electric Savings (kWh)	Annual Natural Gas Savings (Therms)	Annual Total Savings (MMBtu)	Cumulative Electric Savings (kWh)	Cumulative Natural Gas Savings (Therms)	Cumulative Total Savings (MMBtu)	Average Relative Energy Savings (%)	Average Energy Savings per SF (EUI)
Oklahoma	243,205,691	9,428,502	1,772,668	7,296,170,743	282,855,056	53,180,040	$0.05	3.23
Oregon	104,903,187	7,285,288	1,086,458	3,147,095,618	218,558,641	32,593,754	$0.05	3.06
Pennsylvania	145,815,910	15,467,829	2,044,307	4,374,477,309	464,034,880	61,329,205	$0.05	4.08
Rhode Island	145,639,879	15,473,400	2,044,263	4,369,196,385	464,201,987	61,327,897	$0.05	4.17
South Carolina	267,028,324	7,523,885	1,663,489	8,010,849,729	225,716,537	49,904,673	$0.04	2.72
South Dakota	220,663,755	25,050,843	3,257,989	6,619,912,651	751,525,292	97,739,671	$0.06	4.88
Tennessee	202,871,867	13,289,454	2,021,144	6,086,156,023	398,683,613	60,634,326	$0.05	3.49
Texas	275,799,984	4,775,054	1,418,535	8,273,999,531	143,251,617	42,556,048	$0.04	2.44
Utah	133,792,545	8,834,065	1,339,907	4,013,776,341	265,021,952	40,197,200	$0.05	3.55
Vermont	162,052,234	21,243,363	2,677,259	4,861,567,010	637,300,903	80,317,757	$0.06	5.59
Virginia	182,759,448	15,185,258	2,142,101	5,482,783,431	455,557,746	64,263,032	$0.05	3.72
Washington	112,754,679	7,813,795	1,166,098	3,382,640,365	234,413,860	34,982,955	$0.05	3.64
West Virginia	172,919,331	16,721,925	2,262,193	5,187,579,928	501,657,747	67,865,797	$0.05	4.08
Wisconsin	217,224,061	23,965,619	3,137,730	6,516,721,824	718,968,557	94,131,911	$0.06	4.88
Wyoming	127,610,295	12,461,965	1,681,603	3,828,308,860	373,858,961	50,448,086	$0.06	4.86
National Total/Average	9,524,868,655	706,920,908	103,190,943	285,746,059,641	21,207,627,244	3,095,728,280	$0.05	3.91

Table 46 – Commercial Combined Emissions Impacts

State	Annual Electric Emissions CO2e (tons)	Annual Natural Gas Emissions CO2e (tons)	Cumulative Electric Emissions CO2e (tons)	Cumulative Natural Gas Emissions CO2e (tons)
Alabama	123,891	76,313	3,716,744	2,289,392
Arizona	72,971	39,880	2,189,132	1,196,411
Arkansas	159,437	268,159	4,783,114	8,044,765
California	62,387	40,375	1,871,606	1,211,241
Colorado	57,380	114,422	1,721,387	3,432,647
Connecticut	66,172	166,894	1,985,157	5,006,805
DC	76,613	176,709	2,298,379	5,301,256
Delaware	76,613	176,709	2,298,379	5,301,256
Florida	147,681	28,956	4,430,417	,868,674
Georgia	127,559	69,399	3,826,762	2,081,978
Hawaii	86,730	5,931	2,601,903	177,919
Idaho	60,101	109,236	1,803,023	3,277,091
Illinois	90,482	208,435	2,714,466	6,253,056
Indiana	90,230	208,085	2,706,912	6,242,541
Iowa	93,898	222,553	2,816,946	6,676,578
Kansas	88,709	205,967	2,661,272	6,179,012
Kentucky	76,613	176,709	2,298,379	5,301,256
Louisiana	136,428	52,678	4,092,839	1,580,349
Maine	72,447	231,758	2,173,396	6,952,737
Maryland	77,084	177,589	2,312,518	5,327,681
Massachusetts	66,172	166,894	1,985,157	5,006,805
Michigan	97,705	257,464	2,931,142	7,723,919
Minnesota	95,435	304,297	2,863,047	9,128,924
Mississippi	122,164	79,570	3,664,916	2,387,102
Missouri	90,352	203,407	2,710,571	6,102,210
Montana	59,638	132,222	1,789,151	3,966,659
Nebraska	92,363	211,053	2,770,884	6,331,587
Nevada	61,085	68,306	1,832,563	2,049,184
New Hampshire	70,646	204,234	2,119,383	6,127,015
New Jersey	66,427	166,702	1,992,812	5,001,055
New Mexico	63,478	59,932	1,904,341	1,797,951
New York	68,374	184,934	2,051,216	5,548,007
North Carolina	110,870	104,614	3,326,091	3,138,426
North Dakota	94,758	309,192	2,842,726	9,275,759
Ohio	91,174	209,398	2,735,214	6,281,937
Oklahoma	110,501	101,694	3,315,036	3,050,827
Oregon	47,663	78,578	1,429,892	2,357,337
Pennsylvania	66,252	166,833	1,987,556	5,005,003
Rhode Island	66,172	166,894	1,985,157	5,006,805

State	Annual Electric Emissions CO2e (tons)	Annual Natural Gas Emissions CO2e (tons)	Cumulative Electric Emissions CO2e (tons)	Cumulative Natural Gas Emissions CO2e (tons)
South Carolina	121,325	81,151	3,639,753	2,434,541
South Dakota	100,259	270,194	3,007,776	8,105,826
Tennessee	92,175	143,338	2,765,263	4,300,135
Texas	125,311	51,506	3,759,316	1,545,180
Utah	60,789	95,283	1,823,671	2,858,483
Vermont	73,629	229,127	2,208,867	6,873,821
Virginia	83,037	163,786	2,491,119	4,913,570
Washington	51,230	84,278	1,536,912	2,528,349
West Virginia	78,566	180,360	2,356,992	5,410,797
Wisconsin	98,696	258,489	2,960,891	7,754,675
Wyoming	57,980	134,413	1,739,403	4,032,380
National Total	4,327,652	7,624,897	129,829,550	228,746,911

Table 47 – Commercial Combined Energy Cost Savings and Upgrade Costs

State	Annual Energy Cost Savings ($)	Cumulative Energy Cost Savings ($)	Average Cumulative Energy Cost Savings ($/SF)	Incremental Upgrade Cost (Roof+Pipe Insulation)($)	Average of Incremental Upgrade Cost ($/SF)
Alabama	35,764,686	1,449,060,516	$2.65	622,228,960	$1.20
Arizona	20,686,216	835,748,041	$2.43	412,677,400	$1.23
Arkansas	58,733,391	2,459,673,722	$2.90	1,046,223,534	$1.22
California	18,155,231	736,502,983	$2.29	412,187,872	$1.24
Colorado	22,476,941	947,911,727	$2.85	442,197,298	$1.32
Connecticut	28,533,545	1,215,455,079	$2.78	518,467,818	$1.27
DC	31,800,568	1,349,416,350	$2.64	657,479,725	$1.27
Delaware	31,800,568	1,349,416,350	$2.64	657,479,725	$1.27
Florida	37,994,291	1,510,198,666	$2.51	620,072,626	$1.17
Georgia	36,137,486	1,459,847,191	$2.65	622,228,960	$1.20
Hawaii	21,474,942	847,664,247	$2.32	382,099,920	$1.13
Idaho	22,749,455	955,723,210	$2.87	427,722,230	$1.27
Illinois	37,537,859	1,592,784,610	$2.71	724,985,335	$1.27
Indiana	37,450,560	1,589,155,594	$2.71	724,985,335	$1.27
Iowa	39,422,234	1,674,787,927	$3.13	724,985,335	$1.27
Kansas	36,923,115	1,567,229,606	$2.71	724,985,335	$1.27
Kentucky	31,800,568	1,349,416,350	$2.64	657,479,725	$1.27
Louisiana	37,039,098	1,485,934,610	$2.65	622,228,960	$1.20
Maine	34,905,906	1,502,355,306	$3.43	523,788,436	$1.37
Maryland	31,980,775	1,356,995,698	$2.71	657,479,725	$1.27
Massachusetts	28,533,545	1,215,455,079	$2.78	518,467,818	$1.27
Michigan	42,956,153	1,833,300,189	$3.21	727,895,765	$1.34
Minnesota	45,907,246	1,975,572,392	$3.21	756,916,427	$1.34
Mississippi	35,589,065	1,443,979,062	$2.65	622,228,960	$1.20
Missouri	37,130,395	1,573,946,286	$2.70	724,307,729	$1.25
Montana	24,355,935	1,031,766,298	$3.08	427,879,420	$1.27
Nebraska	38,189,861	1,619,888,401	$2.78	724,985,335	$1.27
Nevada	19,927,947	821,852,822	$2.41	426,163,326	$1.24
New Hampshire	32,411,068	1,388,838,750	$3.13	518,467,818	$1.27
New Jersey	28,581,124	1,217,218,567	$2.71	518,467,818	$1.27
New Mexico	19,882,269	815,366,262	$2.41	422,128,084	$1.24
New York	30,416,673	1,299,606,394	$2.97	518,467,818	$1.27
North Carolina	34,721,453	1,423,890,311	$2.68	629,984,129	$1.25
North Dakota	46,108,869	1,986,241,851	$3.43	761,448,075	$1.37
Ohio	37,777,645	1,602,752,533	$2.71	724,985,335	$1.27
Oklahoma	34,413,720	1,410,154,397	$2.51	630,445,587	$1.24
Oregon	17,439,434	729,754,101	$2.17	427,565,041	$1.27

State	Annual Energy Cost Savings ($)	Cumulative Energy Cost Savings ($)	Average Cumulative Energy Cost Savings ($/SF)	Incremental Upgrade Cost (Roof+Pipe Insulation)($)	Average of Incremental Upgrade Cost ($/SF)
Pennsylvania	28,548,458	1,216,007,814	$2.71	518,467,818	$1.27
Rhode Island	28,533,545	1,215,455,079	$2.78	518,467,818	$1.27
South Carolina	35,503,800	1,441,511,980	$2.65	622,228,960	$1.20
South Dakota	44,527,778	1,902,228,821	$3.13	724,985,335	$1.27
Tennessee	33,081,251	1,381,083,992	$2.63	644,863,662	$1.23
Texas	34,253,893	1,375,758,066	$2.45	625,557,046	$1.20
Utah	21,873,112	913,448,839	$2.68	426,867,565	$1.24
Vermont	34,996,083	1,504,427,863	$3.48	518,467,818	$1.27
Virginia	32,393,061	1,365,476,050	$2.68	652,443,902	$1.25
Washington	18,731,174	783,739,864	$2.48	427,589,224	$1.27
West Virginia	32,547,610	1,380,836,190	$2.71	657,479,725	$1.27
Wisconsin	43,273,399	1,846,348,946	$3.13	724,985,335	$1.27
Wyoming	24,117,408	1,023,614,078	$3.04	437,155,521	$1.34
National Total/Average	1,620,090,408	67974799,062	$2.77	29,762,348,466	$1.26

Table 48 – Commercial Combined Economic Benefits

State	PV of Lifetime Energy Cost Savings ($)	Incremental Upgrade Cost (Roof+Pipe Insulation) ($)	Average BCR (Benefit-to-Cost Ratio)
Alabama	933,553,642	622,228,960	1.41
Arizona	538,647,274	412,677,400	1.28
Arkansas	1,577,304,870	1,046,223,534	1.57
California	474,406,226	412,187,872	1.21
Colorado	607,277,371	442,197,298	1.42
Connecticut	777,610,915	518,467,818	1.44
DC	863,769,108	657,479,725	1.38
Delaware	863,769,108	657,479,725	1.38
Florida	975,618,333	620,072,626	1.35
Georgia	940,898,757	622,228,960	1.41
Hawaii	548,161,372	382,099,920	1.28
Idaho	612,605,985	427,722,230	1.49
Illinois	1,019,558,079	724,985,335	1.41
Indiana	1,017,228,526	724,985,335	1.41
Iowa	1,071,870,109	724,985,335	1.61
Kansas	1,003,153,707	724,985,335	1.41
Kentucky	863,769,108	657,479,725	1.38
Louisiana	958,662,815	622,228,960	1.41
Maine	959,813,390	523,788,436	1.65
Maryland	868,626,602	657,479,725	1.41
Massachusetts	777,610,915	518,467,818	1.44
Michigan	1,172,585,904	727,895,765	1.58
Minnesota	1,262,163,096	756,916,427	1.58
Mississippi	930,093,459	622,228,960	1.41
Missouri	1,007,635,064	724,307,729	1.41
Montana	660,592,377	427,879,420	1.61
Nebraska	1,036,956,656	724,985,335	1.44
Nevada	528,152,741	426,163,326	1.27
New Hampshire	887,820,509	518,467,818	1.61
New Jersey	778,762,093	518,467,818	1.41
New Mexico	524,398,766	422,128,084	1.27
New York	831,105,245	518,467,818	1.53
North Carolina	915,770,406	629,984,129	1.41
North Dakota	1,268,807,653	761,448,075	1.65
Ohio	1,025,956,729	724,985,335	1.41
Oklahoma	907,037,286	630,445,587	1.32
Oregon	468,018,339	427,565,041	1.15
Pennsylvania	777,971,732	518,467,818	1.41

State	PV of Lifetime Energy Cost Savings ($)	Incremental Upgrade Cost (Roof+Pipe Insulation) ($)	Average BCR (Benefit-to-Cost Ratio)
Rhode Island	777,610,915	518,467,818	1.44
South Carolina	928,413,515	622,228,960	1.41
South Dakota	1,216,511,560	724,985,335	1.61
Tennessee	886,024,610	644,863,662	1.39
Texas	887,437,062	625,557,046	1.31
Utah	585,991,256	426,867,565	1.41
Vermont	961,293,572	518,467,818	1.78
Virginia	874,843,957	652,443,902	1.41
Washington	502,647,369	427,589,224	1.30
West Virginia	883,905,629	657,479,725	1.41
Wisconsin	1,180,974,652	724,985,335	1.61
Wyoming	655,201,717	437,155,521	1.50
National Total/Average	43,578,600,081	26,388,669,409	1.75

Table 49 –Commercial Roof Insulation, Energy Savings by Building and Fuel Type

Commercial Subsector	Building Type	Annual		Cumulative	
		Electric Savings (kWh)	Natural Gas Savings (Therms)	Electric Savings (kWh)	Natural Gas Savings (Therms)
Educational	Primary School	2,315,027,715	302,689,433	69,450,831,456	9,080,682,996
	Secondary School	1,188,430,197	135,540,075	35,652,905,922	4,066,202,261
Federal	Medium Office	227,905,300	863,715	6,837,158,987	25,911,464
	Small Office	196,021,418	2,818,932	5,880,642,526	84,567,966
Private	Medium Office	1,250,036,619	5,247,301	37,501,098,555	157,419,021
	Midrise Apartment	220,363,502	20,542,599	6,610,905,074	616,277,973
	Stand-alone Retail	2,448,749,201	159,422,166	73,462,476,021	4,782,664,987
	Small Office	1,552,241,666	21,064,733	46,567,249,980	631,941,989
Total		**9,398,775,617**	**648,188,955**	**281,963,268,521**	**19,445,668,656**

Table 50 – Commercial Roof Insulation, CO2e Emissions Savings (tons) by Building Type

Commercial Subsector	Building Type	Annual CO2e (tons)	Cumulative CO2e (tons)
Educational	Primary School	4,316,597	129,497,917
	Secondary School	2,001,879	60,056,379
Federal	Medium Office	112,948	3,388,449
	Small Office	119,467	3,584,023
Private	Medium Office	624,883	18,746,480
	Midrise Apartment	321,692	9,650,755
	Stand-alone Retail	2,832,263	84,967,901
	Small Office	932,466	27,973,986
Total		**11,262,196**	**337,865,890**

Table 51 – Commercial Roof Insulation, Cumulative Energy Cost Savings and Upgrade Costs by Building Type

Commercial Subsector	Building Type	Cumulative Energy Cost Savings ($)	Incremental Upgrade Cost ($)
Educational	Primary School	21,462,090,025	7,234,402,278
	Secondary School	10,268,388,100	2,147,965,905
Federal	Medium Office	1,020,489,535	552,986,520
	Small Office	956,099,796	507,985,113
Private	Medium Office	5,616,528,403	2,919,239,333
	Midrise Apartment	1,730,729,103	538,310,714
	Stand-alone Retail	16,632,999,742	8,434,411,298
	Small Office	7,523,621,526	4,041,938,920
Total		**65,210,946,231**	**26,377,240,081**

Table 52 – Commercial Roof Insulation, Weighted Average Economics by Building Type

Commercial Subsector	Building Type	Average BCR (Benefit-to Cost Ratio)
Educational	Primary School	1.79
	Secondary School	2.92
Federal	Medium Office	1.20
	Small Office	1.20
Private	Medium Office	1.20
	Midrise Apartment	2.07
	Stand-alone Retail	1.31
	Small Office	1.20
Average		**1.61**

Table 53 –Commercial Pipe Insulation, Energy Savings by Building and Fuel Type

Commercial Subsector	Building Type	Annual		Cumulative	
		Electric Savings (kWh)	Natural Gas Savings (Therms)	Electric Savings (kWh)	Natural Gas Savings (Therms)
Educational	Primary School	0	20,814,520	0	624,435,606
	Secondary School	16,341,233	37,099,943	490,236,984	1,112,998,304
Federal	Medium Office	0	128,682	0	3,860,462
	Small Office	289,119	0	8,673,561	0
Private	Medium Office	0	688,807	0	20,664,216
	Midrise Apartment	107,163,317	0	3214,899,513	0
	Stand-alone Retail	0	0	0	0
	Small Office	2,299,369	0	68,981,063	0
Total		**126,093,037**	**58,731,953**	**3,782,791,120**	**1,761,958,588**

Table 54 – Commercial Pipe Insulation, CO2e Emissions Savings (tons) by Building Type

Commercial Subsector	Building Type	Annual CO2e (tons)	Cumulative CO2e (tons)
Educational	Primary School	224,502	6,735,058
	Secondary School	407,578	12,227,354
Federal	Medium Office	1,388	41,638
	Small Office	131	3,941
Private	Medium Office	7,429	222,881
	Midrise Apartment	48,690	1,460,699
	Stand-alone Retail	0	0
	Small Office	1,045	31,342
Total		**690,764**	**20,722,913**

Table 55 – Commercial Pipe Insulation, Cumulative Energy Cost Savings and Upgrade Costs by Building Type

Commercial Subsector	Building Type	Cumulative Energy Cost Savings ($)	Incremental Upgrade Cost ($)
Educational	Primary School	785,803,673	940,910,596
	Secondary School	1,471,454,823	710,824,400
Federal	Medium Office	4,858,091	169,716,028
	Small Office	1,253,219	51,710,420
Private	Medium Office	26,004,309	891,670,985
	Midrise Apartment	464,511,835	208,405,853
	Stand-alone Retail	0	0
	Small Office	9,966,881	411,870,104
Total		**2,763,852,832**	**3,385,108,385**

Table 56 – Commercial Pipe Insulation, Weighted Average Economics by Building Type

Commercial Subsector	Building Type	Average BCR (Benefit-to-Cost Ratio)
Educational	Primary School	0.52
	Secondary School	1.21
Federal	Medium Office	0.02
	Small Office	0.02
Private	Medium Office	0.02
	Midrise Apartment	1.43
	Stand-alone Retail	N/A
	Small Office	0.02
Average		**0.46**

Table 57 – Commercial Data Sources

Model Input	Data Source	Description of Data Source and Use	Data Location
Baseline: Building Energy Model	DOE New Construction (2004 vintage) Commercial Reference Buildings	2004 DOE Commercial Reference Building Models created using OpenStudio workflow measures, modified, and simulated in OpenStudio/EnergyPlus. Baseline roof insulation R-value modified to be R12.5 for all modeled building types, in all climate zones; baseline roof 3-year aged solar reflectance and thermal emittance modified to be 0.3 and 0.9, respectively, for all modeled building types, in all climate zones.	https://www.energy.gov/eere/buildings/commercial-reference-buildings
Intervention: Roof Insulation R-Value	DOE Building Codes Program, ANSI/ASHRAE/IES Standard 90.1-2019: Section 5, Building Envelope and Normative Appendix G.	Baseline building energy models modified to meet ANSI/ASHRAE/IES Standard 90.1-2019: Building Envelope minimum prescriptive R-value requirements, by climate zone and construction type for insulation and ASHRAE Standard 90.1-2019, Normative Appendix G for 3-year aged solar reflectance and thermal emittance.	https://www.energycodes.gov/technical-assistance/training/courses/ansiashraeies-standard-901-2019
Intervention: Roof 3-year Solar Reflectance and Thermal Emittance Values	ANSI/ASHRAE/IES Standard 90.1-2019: Envelope and Appendix	Baseline building energy models modified to meet ANSI/ASHRAE/IES Standard 90.1-2019 prescriptive cool roof requirements irrespective of climate zone (for the ASHRAE Use Case) and to meet average cool and black roof product performance from the Cool Roof Rating Council Directory (for the Products Use Case).	Product Directories - Cool Roof Rating Council (coolroofs.org)
Economics: Energy Rates	EIA's Annual Energy Outlook 2021	Obtained from DOE's EIA Annual Energy Outlook 2021 – national average.	https://www.eia.gov/outlooks/aeo/data/browser/#/?id=3-AEO2021&region=1-0&cases=ref2021&start=2019&end=2050&f=A&linechart=~ref2021-d113020a.79-3-AEO2021.1-0~ref2021-d113020a.80-3-AEO2021.1-0&map=ref2021-d113020a.4-3-AEO2021.1-0&ctype=linechart&chartindexed=0&maptype=0&sid=~~~~&sourcekey=0

Model Input	Data Source	Description of Data Source and Use	Data Location
Economics: Energy Escalation Rates	EIA's Annual Energy Outlook 2021	Obtained from DOE's EIA Annual Energy Outlook 2021 – national average, escalated annually.	https://www.eia.gov/outlooks/aeo/data/browser/#/?id=3-AEO2021&region=1-0&cases=ref2021&start=2019&end=2050&f=A&linechart=~ref2021-d113020a.79-3-AEO2021.1-0~ref2021-d113020a.80-3-AEO2021.1-0&map=ref2021-d113020a.4-3-AEO2021.1-0&ctype=linechart&chartindexed=0&maptype=0&sid=~~~~&sourcekey=0
Economics: Capital Costs	RS Means, 2019 / CRRC Roof Product Directory	Roof insulation costs derived from 2019 RS Means ($/ft2) for materials and labor – national average, varies by baseline-to-code compliant difference. Cool roof membrane costs derived from cost research using standard products listed in the CRRC Roof Product Directory. Pipe insulation costs derived from 3E Plus (bare pipe use case) and RS Means (damaged/under-insulated use case).	RS Means not publicly available
Economics: Discount Rate	DOE, Energy Efficiency & Renewable Energy, Federal Energy Management Program	3% FEMP prescribed floor discount rate used in lieu of 2021 nominal discount rate.	https://www.energy.gov/eere/femp/articles/2021-discount-rates
Economics: Effective Useful Life	Insulation Effective Useful Life (EUL)	Insulation EUL derived through consultation with PIMA based on PIMA's Environmental Product Declaration and validated with the California Energy Codes and Standards Non-Residential High Performance Envelope CASE Report.	https://cdn.ymaws.com/www.polyiso.org/resource/resmgr/health&environment/EPD_Roof_2020.pdf https://title24stakeholders.com/measures/cycle-2022/nonresidential-high-performance-envelope/ https://title24stakeholders.com/wp-content/uploads/2020/10/2020-T24-NR-HP-Envelope-Final-CASE-Report.pdf
Emission Factors: Electric	EPA eGRID	National-level emission factors obtained from Table 1: Subregion Output Emission Rates (eGRID2018).	https://www.epa.gov/sites/default/files/2020-01/documents/egrid2018_summary_tables.pdf
Emission Factors: Natural Gas	EPA Emission Factors for Greenhouse Gas Inventories	National-level emission factors obtained from Table 1: Stationary Combustion for natural gas.	https://www.epa.gov/sites/default/files/2021-04/documents/emission-factors_mar2020.pdf

Table 58 – Commercial Attachments

File Name	File Description
Commercial Energy Savings Costs BEM 08_10_2022	Contains baseline and intervention building-level energy model energy savings results and incremental capital costs, by building type and climate zone, for code-compliant roof upgrades (roof insulation entirely above deck and cool roof). Data serves as input to the CBECS 2018 Market Analysis file.
3E Plus Commercial Insulation Results 08_10_2022	Contains baseline and intervention pipe heat loss results, from NAIMA's 3E Plus online calculator, used to derive energy savings for the bare pipe use case. Also includes calculations for adjusting bare pipe insulation results to represent the damaged/under-insulated use case. Data serves as input to the Commercial Energy Savings Cost Insulation file.
Commercial Energy Savings Costs Insulation 08_10_2022	Contains framework for intaking bare pipe and damaged/under-insulated piping post-processed results from 3E to calculate building-level energy savings results and incremental costs. Data serves as input to the CBECS 2018 Market Analysis file.
CBECS 2018 Market Analysis 08_10_2022	Contains development of national-level estimates of energy savings from building-level building energy models and pipe insulation calculations. Includes mapping of building types to 2018 CBECS data for estimating the total market size for each building type by commercial subsector and build-up of national-level estimates of energy savings. Data serves as input to the Energy Emissions Economic Analysis file.
Roof Energy Emissions Economic Analysis 08_10_2022	Quantifies energy, emissions, and life-cycle economic benefits that accrue for the roof upgrade measure relative to its baseline condition. Benefits are presented in a series of two-way tables and charts for inclusion in the final report. Underlying economic and emissions assumptions are included in the datafile along with links to corresponding data sources.
Pipe Energy Emissions Economic Analysis 08_10_2022	Quantifies energy, emissions, and life-cycle economic benefits that accrue for the pipe insulation measure relative to its baseline condition. Benefits are presented in a series of two-way tables and charts for inclusion in the final report. Underlying economic and emissions assumptions are included in the datafile along with links to corresponding data sources.
Combined Energy Emissions Economic Analysis 08_10_2022	Quantifies the combined energy, emissions, and life-cycle economic benefits that accrue relative to the baseline condition for the roof upgrade and pipe insulation measures. Benefits are presented in a series of two-way tables and charts for inclusion in the final report. Underlying economic and emissions assumptions are included in the datafile along with links to corresponding data sources.

Appendix C – Industrial

Table 59 – Industrial Energy Impacts

State	Annual Energy Savings		Cumulative Energy Savings		Average Annual Energy Savings per Linear Foot of Pipe (MMBtu/LF)
	Natural Gas Savings (Therms)	Natural Gas Savings (MMBtu)	Natural Gas Savings (Therms)	Natural Gas Savings (MMBtu)	
Alabama	134,099,385	13,409,939	2,681,987,706	268,198,771	198
Alaska	80,346,335	8,034,634	1,606,926,704	160,692,670	199
Arizona	79,913,802	7,991,380	1,598,276,033	159,827,603	198
Arkansas	134,236,594	13,423,659	2,684,731,872	268,473,187	198
California	79,961,032	7,996,103	1,599,220,647	159,922,065	198
Colorado	80,185,069	8,018,507	1,603,701,384	160,370,138	199
Connecticut	95,285,209	9,528,521	1,905,704,185	190,570,418	198
Delaware	134,583,008	13,458,301	2,691,660,170	269,166,017	198
Florida	133,619,279	13,361,928	2,672,385,588	267,238,559	197
Georgia	134,030,550	13,403,055	2,680,610,998	268,061,100	198
Hawaii	79,660,611	7,966,061	1,593,212,226	159,321,223	197
Idaho	80,179,300	8,017,930	1,603,585,998	160,358,600	199
Illinois	154,463,985	15,446,398	3,089,279,692	308,927,969	198
Indiana	154,447,413	15,444,741	3,088,948,264	308,894,826	198
Iowa	154,610,935	15,461,094	3,092,218,703	309,221,870	199
Kansas	154,347,291	15,434,729	3,086,945,824	308,694,582	198
Kentucky	134,583,008	13,458,301	2,691,660,170	269,166,017	198
Louisiana	133,864,072	13,386,407	2,677,281,448	267,728,145	198
Maine	95,378,974	9,537,897	1,907,579,482	190,757,948	199
Maryland	134,617,375	13,461,738	2,692,347,501	269,234,750	198
Massachusetts	95,285,209	9,528,521	1,905,704,185	190,570,418	198
Michigan	154,684,540	15,468,454	3,093,690,796	309,369,080	199
Minnesota	154,811,061	15,481,106	3,096,221,217	309,622,122	199
Mississippi	134,131,813	13,413,181	2,682,636,255	268,263,625	198
Missouri	154,354,770	15,435,477	3,087,095,391	308,709,539	198
Montana	80,223,257	8,022,326	1,604,465,131	160,446,513	199
Nebraska	154,587,750	15,458,775	3,091,755,007	309,175,501	198
Nevada	80,066,112	8,006,611	1,601,322,230	160,132,223	198
New Hampshire	95,336,646	9,533,665	1,906,732,919	190,673,292	199
New Jersey	95,185,193	9,518,519	1,903,703,868	190,370,387	198
New Mexico	80,030,913	8,003,091	1,600,618,257	160,061,826	198
New York	95,295,580	9,529,558	1,905,911,591	190,591,159	199
North Carolina	134,286,081	13,428,608	2,685,721,629	268,572,163	198
North Dakota	154,825,941	15,482,594	3,096,518,822	309,651,882	199

State	Annual Energy Savings		Cumulative Energy Savings		Average Annual Energy Savings per Linear Foot of Pipe (MMBtu/LF)
	Natural Gas Savings (Therms)	Natural Gas Savings (MMBtu)	Natural Gas Savings (Therms)	Natural Gas Savings (MMBtu)	
Ohio	154,509,502	15,450,950	3,090,190,035	309,019,004	198
Oklahoma	134,262,424	13,426,242	2,685,248,480	268,524,848	198
Oregon	80,117,761	8,011,776	1,602,355,212	160,235,521	198
Pennsylvania	95,253,861	9,525,386	1,905,077,220	190,507,722	198
Rhode Island	95,285,209	9,528,521	1,905,704,185	190,570,418	198
South Carolina	134,147,556	13,414,756	2,682,951,130	268,295,113	198
South Dakota	154,706,986	15,470,699	3,094,139,727	309,413,973	199
Tennessee	134,435,413	13,443,541	2,688,708,264	268,870,826	198
Texas	133,961,859	13,396,186	2,679,237,182	267,923,718	198
Utah	80,148,076	8,014,808	1,602,961,510	160,296,151	198
Vermont	95,370,937	9,537,094	1,907,418,742	190,741,874	199
Virginia	134,539,598	13,453,960	2,690,791,962	269,079,196	198
Washington	80,129,482	8,012,948	1,602,589,647	160,258,965	198
West Virginia	134,725,473	13,472,547	2,694,509,470	269,450,947	198
Wisconsin	154,683,388	15,468,339	3,093,667,751	309,366,775	199
Wyoming	80,227,843	8,022,784	1,604,556,867	160,455,687	199
National Total/Average	5,902,023,464	590,202,346	118,040,469,278	11,804,046,928	198

Table 60 – Industrial Energy Impacts

State	Annual CO_2e (tons)	Cumulative CO_2e (tons)
Alabama	1,446,374	28,927,471
Alaska	866,602	17,332,043
Arizona	861,937	17,238,738
Arkansas	1,447,853	28,957,070
California	862,446	17,248,927
Colorado	864,863	17,297,255
Connecticut	1,027,730	20,554,607
Delaware	1,451,590	29,031,797
Florida	1,441,195	28,823,905
Georgia	1,445,631	28,912,622
Hawaii	859,206	17,184,121
Idaho	864,801	17,296,011
Illinois	1,666,023	33,320,455
Indiana	1,665,844	33,316,880
Iowa	1,667,608	33,352,154
Kansas	1,664,764	33,295,282
Kentucky	1,451,590	29,031,797
Louisiana	1,443,836	28,876,711
Maine	1,028,742	20,574,834
Maryland	1,451,961	29,039,210
Massachusetts	1,027,730	20,554,607
Michigan	1,668,402	33,368,032
Minnesota	1,669,766	33,395,325
Mississippi	1,446,723	28,934,467
Missouri	1,664,845	33,296,895
Montana	865,275	17,305,493
Nebraska	1,667,358	33,347,153
Nevada	863,580	17,271,594
New Hampshire	1,028,285	20,565,703
New Jersey	1,026,652	20,533,032
New Mexico	863,200	17,264,001
New York	1,027,842	20,556,844
North Carolina	1,448,387	28,967,745
North Dakota	1,669,927	33,398,535
Ohio	1,666,514	33,330,274
Oklahoma	1,448,132	28,962,642
Oregon	864,137	17,282,736
Pennsylvania	1,027,392	20,547,845
Rhode Island	1,027,730	20,554,607

State	Annual CO2e (tons)	Cumulative CO2e (tons)
South Carolina	1,446,893	28,937,863
South Dakota	1,668,644	33,372,874
Tennessee	1,449,998	28,999,958
Texas	1,444,890	28,897,805
Utah	864,464	17,289,275
Vermont	1,028,655	20,573,100
Virginia	1,451,122	29,022,433
Washington	864,263	17,285,264
West Virginia	1,453,126	29,062,529
Wisconsin	1,668,389	33,367,784
Wyoming	865,324	17,306,482
National Total	63,658,239	1,273,164,785

Table 61 – Industrial Energy Cost Savings and Upgrade Costs

State	Annual Energy Cost Savings ($)	Cumulative Energy Cost Savings ($)	Average Annual Energy Cost Savings per Linear Foot ($/lf)	Pipe Insulation Capital Cost ($)	Average Pipe Insulation Capital Cost per Linear Foot ($/lf)
Alabama	108,147,386	2,876,581,367	199	88,235,036	149
Alaska	64,797,062	1,723,518,495	201	47,522,555	149
Arizona	64,448,235	1,714,240,168	199	47,522,555	149
Arkansas	108,258,041	2,879,524,638	199	88,235,036	149
California	64,486,326	1,715,253,319	200	47,522,555	149
Colorado	64,667,005	1,720,059,160	200	47,522,555	149
Connecticut	76,844,844	2,043,974,003	200	66,056,328	149
Delaware	108,537,415	2,886,955,624	200	88,235,036	149
Florida	107,760,194	2,866,282,560	199	88,235,036	149
Georgia	108,091,872	2,875,104,771	199	88,235,036	149
Hawaii	64,244,045	1,708,808,952	199	47,522,555	149
Idaho	64,662,352	1,719,935,402	200	47,522,555	149
Illinois	124,570,863	3,313,424,733	200	95,553466	149
Indiana	124,557,499	3,313,069,258	200	95,553,466	149
Iowa	124,689,375	3,316,576,986	200	95,553,466	149
Kansas	124,476,753	3,310,921,529	200	95,553,466	149
Kentucky	108,537,415	2,886,955,624	200	88,235,036	149
Louisiana	107,957,613	2,871,533,643	199	88,235,036	149
Maine	76,920,462	2,045,985,364	200	66,056,328	149
Maryland	108,565,130	2,887,692,825	200	88,235,036	149
Massachusetts	76,844,844	2,043,974,003	200	66,056,328	149
Michigan	124,748,735	3,318,155,888	200	95,553,466	149
Minnesota	124,850,770	3,320,869,905	200	95,553,466	149
Mississippi	108,173,538	2,877,276,971	199	88,235,036	149
Missouri	124,482,784	3,311,081,949	200	95,553,466	149
Montana	64,697,802	1,720,878,321	200	47,522,555	149
Nebraska	124,670,677	3,316,079,647	200	95,553,466	149
Nevada	64,571,069	1,717,507,384	200	47,522,555	149
New Hampshire	76,886,326	2,045,077,378	200	66,056,328	149
New Jersey	76,764,184	2,041,828,552	200	66,056,328	149
New Mexico	64,542,682	1,716,752,334	200	47,522,555	149
New York	76,853,207	2,044,196,458	200	66,056,328	149
North Carolina	108,297,951	2,880,586,207	200	88,235,036	149
North Dakota	124,862,771	3,321,189,103	200	95,553,466	149
Ohio	124,607,571	3,314,401,127	200	95,553,466	149
Oklahoma	108,278,872	2,880,078,729	199	88,235,036	149
Oregon	64,612,723	1,718,615,314	200	47,522,555	149

State	Annual Energy Cost Savings ($)	Cumulative Energy Cost Savings ($)	Average Annual Energy Cost Savings per Linear Foot ($/lf)	Pipe Insulation Capital Cost ($)	Average Pipe Insulation Capital Cost per Linear Foot ($/lf)
Pennsylvania	76,819,562	2,043,301,548	200	66,056,328	149
Rhode Island	76,844,844	2,043,974,003	200	66,056,328	149
South Carolina	108,186,235	2,877,614,692	199	88,235,036	149
South Dakota	124,766,837	3,318,637,391	200	95,553,466	149
Tennessee	108,418,383	2,883,789,540	200	88,235,036	149
Texas	108,036,475	2,873,631,276	199	88,235,036	149
Utah	64,637,171	1,719,265,604	200	47,522,555	149
Vermont	76,913,981	2,045,812,962	200	66,056,328	149
Virginia	108,502,405	2,886,024,423	200	88,235,036	149
Washington	64,622,176	1,718,866,760	200	47,522,555	149
West Virginia	108,652,309	2,890,011,657	200	88,235,036	149
Wisconsin	124,747,805	3,318,131,171	200	95,553,466	149
Wyoming	64,701,501	1,720,976,713	200	47,522,555	149
National Total/Average	4,759,816,077	126,604,985,434	200	3,770,702,336	149

Table 62 – Industrial Economic Benefits

State	Total PV of Lifetime Energy Cost Savings ($)	Pipe Insulation Capital Cost ($)	Average Simple Payback Period (Years)	Average BCR (Benefit to Cost Ratio)
Alabama	2,143,113,936	88,235,036	1.05	25.29
Alaska	1,284,057,718	47,522,555	1.04	25.46
Arizona	1,277,145,168	47,522,555	1.05	25.30
Arkansas	2,145,306,735	88,235,036	1.05	25.31
California	1,277,899,987	47,522,555	1.05	25.31
Colorado	1,281,480,440	47,522,555	1.04	25.40
Connecticut	1,522,803,847	66,056,328	1.04	25.39
Delaware	2,150,842,977	88,235,036	1.05	25.35
Florida	2,135,441,107	88,235,036	1.05	25.24
Georgia	2,142,013,841	88,235,036	1.05	25.28
Hawaii	1,273,098,798	47,522,555	1.05	25.20
Idaho	1,281,388,238	47,522,555	1.04	25.39
Illinois	2,468,571,480	95,553,466	1.04	25.37
Indiana	2,468,306,643	95,553,466	1.04	25.37
Iowa	2,470,919,975	95,553,466	1.04	25.39
Kansas	2,466,706,540	95,553,466	1.05	25.35
Kentucky	2,150,842,977	88,235,036	1.05	25.35
Louisiana	2,139,353,275	88,235,036	1.05	25.26
Maine	1,524,302,353	66,056,328	1.04	25.42
Maryland	2,151,392,207	88,235,036	1.05	25.35
Massachusetts	1,522,803,847	66,056,328	1.04	25.39
Michigan	2,472,096,290	95,553,466	1.04	25.41
Minnesota	2,474,118,291	95,553,466	1.04	25.43
Mississippi	2,143,632,176	88,235,036	1.05	25.29
Missouri	2,466,826,056	95,553,466	1.05	25.35
Montana	1,282,090,733	47,522,555	1.04	25.41
Nebraska	2,470,549,447	95,553,466	1.04	25.39
Nevada	1,279,579,313	47,522,555	1.05	25.35
New Hampshire	1,523,625,885	66,056,328	1.04	25.41
New Jersey	1,521,205,440	66,056,328	1.05	25.36
New Mexico	1,279,016,785	47,522,555	1.05	25.34
New York	1,522,969,580	66,056,328	1.04	25.39
North Carolina	2,146,097,627	88,235,036	1.05	25.31
North Dakota	2,474,356,100	95,553,466	1.04	25.43
Ohio	2,469,298,914	95,553,466	1.04	25.38
Oklahoma	2,145,719,545	88,235,036	1.05	25.31
Oregon	1,280,404,745	47,522,555	1.04	25.37
Pennsylvania	1,522,302,854	66,056,328	1.04	25.38

State	Total PV of Lifetime Energy Cost Savings ($)	Pipe Insulation Capital Cost ($)	Average Simple Payback Period (Years)	Average BCR (Benefit to Cost Ratio)
Rhode Island	1,522,803,847	66,056,328	1.04	25.39
South Carolina	2,143,883,785	88,235,036	1.05	25.30
South Dakota	2,472,455,020	95,553,466	1.04	25.41
Tennessee	2,148,484,177	88,235,036	1.05	25.33
Texas	2,140,916,056	88,235,036	1.05	25.28
Utah	1,280,889,224	47,522,555	1.04	25.38
Vermont	1,524,173,910	66,056,328	1.04	25.42
Virginia	2,150,149,212	88,235,036	1.05	25.34
Washington	1,280,592,077	47,522,555	1.04	25.38
West Virginia	2,153,119,786	88,235,036	1.05	25.36
Wisconsin	2,472,077,876	95,553,466	1.04	25.41
Wyoming	1,282,164,036	47,522,555	1.04	25.41
National Total/Average	94,323,390,876	3770,702,336	1.05	25.36

Table 63 – Industrial Energy Savings by Region and State

U.S. Census Region (EIA MECS)	State	Annual Natural Gas Energy Savings [MMBtu]
Midwest Census Region	IA	15,461,094
	IL	15,446,398
	IN	15,444,741
	KS	15,434,729
	MI	15,468,454
	MN	15,481,106
	MO	15,435,477
	ND	15,482,594
	NE	15,458,775
	OH	15,450,950
	SD	15,470,699
	WI	15,468,339
Northeast Census Region	CT	9,528,521
	MA	9,528,521
	ME	9,537,897
	NH	9,533,665
	NJ	9,518,519
	NY	9,529,558
	PA	9,525,386
	RI	9,528,521
	VT	9,537,094
South Census Region	AL	13,409,939
	AR	13,423,659
	DE	13,458,301
	FL	13,361,928
	GA	13,403,055
	KY	13,458,301
	LA	13,386,407
	MD	13,461,738
	MS	13,413,181
	NC	13,428,608
	OK	13,426,242
	SC	13,414,756
	TN	13,443,541
	TX	13,396,186
	VA	13,453,960
	WV	13,472,547
West Census Region	AK	8,034,634
	AZ	7,991,380
	CA	7,996,103

U.S. Census Region (EIA MECS)	State	Annual Natural Gas Energy Savings [MMBtu]
	CO	8,018,507
	HI	7,966,061
	ID	8,017,930
	MT	8,022,326
	NM	8,003,091
	NV	8,006,611
	OR	8,011,776
	UT	8,014,808
	WA	8,012,948
	WY	8,022,784
Total		**590,202,346**

Figure 14 –Energy Savings (MMBtu) by Region and State

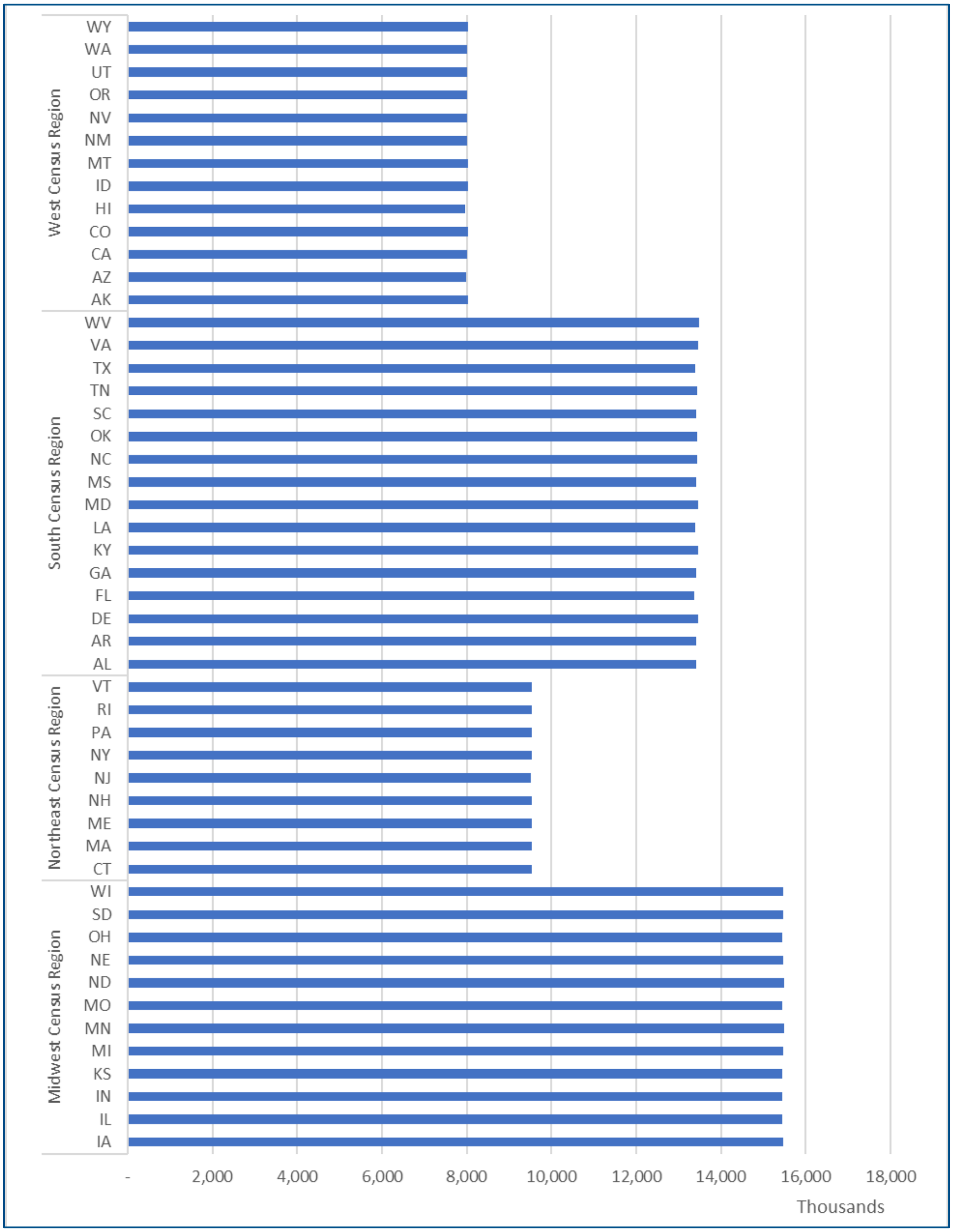


Table 64 – Industrial Energy Savings by Industrial Sector, Pipe Location, and Process Temperature

Industrial Sector	Pipe Location	Process Temperature [Mean Fluid Temperature (°F)]	Annual Natural Gas Energy Savings [MMBtu]
		125	103,087
		175	230,759
		225	387,072
		300	671,700
		400	1,145,243
		600	2,516,917
		800	4,667,750
		1,000	7,889,566
	Indoor	1,200	12,502,544
		125	818,751
		175	1,463,192
		225	2,159,495
		300	3,304,808
		400	5,039,297
		600	9,551,324
		800	16,060,749
		1,000	25,359,507
Chemicals	Outdoor	1,200	38,300,033
		125	132,575
		175	296,768
		225	497,795
		300	863,842
		400	1,472,843
		600	3,236,887
		800	6,002,973
		1,000	10,146,398
	Indoor	1,200	16,078,930
		125	0
		175	0
		225	0
		300	0
		400	0
		600	0
		800	0
		1,000	0
Food	Outdoor	1,200	0
		125	0
		175	0
Nonmetallic Mineral Products	Indoor	225	0

Industrial Sector	Pipe Location	Process Temperature [Mean Fluid Temperature (°F)]	Annual Natural Gas Energy Savings [MMBtu]
		300	0
		400	0
		600	0
		800	14,292,191
		1,000	24,157,072
		1,200	38,281,554
		125	0
		175	0
		225	0
		300	0
		400	0
		600	0
		800	0
		1,000	0
	Outdoor	1,200	0
		125	32,197
		175	72,072
		225	120,892
		300	209,789
		400	357,688
		600	786,095
		800	1,457,854
		1,000	2,464,106
	Indoor	1,200	3,904,853
		125	255,442
		175	456,714
		225	674,184
		300	1,031,891
		400	1,573,613
		600	2,982,832
		800	5,015,888
		1,000	7,920,122
Paper	Outdoor	1,200	11,961,772
		125	0
		175	0
		225	0
		300	0
		400	0
		600	0
Petroleum and Coal Products	Indoor	800	1,377,763

Industrial Sector	Pipe Location	Process Temperature [Mean Fluid Temperature (°F)]	Annual Natural Gas Energy Savings [MMBtu]
		1,000	2,328,735
		1,200	3,690,332
	Outdoor	125	0
		175	0
		225	0
		300	0
		400	0
		600	0
		800	4,746,773
		1,000	7,491,391
		1,200	11,310,913
Plastics and Rubber Products	Indoor	125	209,362
		175	468,653
		225	786,115
		300	1,364,173
		400	2,325,904
		600	5111,671
		800	9,479,855
		1,000	16,023,124
		1,200	25,391,740
	Outdoor	125	0
		175	0
		225	0
		300	0
		400	0
		600	0
		800	0
		1,000	0
		1,200	0
Primary Metals	Indoor	125	0
		175	0
		225	0
		300	0
		400	0
		600	0
		800	19,514,499
		1,000	32,983,969
		1,200	52,269,479
	Outdoor	125	0
		175	0

Industrial Sector	Pipe Location	Process Temperature [Mean Fluid Temperature (°F)]	Annual Natural Gas Energy Savings [MMBtu]
		225	0
		300	0
		400	0
		600	0
		800	16,834,921
		1,000	26,553,268
		1,200	40,077,719
Transportation Equipment	Indoor	125	,427,302
		175	,956,508
		225	1,604,438
		300	2,784,238
		400	4,747,102
		600	10,432,771
		800	0
		1,000	0
		1,200	0
	Outdoor	125	0
		175	0
		225	0
		300	0
		400	0
		600	0
		800	0
		1,000	0
		1,200	0
Total			**590,202,346**

Table 65 – Industrial average Energy Savings by Pipe Location, Process Temperature, and Insulation Condition

Pipe Location	Process Temperature [Mean Fluid Temperature (°F)]	Average Uninsulated Savings [Btu/hr/ft]	Average Damaged Insulation Savings [Btu/hr/ft]
Indoor	125	95	68
	175	212	151
	225	356	254
	300	618	441
	400	1,054	752
	600	2,316	1,652
	800	4,295	3,063
	1,000	7,259	5,178
	1,200	11,504	8,205
Outdoor	125	287	71
	175	511	127
	225	752	187
	300	1,150	286
	400	1,751	435
	600	3,316	824
	800	5,574	1,385
	1,000	8,799	2,186
	1,200	13,288	3,301
Average		**3508**	**1,587**

Figure 15 –Energy Savings (Btu/hr/ft) by Pipe Location and Temperature (°F) and Insulation Condition

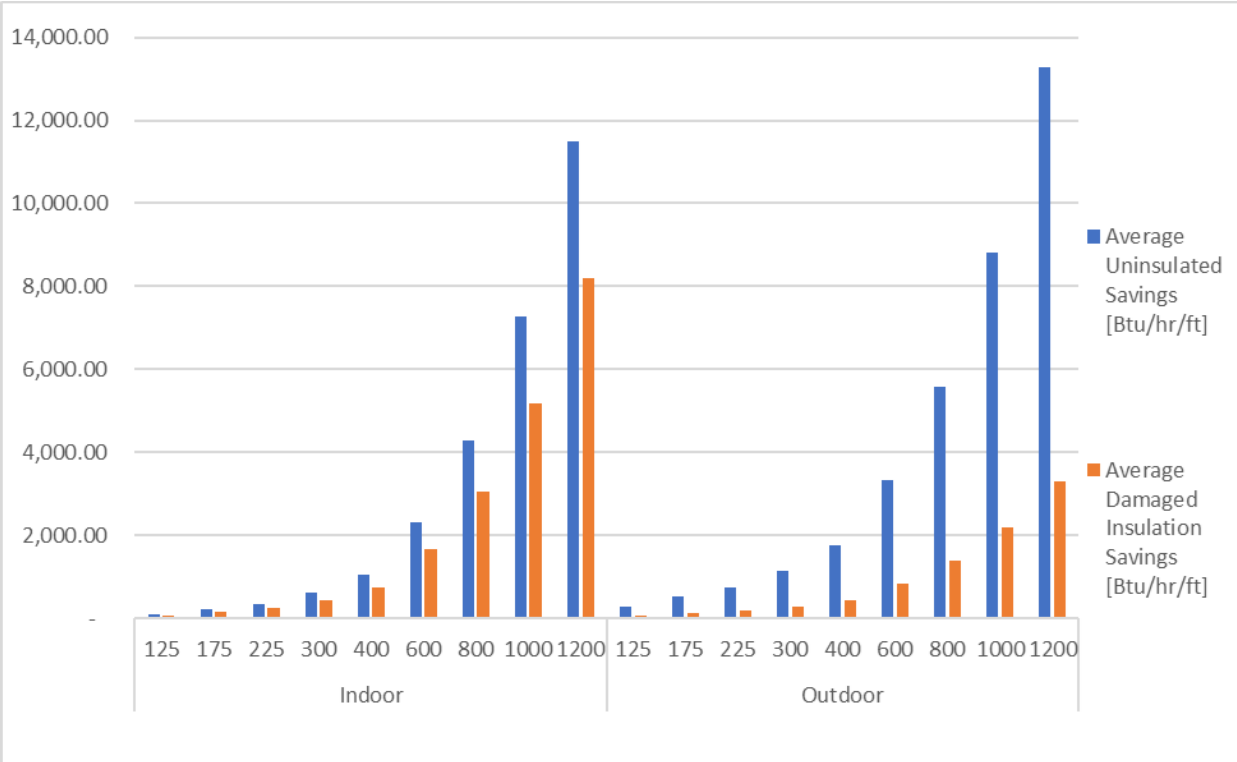


Table 66 – Industrial Average Energy Savings by Pipe Location, Climate Zone, and Pipe Condition

Pipe Location	Climate Zone	Average Uninsulated Savings [Btu/hr/ft]	Average Damaged/Under Insulated Insulation Savings [Btu/hr/ft]
Indoor	1A	3,079	2,196
	2A	3,079	2,196
	2B	3,079	2,196
	3A	3,079	2,196
	3B	3,079	2,196
	3C	3,079	2,196
	4A	3,079	2,196
	4B	3,079	2,196
	4C	3,079	2,196
	5A	3,079	2,196
	5B	3,079	2,196
	6A	3,079	2,196
	6B	3,079	2,196
	7A	3,079	2,196
	8A	3,079	2,196
Outdoor	1A	3,847	956
	2A	3,871	962
	2B	3,871	962
	3A	3,908	971
	3B	3,900	969
	3C	3,912	972
	4A	3,936	978
	4B	3,928	976
	4C	3,948	981
	5A	3,965	985
	5B	3,957	983
	6A	3,981	989
	6B	3,977	988
	7A	4,005	995
	8A	4,042	1,004
Average		**3,508**	**1,587**

Figure 16 – Average Energy Savings by Pipe Location, Climate Zone, and Pipe Condition

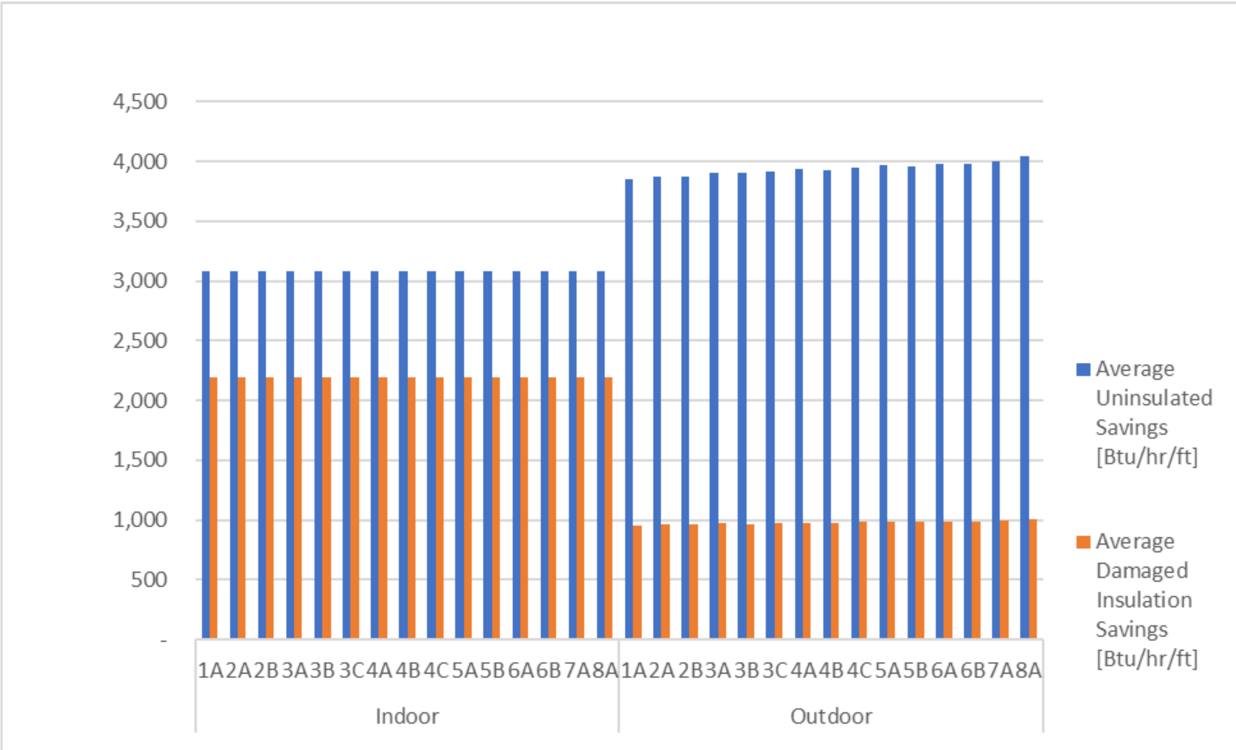


Table 67 – Industrial Data Sources

Model Input	Data Source	Description of Data Source and Use	Data Location
Baseline Conditions	U.S. Department of Energy's (DOE) Industrial Assessment Center, DOE's Energy Information Administration (EIA) Manufacturing Energy Consumption Survey (MECS), Insulation Industry Trade Association Coalition	Study scope (industrial sectors and system types) developed through analysis of DOE's IAC Database. Market potential developed using MECS. Baseline conditions and assumptions developed with input from the Consultation with Insulation Industry Trade Association Coalition	Industrial Assessment Centers (iac.university) Energy Information Administration (EIA)- About the Manufacturing Energy Consumption Survey (MECS)
Intervention:	ANSI/ASHRAE/IES Standard 90.1-2019: Section 6.	Baseline conditions modified to meet ANSI/ASHRAE/IES Standard 90.1-2019: Minimum Piping Insulation Thickness requirements of Section 6 Heating, Ventilating, and Air Conditioning Table 6.8.3-1 and Table 6.8.3-2 for Heating and Hot water and Cooling Systems, respectively, according to system fluid temperature and nominal pipe size.	ASHRAE not publicly available
Economics: Energy Rates	EIA's Annual Energy Outlook 2021	Obtained from DOE's EIA Annual Energy Outlook 2021 – national average.	https://www.eia.gov/outlooks/aeo/data/browser/#/?id=3-AEO2021&region=1-0&cases=ref2021&start=2019&end=2050&f=A&linechart=~ref2021-d113020a.79-3-AEO2021.1-0~ref2021-d113020a.80-3-AEO2021.1-0&map=ref2021-d113020a.4-3-AEO2021.1-0&ctype=linechart&chartindexed=0&maptype=0&sid=~~~~&sourcekey=0
Economics: Energy Escalation Rates	EIA's Annual Energy Outlook 2021	Obtained from DOE's EIA Annual Energy Outlook 2021 – national average, escalated annually.	https://www.eia.gov/outlooks/aeo/data/browser/#/?id=3-AEO2021&region=1-0&cases=ref2021&start=2019&end=2050&f=A&linechart=~ref2021-d113020a.79-3-AEO2021.1-0~ref2021-d113020a.80-3-AEO2021.1-0&map=ref2021-d113020a.4-3-AEO2021.1-0&ctype=linechart&chartindexed=0&maptype=0&sid=~~~~&sourcekey=0
Economics: Capital Costs	RSMeans, 2019 / 3E Plus, and Internet Research	Capital costs include material and labor for pipe insulation and jacket installation and equipment rental. For the damaged use case, costs	RSMeans not publicly available https://3eplus.org/

Model Input	Data Source	Description of Data Source and Use	Data Location
		also include labor and equipment costs for removal of damaged pipe insulation. Capital costs were derived from 3E Plus for the bare pipe use case and adjusted using RSMeans data for the damaged/under-insulated use case.	
Economics: Discount Rate	DOE, Energy Efficiency & Renewable Energy, Federal Energy Management Program (FEMP)	3% FEMP prescribed floor discount rate used in lieu of 2021 nominal discount rate.	https://www.energy.gov/eere/femp/articles/2021-discount-rates
Economics: Effective Useful Life	Insulation Effective Useful Life (EUL)	Pipe insulation EUL obtained from the Building Owners and Managers Association's (BOMA) Preventive Maintenance Guidebook Best Practices to Maintain Efficient and Sustainable Buildings for blanket insulation "not subject to condensation or leaks".	Project Lifespan Estimates.pdf (illinois.edu)
Emission Factors: Natural Gas	EPA Emission Factors for Greenhouse Gas Inventories	National-level emission factors obtained from Table 1: Stationary Combustion for natural gas.	https://www.epa.gov/sites/default/files/2021-04/documents/emission-factors_mar2020.pdf

Table 68 – Industrial Attachments

File Name	File Description
Industrial Insulation Scoping 08_08_2022	Contains analysis of U.S. Department of Energy's (DOE) Industrial Assessment Center (IAC) Database used to frame and inform study's scope. Serves as basis for identifying and selecting natural gas fired steam systems to be analyzed (steam and steam condensate) for select industrial sectors, based on measure prevalence and energy savings. Basis for determining system equivalent full load hours estimates by industrial sector. Data serves as input to the Industrial Insulation Energy Savings file.
Industrial Insulation Pipe Heat Loss Energy Savings 08_08_2022	Contains baseline and intervention pipe heat loss results, from the North American Insulation Manufacturers Association's (NAIMA) 3E Plus online calculator. Used to derive heat loss for a limited number of bare pipe use cases that were interpolated and then adjusted using energy savings reduction results from engineering calculations to represent the damaged/under-insulated use case. Data serves as input to the Industrial Insulation Energy Savings file.
Industrial Insulation Energy Savings 08_08_2022	Contains analytical framework for determining industrial market size from the U.S. Energy Information Administration's (EIA) Manufacturing Energy Consumption Survey (MECS) and for calculating industrial insulation energy savings impacts for all permutations of industrial subsystems, system characteristics (pipe size, temperature, insulation condition), and pipe location (indoors, outdoors). The file intakes and pairs energy savings per linear foot calculated using NAIMA's 3E Plus online heat loss calculator with insulation assumptions (from IAC database, EIA's MECS, and discussions with the Consultation with Insulation Industry Trade Association Coalition) to calculate national-level energy savings. Data serves as input to the Industrial Insulation MECS file.
Industrial Insulation Capital Costs 08_08_2022	Intakes hard coded data from the Industrial Insulation Energy Savings file and applies linear foot capital costs to each permutation (industrial sector, pipe location, system temperature, etc.) according to pipe size, insulation thickness, and evaluated insulation condition (bare pipe, damaged/under insulated). Data serves as input to the Energy Emissions Economic Analysis file.
Energy Emissions Economic Analysis 08_08_2022	Intakes aggregate energy savings and capital cost data by state and industrial sector from Quantifies the energy, emissions, and life-cycle economic benefits that accrue relative to the baseline condition for pipe insulation measures. Benefits are presented in a series of two-way tables and charts for inclusion in the final report. Underlying economic and emissions assumptions are included in the datafile along with links to corresponding data sources.

Appendix D – Resources

Residential

U.S. Department of Energy, Energy Efficiency & Renewable Energy, Prepared by Pacific Northwest National Laboratory; Methodology for Evaluating Cost-Effectiveness of Commercial Energy Code Changes; August 2005. Found at: Methodology for Evaluating Cost-effectiveness of Commercial Energy Code Changes (energycodes.gov)

National Institute of Standards and Technology, U.S. Department of Commerce; NIST Handbook 135, Life Cycle Costing Manual for the Federal Energy Management Program; NIST.HB.135-2020. Found at: Life Cycle Cost Manual for the Federal Energy Management Program (nist.gov)

Commercial

Polyisocyanurate Insulation Manufacturers Association (PIMA); Environmental Product Declaration; Polyiso Roof Insulation Boards; November 4, 2020; Found at: https://www.polyiso.org/page/EPDs

U.S. Department of Energy, Energy Efficiency & Renewable Energy, Prepared by Pacific Northwest National Laboratory; Methodology for Evaluating Cost-Effectiveness of Commercial Energy Code Changes; August 2005. Found at: Methodology for Evaluating Cost-effectiveness of Commercial Energy Code Changes (energycodes.gov)

National Renewable Energy Laboratory; U.S. Department of Energy Commercial Reference Building Models of the National Building Stock; Technical Report, NREL/TP-5500-46861; February 2011. Found at: U.S. Department of Energy Commercial Reference Building Models of the National Building Stock (nrel.gov)

National Institute of Standards and Technology, U.S. Department of Commerce; NIST Handbook 135, Life Cycle Costing Manual for the Federal Energy Management Program; NIST.HB.135-2020. Found at: Life Cycle Cost Manual for the Federal Energy Management Program (nist.gov)

Codes and Standards Enhancement (CASE) Initiative 2022 California Energy Code; Nonresidential High-Performance Envelope, Final CASE Report; Prepared by Energy Solutions and Determinant; 2022-NR-ENV1-F, Envelope, October 2020. Found at: 2020-T24-NR-HP-Envelope-Final-CASE-Report.pdf (title24stakeholders.com)

U.S. Department of Energy, Energy Efficiency & Renewable Energy, Building Energy Codes Program; ANSI/ASHRAE/IES Standard 90.1-2019: Envelope; Prepared by Pacific Northwest National Laboratory for the U.S. Department of Energy; PNNL-SA-153209; May 2020. Found at: ANSI/ASHRAE/IES Standard 90.1-2019 | Building Energy Codes Program

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Cool Roof Rating Council Directory; Found at: Product Directories - Cool Roof Rating Council (coolroofs.org)

NRCA; July 2014; It's a Wash, There is much to consider when cleaning a low-sloped cool roof membrane; Found at: It's a wash | Professional Roofing magazine

BOMA; Preventive Maintenance Guidebook Best Practices to Maintain Efficient and Sustainable Buildings; Found at: Project Lifespan Estimates.pdf (illinois.edu)

Industrial

U.S. Department of Energy, Energy Efficiency & Renewable Energy, Prepared by Pacific Northwest National Laboratory; Methodology for Evaluating Cost-Effectiveness of Commercial Energy Code Changes; August 2005. Found at: Methodology for Evaluating Cost-effectiveness of Commercial Energy Code Changes (energycodes.gov)

National Institute of Standards and Technology, U.S. Department of Commerce; NIST Handbook 135, Life Cycle Costing Manual for the Federal Energy Management Program; NIST.HB.135-2020. Found at: Life Cycle Cost Manual for the Federal Energy Management Program (nist.gov)

U.S. Department of Energy, Energy Efficiency & Renewable Energy, Building Energy Codes Program; ANSI/ASHRAE/IES Standard 90.1-2019: Envelope; Prepared by Pacific Northwest National Laboratory for the U.S. Department of Energy; PNNL-SA-153209; May 2020. Found at: ANSI/ASHRAE/IES Standard 90.1-2019 | Building Energy Codes Program

BOMA; Preventive Maintenance Guidebook Best Practices to Maintain Efficient and Sustainable Buildings; Found at: Project Lifespan Estimates.pdf (illinois.edu)

U.S. Department of Energy, Energy Efficiency & Renewable Energy, Industrial Assessment Center Database; Found at: Industrial Assessment Centers (iac.university)

U.S. Energy Information Administration, Independent Statistics & Analysis, Manufacturing Energy Consumption Survey; Found at: Energy Information Administration (EIA)- About the Manufacturing Energy Consumption Survey (MECS)

North American Insulation Manufacturers Association (NAIMA); 3E Plus Insulation Thickness Computer Program; Found at: https://3eplus.org/

END OF REPORT