Energy Research and Development Division

FINAL PROJECT REPORT

Solar-Reflective "Cool" Walls: Benefits, Technologies, and Implementation

Appendix A: Simulated HVAC Energy Savings in an Isolated Building (Task 2.1 Report)

California Energy Commission
Gavin Newsom, Governor

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Appendix A: Simulated HVAC energy savings in an isolated building (Task 2.1 report)

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Abstract

Solar-reflective "cool" walls reduce absorption of sunlight by the building envelope, which may decrease cooling load in warm weather and increase heating load in cool weather. Changes to annual heating, ventilation, and air conditioning (HVAC) energy use depend on climate, wall construction, wall orientation, building geometry, HVAC efficiency, and operating schedule. Changes to annual energy cost and energy-related emissions vary with local energy prices and emission factors. We used EnergyPlus to perform over 100,000 building energy simulations, spanning 10 different building categories, three building vintages, 16 California climate zones, and 15 United States climate zones. The simulations parametrically varied wall albedo (solar reflectance), roof albedo, combination of walls modified, and building orientation. Cool walls yielded annual source energy, energy cost, and emission savings in all California climate zones and in warm U.S. (ASHRAE) climate zones.

In California, cool walls reduced whole-building annual HVAC energy use 3.0 percent to 25 percent in single-family homes, 0.5 percent to 3.7 percent in medium offices, and 0.0 percent to 9.0 percent in stand-alone retail stores. In warm U.S. climates—zones 1A (Miami, FL) through 4B (Albuquerque, NM)—cool walls reduced whole-building annual HVAC energy use 2.0 percent to 8.5 percent in single-family homes, 0.0 percent to 4.2 percent in medium offices, and -0.5 percent to 5 percent in stand-alone retail stores. Cool walls also yielded small annual HVAC source energy savings in some cold U.S. climates—zones 4C (San Francisco, CA) through 7 (Duluth, MN)—for certain building categories and vintages. Annual HVAC source energy savings intensities (savings per unit surface area modified) from east, south, and west walls were similar, and always greater than those from the north wall.

While walls often receive less incident solar energy per unit area than roofs, they are also less insulated than roofs. Therefore, savings intensities from modifying the four walls (albedo

increase 0.35) were often comparable to those from modifying the roof (albedo increase of 0.30 in residential and 0.40 in commercial). The ratio of whole-building savings from cool walls (raising the albedo of all four walls) to that from a cool roof also depends on the ratio of net wall area (wall area excluding openings) to roof area. In California, the ratio of whole-building cool wall savings to cool roof savings was 1.5 to 3.5 in single-family homes, 0.40 to 1.0 in medium offices, and 0.20 to 0.85 in stand-alone retail stores. In warm U.S. climates (zones 1A through 4B), the ratio of whole-building cool wall savings to cool roof savings was 0.80 to 1.9 in single-family homes, 0.20 to 1.9 in medium offices, and 0.30 to 2.1 in stand-alone retail stores.

1 Introduction

Solar-reflective "cool" walls reduce absorption of sunlight by the building envelope, which may decrease a building's cooling load in warm weather and increase its heating load in cool weather. The change in a building's annual heating, ventilation, and air conditioning (HVAC) energy use depends on climate, wall construction, wall geometry, and wall orientation, along with other details of the building, such as HVAC efficiency and operating schedule.

The solar irradiation (solar energy per unit surface area) that strikes a surface decreases with beam incidence angle, or angle between solar beam and surface normal. At noon in summer, the sun is high, and a horizontal roof receives beam (direct) solar irradiation at a small incidence angle. In winter, the sun is lower, the roof's solar incidence angle is greater, and the days are shorter (Abood 2015); in some climates, winter skies may also be cloudier (Wilcox and Marion 2008). Thus, we expect a horizontal roof to receive more daily solar irradiation in summer than in winter.

The decrease in cooling load and increase in heating load upon raising wall albedo are each proportional to the sunlight intercepted by the walls. Thus, we expect walls that receive more sunlight to contribute more to the changes in cooling and heating loads.

Consider a building in the northern hemisphere with walls that face north, east, south, and west. On a clear day, we expect east and west walls to receive similar daily solar irradiation given the east-west symmetry of the solar path. Beam solar irradiation strikes the east wall in the morning and the west wall in the afternoon. The summer sun rises in the northeast and sets in the northwest. The solar path in summer peaks close to zenith in the southern sky. In winter, the sun rises in the southeast and sets in the southwest; the solar path peaks in the southern sky at a small elevation angle (Abood 2015; Schroeder 2011). Therefore, the north wall receives beam solar irradiation only during early morning and late afternoon of summer days. Under clear skies, the south wall will receive more beam sunlight in winter than in summer because the sun is lower, the wall's minimum beam incidence angle is smaller, and the wall is exposed to more hours of direct illumination (Abood 2015).

Given the differences in exposure to daily solar irradiation based on orientation, we expect the north wall to yield the smallest summer cooling energy savings and smallest winter heating energy penalties among all walls. In summer, we expect the east and west walls to yield greater cooling energy savings than the north and south walls. During winter, we expect the south wall to yield the greatest heating energy penalties and the north wall to yield the smallest heating energy penalties. In the United States (U.S.), the first building codes were developed in mid-1970s (Hunn 2010). Before the adoption of the first building codes, residential buildings were erected with little insulation in roofs and often had little to no insulation in walls (Huang et al. 1999). Since then, new codes have been released periodically, often raising insulation requirements. The efficiency of HVAC systems has also increased over time (Table 8-1 in CEC 2016b). The service life of an HVAC system depends on its maintenance but is typically 15 to 25 years (Comfort-Pro 2015). Therefore, we expect cooling savings and heating penalties to be greatest in old buildings that were erected prior to the first building codes and have HVAC systems near end of service life. New buildings comply with the most stringent insulation and HVAC efficiency requirements. Hence, we expect new buildings to yield the smallest cooling savings and heating penalties.

Past and current U.S. building codes prescribe more insulation in roofs than in walls (Table 8-1 in CEC 2016b; Huang et al. 1999; Blum 2007). Therefore, code-complaint walls provide less resistance to heat flow across the envelope than code-compliant roofs. If a building's four walls (considered together) and roof have the same total opaque surface area, receive equal solar energy, and undergo the same increase in albedo (solar reflectance), we expect the walls to yield greater cooling energy savings and heating energy penalties. Of course, cool surface energy savings will also scale with solar irradiation and modified surface area.

Envelope insulation, solar irradiation, and surface area are considered in detail in the current study. However, for a simple example, consider how the ratio of roof area to net wall area (wall area excluding openings, such as windows and doors) can vary between buildings. A one-floor building with a large footprint, such as a single-story box store, will often have a large roof area to net wall area ratio. This ratio decreases with building height since the wall area is proportional to the number of floors while the roof area remains the same. In multi-floor buildings, a cool roof affects the HVAC energy use of only the top floor while cool walls influence the HVAC energy use of every above-grade floor. Thus, all else being equal, we expect cooling savings and heating penalties from cool walls to be greater than those from a roof when the building has a small ratio of roof area to net wall area.

Many workers have simulated cool roof energy savings and penalties in the U.S. (Akbari et al. 1999; Akbari and Konopacki 2005; Levinson and Akbari 2010; Parker et al. 1998), China (Gao et al. 2014); India (Bhatia et al. 2011), Spain (Boixo et al. 2012), and in major cities around the word (Synnefa et al. 2007). However, cool *wall* studies are few and limited in scope. For example, Petrie et al. (2007) used the building energy simulation tool DOE 2.2 to estimate cool-wall energy savings and penalties for a small house in seven U.S. cities, while Moujaes and Brickman (2003) used the 1-D transient heat transfer model RESHEAT to estimate the cool-wall cooling load reduction for a house in Las Vegas, NV.

To quantify the effect of cool walls on individual buildings, we created code-compliant building prototypes representing three vintages of 10 categories of buildings. Using EnergyPlus—a whole building energy use simulation program—we modeled the cooling, heating, and fan energy uses of each prototype to evaluate annual site energy, site peak power demand, source energy, energy cost, and emission savings upon raising wall albedo or roof albedo. Prototype simulations parametrically varied wall albedo or roof albedo, combination of walls modified, and orientation of the building's long axis (east-west or north-south). Simulations spanned climate zones across California and the United States.

We present in this report a subset of the California and U.S. savings and penalties to compare (a) cool wall savings to cool roof savings; (b) cool wall savings between locations; (c) cool wall savings from modifying different wall combinations; (d) savings from different vintages; and (e) the sum of savings from walls modified one at a time to savings from modifying the same set of walls simultaneously.

2 Methodology

2.1 Locations

The effects of cool walls in California were evaluated in the 16 building climate zones established by California Energy Commission (CEC) (CEC 2015). To represent these 16 California climate zones (CACZs), the building energy simulations were executed using weather data from 16 representative cities or towns (Table 1). Figure 1 shows the region covered by each California climate zone.

We also evaluated cool wall effects in 15 ASHRAE climates zones across the United States, which we refer to as United States climate zones (USCZs). Table 2 lists the cities used to represent the U.S. climate zones and Figure 2 shows the region of each U.S. climate zone. The U.S. climate zones are numbered from hottest (USCZ 1A) to coldest (USCZ 8). The letters in the U.S. climate zone name help distinguish between humid (A), dry (B), and marine (C) climates Briggs et al. (2003a,b).

Table 1. Cities or towns in California used to represent its 16 building climate zones.

City or town	CACZ		City or town	CACZ
Arcata	1		Burbank	9
Santa Rosa	2		Riverside	10
Oakland	3		Red bluff	11
San Jose	4		Sacramento	12
Santa Maria	5		Fresno	13
Long Beach	6		China Lake	14
San Diego	7		Imperial	15
Fullerton	8		Mount Shasta	16

Table 2. Cities in United States used to represent ASHRAE climate zones.

City	State	ASHRAE CZ
Miami	Florida	1A
Houston	Texas	2A
Phoenix	Arizona	2B
Memphis	Tennessee	3A
El Paso	Texas	3B
San Francisco	California	3C
Baltimore	Maryland	4A
Albuquerque	New Mexico	4B
Salem [a]	Oregon	4C
Seattle [b]	Washington	4C
Chicago [a]	Illinois	5A
Peoria [b]	Illinois	5A
Boise	Idaho	5B
Burlington	Vermont	6A
Helena	Montana	6B
Duluth	Minnesota	7
Fairbanks	Alaska	8

[a] For commercial prototypes only.

[b] For residential prototypes only.

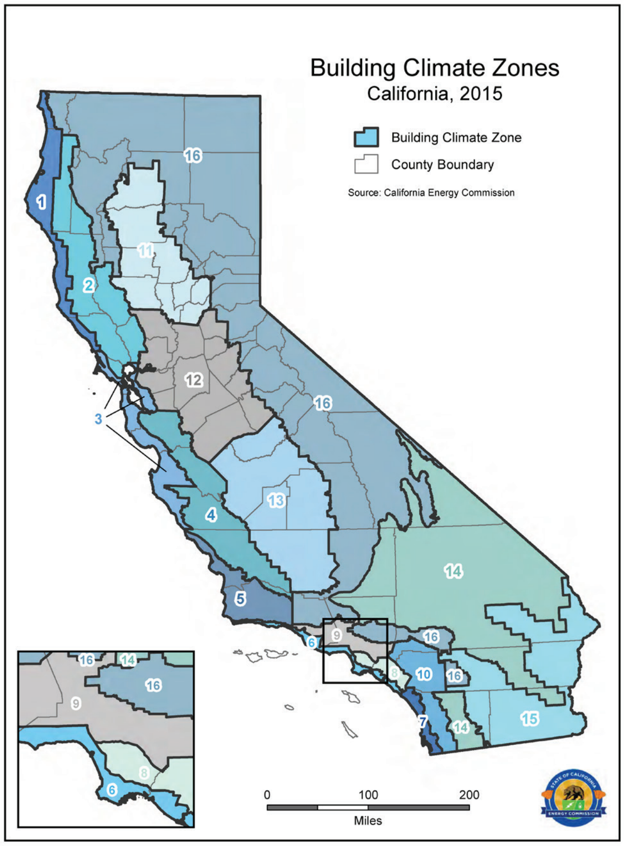

Figure 1. Map of California building climate zones (CEC 2015).

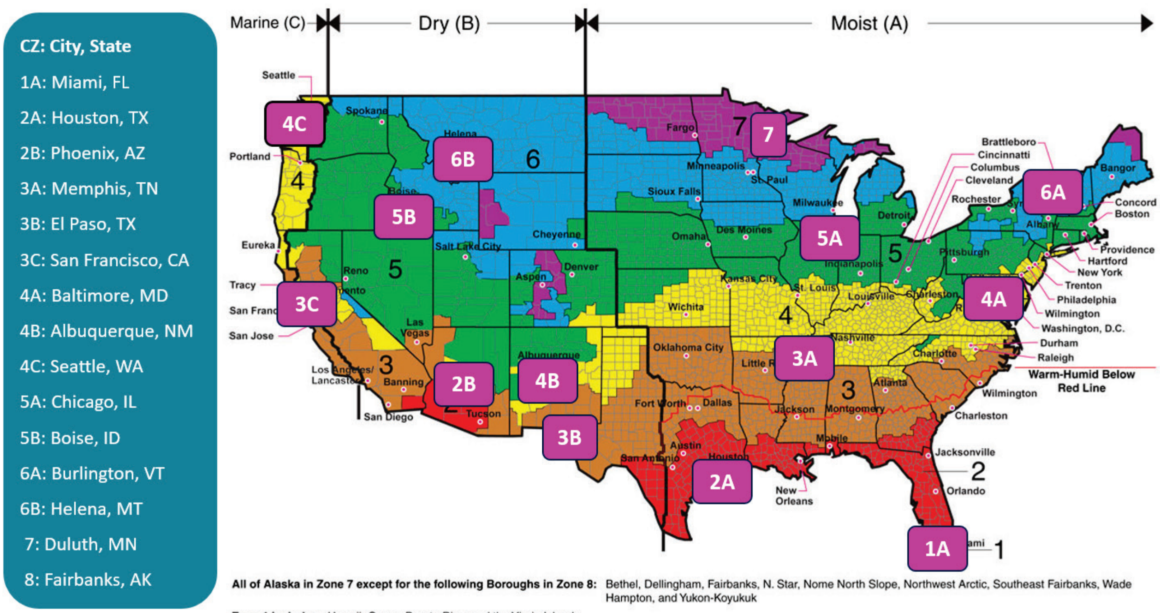

Figure 2. Map of ASHRAE climate zones in the United States, locating representative cities. Adapted from Briggs et al. (2003a,b).

2.2 Representative building vintages

The 2012 Commercial Building Energy Consumption Survey, or CBECS (EIA 2012) and 2009 Residential Energy Consumption Survey, or RECS (EIA 2009) were used to assess the age distribution of the country's current building stock by census division (for commercial buildings) or by state (for residential buildings). In most of the U.S. (including California), 40 percent to 60 percent of the buildings were erected before 1980. The decade of 1980 was typically the next period with significant building construction. In recent years, many states have also experienced rapid construction. Task Report Appendix A details our analysis of the age of U.S. buildings.

To represent California and U.S. building stock, this study analyses the effects of cool walls in three different building vintages: (a) *new* (for construction following current building codes), (b) *older* (for buildings erected in the 1980s), and (c) *oldest* (for pre-1980 buildings). In many U.S. regions, the older and oldest vintage prototypes represent about 75 percent of the residential building stock and 70 percent of the commercial building stock (Task Report Appendix A).

2.3 Building prototypes

2.3.1 Source of residential-building prototypes

The United States Department of Energy (hereafter, DOE) provides through its Building Energy Codes Program (BECP) a collection of prototypes for two building categories: single-family home and apartment building. These prototypes were generated to evaluate the energy and economic savings available by upgrading building energy efficiency standards to the latest version of the International Energy Conservation Code (IECC). BECP provides three sets of prototypes, each following a different IECC edition (year 2006, 2009, or 2012) (PNNL 2016a). BECP's collection of residential prototypes include versions for 199 cities across United States, covering all 15 U.S. climate zones. BECP provides variants of each residential prototype with different building foundations (slab, crawlspace, heated basement, or unheated basement) and heating systems (gas furnace, oil furnace, heat pump, or electric resistance).

To study cool walls in California, we selected BECP single-family home and apartment building prototypes with concrete slab foundation and gas furnace heating. These two prototypes were then modified following HVAC efficiency and building envelope insulation prescriptions in California Title 24 building energy efficiency standards. A version of each prototype was generated for each of California's 16 climate zones. In new construction prototypes, we set the HVAC efficiencies as well as the roof and wall insulations in accordance with 2016 Title 24 (CEC 2016b). Roof and wall insulation levels in older vintage prototypes were assigned following 1988 Title 24 (CEC 1988). Roof and wall insulation in the oldest vintage were set using envelope properties typical of buildings constructed before 1978—the year of the first Title 24 standards. The HVAC efficiencies of the older and oldest California residential prototypes comply with 2005 Title 24 standards (CEC 2005). California prototype HVAC efficiencies and insulation levels are further detailed in Section 2.3.4 and Section 2.3.5, respectively.

To study cool walls throughout the U.S., we selected BECP prototypes defined in the 15 U.S. climate zones listed in Table 2. Each prototype has a concrete slab foundation. We simulated three heating systems (gas furnace, heat pump, and electric resistance) in each U.S. climate zone. Each of the 15 cities used to represent the 15 ASHRAE climate zones is located in a different U.S. state. Since the rate of IECC adoption varies by state (BCAP 2017), the prototypes selected to represent new residential buildings in each of the 15 cities follow the IECC edition currently mandated in the state containing that city (Table 3).

Starting from these new construction prototypes, we generated the older and oldest vintage prototypes, setting roof and wall insulation following Huang et al. (1999), and HVAC efficiency following IECC 2006. HVAC efficiencies and insulation levels in the U.S. prototypes are further detailed in Section 2.3.4 and Section 2.3.5, respectively.

Table B-2 describes the geometry, envelope construction, and HVAC system for each vintage of the single-family home.

2.3.2 Source of commercial-building prototypes

DOE, in collaboration with three national laboratories[1], developed reference prototypes of 15 commercial building categories that represent realistic building characteristics and construction practices in U.S. (Deru et al. 2011). DOE produced a suite of prototypes that follow pre-1980 construction practices. They generated another version of the prototypes that follow ASHRAE Standard 90.1-1989. To represent new constructions, DOE has periodically released versions of their prototypes that follow recent editions of ASHRAE 90.1 (i.e., 2004, 2007, 2010, and 2013) (PNNL 2016b).

The California Energy Commission (CEC) adapted the prototypes of eight of the 15 DOE commercial building categories to meet 2008 Title 24. For our California study, we modified the CEC prototypes to represent oldest, older, and new vintages in California. The insulation levels in the oldest vintage follow pre-Title 24 construction practices. In the older vintage, insulation levels comply with 1988 Title 24 Standard (CEC 1988). The HVAC efficiencies in the older and oldest vintage meet 2005 Title 24 Standard (CEC 2005). In the new vintage, insulation levels and HVAC efficiencies comply with 2016 Title 24 Standard (CEC 2016a).

For our U.S. study, we selected from DOE prototypes the eight commercial building categories used in the California study. The suite of DOE prototypes that follow pre-1980 construction practices were used to represent oldest vintage. The versions of the DOE prototypes that

[1] The National Renewable Energy Laboratory (NREL), Pacific Northwestern National Laboratory (PNNL), and Lawrence Berkeley National Laboratory (LBNL).

comply with ASHRAE 90.1-1989 were used to represent older vintage. The HVAC efficiencies in the older and oldest vintage comply with ASHRAE 90.1-2001. We simulated new commercial buildings with the prototypes in each of the 15 cities that follow the ASHRAE 90.1 edition currently mandated in the state containing that city (Table 3).

Task Report Appendix B illustrates the 10 building types simulated in this study. Table B-3 and Table B-4 describe for the medium office and stand-alone retail, respectively, the geometry, envelope construction, and HVAC system by vintage.

Table 3. Building codes adopted by state for new residential and commercial buildings (BCAP 2017).

State	ASHRAE CZ	New vintage prototypes meet the following building code	
		ASHRAE 90.1 (for commercial prototypes)	IECC (for residential prototypes)
Florida	1A	2010	2012
Texas	2A	2013	2012
Arizona	2B	2004	2006
Tennessee	3A	2010	2006
Texas	3B	2013	2012
California	3C	2013	2012
Maryland	4A	2013	2012
New Mexico	4B	2007	2009
Oregon	4C	2010	NA [a]
Washington	4C	NA [a]	2012
Illinois	5A	2013	2012
Idaho	5B	2010	2009
Vermont	6A	2013	2012
Montana	6B	2010	2009
Minnesota	7	2010	2012
Alaska	8	2004	2006

[a] BECP provides commercial, but not residential, prototypes for the city of Salem, Oregon. We modeled buildings in USCZ 4C with BECP commercial prototypes specified for Salem, Oregon, and BECP residential prototypes defined for Seattle, Washington (about 300 km north of Salem).

2.3.3 Building category geometry

Table 4 summarizes the geometry of each building category.

Table 4. Geometry of BECP prototypes representing each building category.

Building category	Floors	Conditioned floor area [1000 m²]	Footprint area [1000 m²]	Roof area [1000 m²]	Net wall area [a] [1000 m²]	Window area [1000 m²]	Window -to-wall ratio [b]	Roof-to-wall ratio [c]	Floor-to-wall ratio [d]
Single-family home	2	0.223	0.112	0.118	0.184	0.033	0.15	0.61	1.16
Apartment building	3	2.01	0.669	0.785	1.17	0.247	0.18	0.57	1.72
Large hotel	6	11.4	1.89	1.98	2.81	1.21	0.30	0.70	4.04
Large office	13	46.3	3.56	3.56	6.95	4.64	0.40	0.51	6.66
Medium office	3	4.98	1.66	1.66	1.32	0.653	0.33	1.25	3.77
Small office	1	0.511	0.511	0.599	0.222	0.060	0.21	2.30	2.36
Fast-food restaurant	1	0.232	0.232	0.232	0.160	0.026	0.16	1.45	1.44
Retail stand-alone	1	2.29	2.29	2.29	1.09	0.084	0.07	2.07	2.10
Strip mall retail	1	2.09	2.09	2.09	1.06	0.124	0.10	1.96	1.97
Sit-down restaurant	1	0.511	0.511	0.511	0.229	0.047	0.18	2.24	2.22

[a] Net wall area excludes windows and doors.

[b] Ratio of window area to gross wall area (area of entire wall, including openings).

[c] Ratio of roof area to net wall area.

[d] Ratio of conditioned floor area to net wall area.

2.3.4 HVAC efficiencies

An air conditioner or furnace has a service life of about 15 to 25 years, depending on how well it is maintained (Comfort-Pro 2015). Thus, we expect that HVAC systems in older and oldest vintage buildings have been replaced at least once and their current HVAC system can be anywhere from new to 25 years old. Since the age of the HVAC system in these vintages varies widely, we assume for purposes of this study that the HVAC system in an older or oldest vintage building is on average 10 years old. For such prototypes, we assigned HVAC efficiencies that comply with building codes in effect 10 to 15 years ago.

For the California study, the HVAC efficiencies in the older and oldest vintage prototypes were modified to match 2005 Title 24 standards, which is a 12-year old code (CEC 2005). The HVAC efficiencies of all new prototypes were set to follow 2016 Title 24 standards (CEC 2016c). Table 5 specifies the air conditioner cooling coefficient of performance (COP), and the gas furnace annual fuel utilization efficiency (AFUE) or electric heat pump heating COP, assigned to each vintage and building category in California.

Table 5. HVAC efficiencies and year of Title 24 (T24) standards used in all California prototypes by vintage.

Building category	Air conditioner cooling COP [a]		Gas furnace AFUE or electric heat pump heating COP [b]	
	Older and oldest (2005 T24)	New (2016 T24)	Older and oldest (2005 T24)	New (2016 T24)
Single-family home	2.64	3.69	0.80	0.80
Apartment building	2.64	3.69	0.80	0.80
Large hotel	2.80	2.96	0.75	0.80
Large office	6.10	6.30	0.75	0.80
Medium office	3.78	3.96	0.80	0.80
Small office	2.96	3.49	3.20	3.49
Fast-food restaurant	2.84	3.49	0.80	0.80
Retail stand-alone	2.84	3.49	0.80	0.80
Strip mall retail	2.84	3.49	0.80	0.80
Sit-down restaurant	2.84	3.49	0.80	0.80

[a] Title 24 typically reports Energy Efficiency Ratio (EER) or Seasonal Energy Efficiency Ratio (SEER). To obtain COP, note that 1 EER = COP × 3.413 and 1 SEER = COP × 3.792 (ECOX 2017).

[b] Small office is heated with an electric heat pump, while all other prototypes are heated with a gas furnace.

For the U.S. study, we modified the HVAC efficiencies in the older and oldest vintage prototypes to comply with ASHRAE 90.1-2001 (ASHRAE 2001) in the commercial buildings and with IECC 2006 (IECC 2006) in the residential buildings. In new vintage prototypes, we set the HVAC efficiencies in accordance with the ASHRAE 90.1 edition currently mandated in the state containing the city simulated for each U.S. climate zone. Table 6 and Table 7 give the furnace AFUE, heat pump heating COP, and air conditioner cooling COP by vintage in the residential and commercial buildings, respectively.

Table 6. HVAC efficiencies used in the U.S. residential buildings by vintage. The table also shows the year of the IECC standards from which the efficiencies were obtained.

Building category	Gas furnace AFUE (year of IECC)		Heat pump heating COP (year of IECC)		Air conditioner cooling COP [a] (year of IECC)	
	Older and oldest	New	Older and oldest	New	Older and oldest	New
Single-family home	0.80 (2006)	0.80 (2006, 2009, 2012)	3.04 (2006)	3.04 (2006) 3.26 (2019, 2012)	2.64 (2006)	2.64 (2006) 3.43 (2019, 2012)
Apartment building	0.80 (2006)	0.80 (2006, 2009, 2012)	3.04 (2006)	3.04 (2006) 3.26 (2019, 2012)	2.64 (2006)	2.64 (2006) 3.43 (2019, 2012)

[a] IECC typically reports EER or SEER. To obtain COP, note that 1 EER = COP × 3.413 and 1 SEER = COP × 3.792 (ECOX 2017).

Table 7. HVAC efficiencies used in the U.S. commercial buildings by vintage. The table also shows the year of the ASHRAE 90.1 standards from which the efficiencies were obtained.

Building category	Gas furnace AFUE (year of ASHRAE 90.1)		Heat pump heating COP (year of ASHRAE 90.1)		Air conditioner cooling COP [b] (year of ASHRAE 90.1)	
	Older and oldest	New	Older and oldest	New	Older and oldest	New
Large hotel	0.75 (2001)	0.75 (2004, 2007, 2010) 0.80 (2013)	NA[a]	NA	2.80 (2001)	2.80 (2004, 2007, 2010) 2.96 (2013)
Large office	0.79 (2001)	0.790 (2004) 0.793 (2007, 2010) 0.813 (2013)	NA	NA	6.10 (2001)	6.10 (2004, 2007, 2010) 6.28 (2013)
Medium office	0.80 (2001)	0.80 (2004, 2007, 2010, 2013)	NA	NA	2.84 (2001)	3.23 (2004, 2007) 3.40 (2010, 2013)
Small office	0.80 (2001)	0.80 (2004, 2007, 2010, 2013)	3.00 (2001)	3.00 (2004) 3.29 (2007, 2010) 3.36 (2013)	2.64 (2001)	3.14 (2004) 3.91 (2007, 2010) 4.12 (2013)
Fast-food restaurant	0.80 (2001)	0.80 (2004, 2007, 2010, 2013)	NA	NA	2.84 (2001)	3.30 (2004, 2007) 3.80 (2010, 2013)
Retail stand-alone	0.80 (2001)	0.80 (2004, 2007, 2010, 2013)	NA	NA	2.84 (2001)	3.30 (2004, 2007) 3.80 (2010, 2013)
Strip mall retail	0.80 (2001)	0.80 (2004, 2007, 2010, 2013)	NA	NA	2.84 (2001)	3.30 (2004, 2007, 2010) 3.80 (2013)
Sit-down restaurant	0.80 (2001)	0.80 (2004, 2007, 2010, 2013)	NA	NA	2.84 (2001)	3.30 (2004, 2007) 3.80 (2010, 2013)

[a] NA = Not applicable.

[b] ASHRAE 90.1 typically reports EER or SEER. To obtain COP, note that 1 EER = COP × 3.413 and 1 SEER = COP × 3.792 (ECOX 2017).

2.3.5 Building envelope

2.3.5.1 Envelope construction

All residential prototypes in California and U.S. were simulated with wood frame walls. Their roofs were simulated with a wood frame attic (Table 8 and Table 9).

In California, the envelope construction of each building category did not vary by vintage. Most commercial buildings were simulated with metal frame walls and a metal frame roof. The large hotel had heavy mass walls (Table 8).

Table 8. Types of wall and roof constructions simulated in each of the California building categories for all vintages.

Building category	Walls	Roof
Single-family home	wood frame	attic and wood frame
Apartment building	wood frame	attic and wood frame
Large hotel	heavy mass	metal frame
Large office	metal frame	metal frame
Medium office	metal frame	metal frame
Small office	metal frame	attic and wood frame
Fast-food restaurant	wood frame	attic and wood frame
Retail stand-alone	metal frame	metal frame
Strip mall retail	metal frame	metal frame
Sit-down restaurant	metal frame	attic and wood frame

In the U.S., the large hotel and large office were simulated with heavy mass walls and a metal frame roof in all vintages. Every medium office and strip mall retail building was modeled with metal frame walls and a metal frame roof. The envelope construction of the small office, fast-food restaurant, retail stand-alone, and sit-down restaurant varied by vintage (Table 9). As an example, the oldest retail stand alone was modeled with metal frame walls, while the older and new vintage were modeled with heavy mass walls.

Table 9. Types of wall and roof constructions simulated by vintage in each of the U.S. building categories.

Building category	Oldest		Older		New	
	Walls	Roof	Walls	Roof	Walls	Roof
Single-family home	wood frame	attic and wood frame	wood frame	attic and wood frame	wood frame	attic and wood frame
Apartment building	wood frame	attic and wood frame	wood frame	attic and wood frame	wood frame	attic and wood frame
Large hotel	heavy mass	metal frame	heavy mass	metal frame	heavy mass	metal frame
Large office	heavy mass	metal frame	heavy mass	metal frame	heavy mass	metal frame
Medium office	metal frame	metal frame	metal frame	metal frame	metal frame	metal frame
Small office	metal frame	metal frame	heavy mass	attic and metal frame	metal frame	attic and wood frame
Fast-food restaurant	heavy mass	metal frame	wood frame	attic and metal frame	metal frame	attic and wood frame
Retail stand-alone	metal frame	metal frame	heavy mass	metal frame	heavy mass	metal frame
Strip mall retail	metal frame	metal frame	metal frame	metal frame	metal frame	metal frame
Sit-down restaurant	metal frame	metal frame	metal frame	attic and metal frame	metal frame	attic and wood frame

2.3.5.2 Thermal insulation

EnergyPlus models each envelope assembly (e.g., roof or wall) as a series of spatially uniform layers. We represent each insulated frame (roof joists or wall studs with cavity insulation) as a layer of continuous insulation with thermal resistance equal to that of the insulated frame. Parallel-path calculation of the equivalent thermal resistance R_e of an insulated frame is detailed in Task Report Appendix C.

We computed equivalent thermal resistances of insulated frames for all California prototypes as well as for the oldest residential U.S. prototypes (Task Report Appendix C). The remaining U.S. prototypes were simulated with the equivalent thermal resistances that were already defined in the original EnergyPlus versions provided by DOE.

Table 10 and Table 11 report wall assembly thermal resistance (indoor surface air film to outdoor surface air film, including insulated frame if present) by vintage and climate zone for the single-family home, medium office, and retail stand-alone prototypes in California and the U.S., respectively.

Table 12 and Table 13 do the same for roof assembly thermal resistance.

Table 10. Wall assembly thermal resistance (indoor surface air film to outdoor surface air film) by vintage and California climate zone for the single-family home, medium office, and retail stand-alone California prototypes.

Vintage	Building category	Thermal resistance of wall assembly [ft²·°F·h·BTU-1] a															
		CZ 01	CZ 02	CZ 03	CZ 04	CZ 05	CZ 06	CZ 07	CZ 08	CZ 09	CZ 10	CZ 11	CZ 12	CZ 13	CZ 14	CZ 15	CZ 16
oldest	Single-family home	5.8	5.8	5.8	5.8	5.8	5.8	5.8	5.8	5.8	5.8	5.8	5.8	5.8	5.8	5.8	5.8
	Medium office	2.5	3.9	3.9	4.1	4.1	3.8	3.8	3.8	3.8	3.8	3.6	3.6	3.6	2.5	2.5	2.5
	Retail stand-alone	2.5	3.9	3.9	4.1	4.1	3.8	3.8	3.8	3.8	3.8	3.6	3.6	3.6	2.5	2.5	2.5
older	Single-family home	16.9	11.3	11.3	11.3	11.3	11.3	11.3	11.3	11.3	11.3	11.3	11.3	11.3	16.9	16.9	16.9
	Medium office	7.4	7.6	7.6	8.0	8.0	7.5	7.5	7.5	7.5	7.5	7.0	7.0	7.0	7.2	7.2	7.4
	Retail stand-alone	7.4	7.6	7.6	8.0	8.0	7.5	7.5	7.5	7.5	7.5	7.0	7.0	7.0	7.2	7.2	7.4
new	Single-family home	19.6	19.6	19.6	19.6	19.6	15.4	15.4	19.6	19.6	19.6	19.6	19.6	19.6	19.6	19.6	19.6
	Medium office	14.5	16.1	12.2	16.1	16.1	14.5	14.5	16.1	16.1	16.1	16.1	16.1	16.1	16.1	16.1	16.1
	Retail stand-alone	14.5	16.1	12.2	16.1	16.1	14.5	14.5	16.1	16.1	16.1	16.1	16.1	16.1	16.1	16.1	16.1

[a] To obtain SI thermal resistance, note that 1 ft²·°F·h·BTU-1 = 0.176 m²·K/W²; that is, R-1 = RSI-0.176.

Table 11. Wall assembly thermal resistance (indoor surface air film to outdoor surface air film) by vintage and U.S. climate zone for the single-family home, medium office, and retail stand-alone U.S. prototypes.

Vintage	Building category	Thermal resistance of wall assembly [ft^2·°F·h·BTU^{-1}]														
		CZ 1A	CZ 2A	CZ 2B	CZ 3A	CZ 3B	CZ 3C	CZ 4A	CZ 4B	CZ 4C	CZ 5A	CZ 5B	CZ 6A	CZ 6B	CZ 7	CZ 8
oldest	Single-family home	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5
	Medium office	4.3	4.3	4.3	4.4	4.3	4.4	5.6	5.4	5.7	6.4	6.2	6.9	6.9	7.3	8.0
	Retail stand-alone	4.3	4.3	4.3	4.4	4.3	4.4	5.6	5.4	5.7	6.4	6.2	6.9	6.9	7.3	8.0
older	Single-family home	11.3	11.3	12.2	11.3	11.3	11.3	11.3	12.2	11.3	12.2	12.2	12.2	12.2	16.9	11.3
	Medium office	4.3	6.6	4.2	7.7	6.2	7.7	11.2	10.0	10.9	12.2	12.2	15.4	13.9	17.2	22.2
	Retail stand-alone	1.8	2.3	1.8	2.8	2.8	2.8	7.6	4.6	9.3	9.3	6.5	13.4	12.0	15.7	20.6
new	Single-family home	11.5	11.5	11.5	11.5	16.3	16.3	16.3	11.5	16.3	16.3	16.3	16.3	16.3	16.3	16.3
	Medium office	8.0	11.8	8.0	11.8	12.9	12.9	15.5	8.0	15.5	18.1	15.5	20.3	15.5	15.5	15.5
	Retail stand-alone	2.2	6.8	2.2	8.3	8.3	8.3	9.8	6.8	9.8	11.3	11.3	12.7	12.7	14.3	12.7

Table 12. Roof assembly thermal resistance (indoor surface air film to outdoor surface air film) by vintage and by California climate zone for the single-family home, medium office, and retail stand-alone California prototypes.

Vintage	Building category	Thermal resistance of roof assembly [ft^2·°F·h·BTU-1]															
		CZ 01	CZ 02	CZ 03	CZ 04	CZ 05	CZ 06	CZ 07	CZ 08	CZ 09	CZ 10	CZ 11	CZ 12	CZ 13	CZ 14	CZ 15	CZ 16
oldest	Single-family home	15.7	15.7	15.7	15.7	15.7	15.7	15.7	15.7	15.7	15.7	15.7	15.7	15.7	15.7	15.7	15.7
	Medium office	6.5	4.9	4.9	4.9	4.9	7.7	7.7	4.9	4.9	4.9	4.9	4.9	4.9	5.1	6.5	5.1
	Retail stand-alone	6.5	4.9	4.9	4.9	4.9	7.7	7.7	4.9	4.9	4.9	4.9	4.9	4.9	5.1	6.5	5.1
older	Single-family home	30.3	30.3	30.3	30.3	30.3	19.3	19.3	30.3	30.3	30.3	30.3	30.3	30.3	38.3	30.3	38.3
	Medium office	12.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	12.5	12.5	12.5
	Retail stand-alone	12.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	12.5	12.5	12.5
new	Single-family home	38.3	38.3	30.3	46.3	30.3	30.3	30.3	46.3	46.3	46.3	46.3	46.3	46.3	46.3	46.3	46.3
	Medium office	29.4	29.4	29.4	29.4	29.4	20.4	20.4	20.4	29.4	29.4	29.4	29.4	29.4	29.4	29.4	29.4
	Retail stand-alone	29.4	29.4	29.4	29.4	29.4	20.4	20.4	20.4	29.4	29.4	29.4	29.4	29.4	29.4	29.4	29.4

Table 13. Roof assembly thermal resistance (indoor surface air film to outdoor surface air film) by vintage and U.S. climate zone for the single-family home, medium office, and retail stand-alone U.S. prototypes.

Vintage	Building category	Thermal resistance of roof assembly [ft²·°F·h·BTU-1]														
		CZ 1A	CZ 2A	CZ 2B	CZ 3A	CZ 3B	CZ 3C	CZ 4A	CZ 4B	CZ 4C	CZ 5A	CZ 5B	CZ 6A	CZ 6B	CZ 7	CZ 8
oldest	Single-family home	10.9	13.3	12.1	13.3	13.3	10.9	10.9	12.1	15.3	15.3	12.1	22.3	12.1	14.8	15.3
	Medium office	9.7	9.7	9.7	9.7	9.7	9.7	11.3	10.9	11.4	13.9	13.1	16.7	16.7	16.3	16.7
	Retail stand-alone	9.7	9.7	9.7	9.7	9.7	9.7	11.3	10.9	11.4	13.9	13.1	16.7	16.7	16.3	16.7
older	Single-family home	27.3	27.3	29.3	27.3	27.3	25.3	27.3	29.3	32.3	32.3	29.3	27.3	29.3	32.3	32.3
	Medium office	13.2	14.8	21.4	13.6	20.5	11.0	16.9	16.6	15.3	18.9	19.6	22.2	20.4	24.7	32.2
	Retail stand-alone	13.2	14.8	21.4	13.6	20.5	11.0	16.9	16.6	15.3	18.9	19.6	22.2	20.4	24.7	32.2
new	Single-family home	27.6	32.4	27.6	27.6	32.4	32.4	37.6	32.4	37.6	37.6	32.4	37.6	37.6	37.6	37.6
	Medium office	15.9	25.6	15.9	20.8	25.6	25.6	31.2	15.9	20.8	31.2	20.8	31.2	20.8	20.8	20.8
	Retail stand-alone	15.9	25.6	15.9	20.8	25.6	25.6	31.2	15.9	20.8	31.2	20.8	31.2	20.8	20.8	20.8

2.3.6 Thermostat schedules

All residential prototypes from DOE had thermostat schedules in which the indoor air cooling temperature setpoint was constant at 24.0˚C and the indoor air heating temperature setpoint was constant at 22.2˚C. These were the thermostat schedules used in our U.S. simulations (Figure 3).

For our California simulations, we adjusted the residential thermostat schedules to match the recommended schedules in the 2016 Title 24 Residential Alternative Calculation Method Reference Manual (CEC 2016d). In the cooling season, the temperature is set to 25.5˚C during the early morning and evening, when residents are expected to be home, and "set up" to a higher value during the day, when residents are expected to be away. In the heating season, the temperature is set to 20.0˚C from morning to evening, and "set back" to a lower value overnight, when residents are expected to be asleep (Figure 3).

In the commercial prototypes, thermostat schedules varied by the type of building and by days of week. For example, the medium and large offices had the weekdays schedules shown in Figure 4. During weekends in the medium and large offices of all California and U.S. prototypes, the indoor air cooling temperature setpoint was constant at 26.7˚C and the indoor air heating temperature setpoint was constant at 15.6˚C.

The retail stand-alone had the weekdays schedules shown in Figure 5. In the weekends, the temperature settings in the retail stand-alone are similar to that in weekdays with the "set up" and "set back" hours shifted to accommodate the operating hours during the weekends. In the U.S. the schedules were identical between the older and oldest vintages, which in turn were slightly different than those in the new vintage. In the California commercial buildings, the thermostat schedules in all vintages were equal or very close to those of the new U.S. commercial buildings.

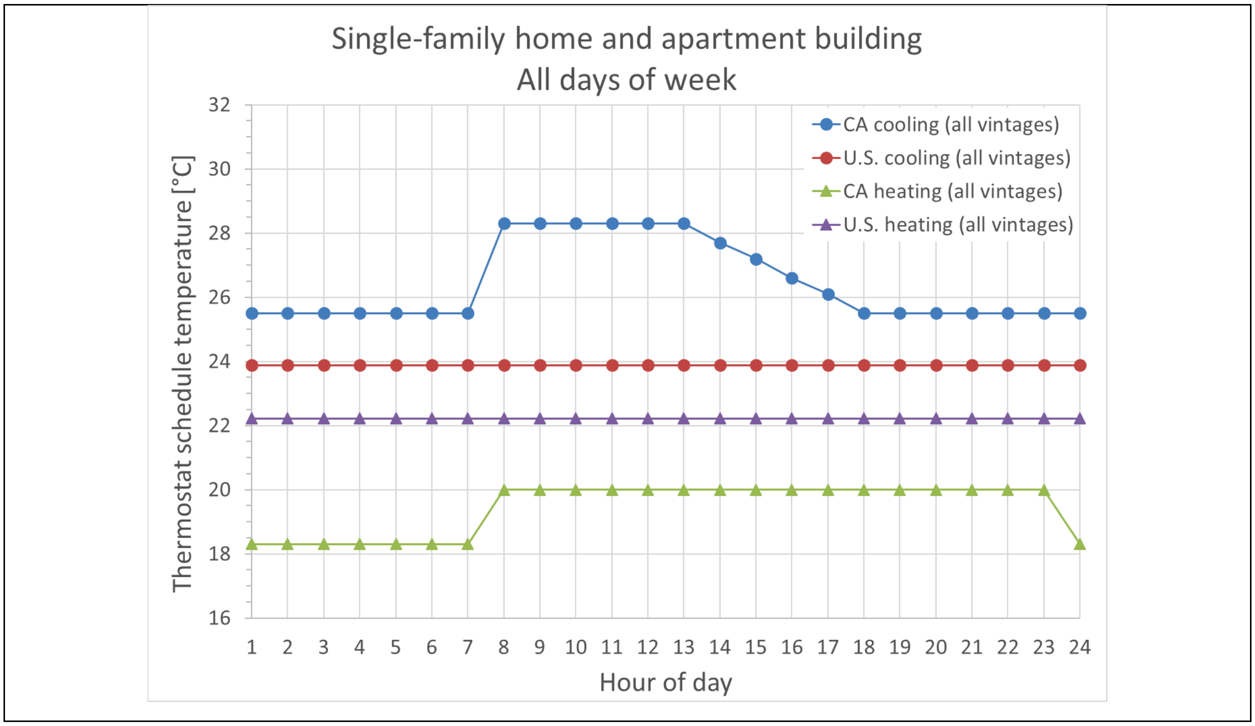

Figure 3. Cooling and heating thermostat schedules in the single-family home and apartment building for California and United States. Thermostat schedules are for every day of the week.

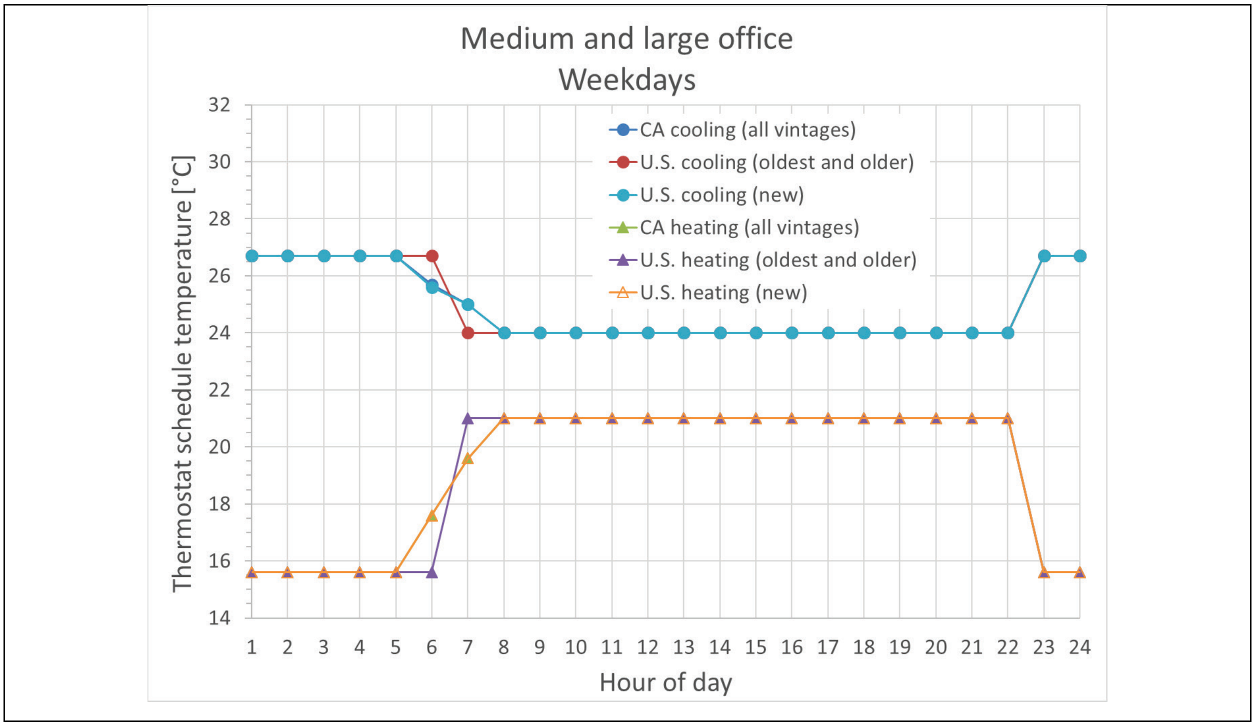

Figure 4. Cooling and heating thermostat schedules for weekdays in the medium and large office for California and United States.

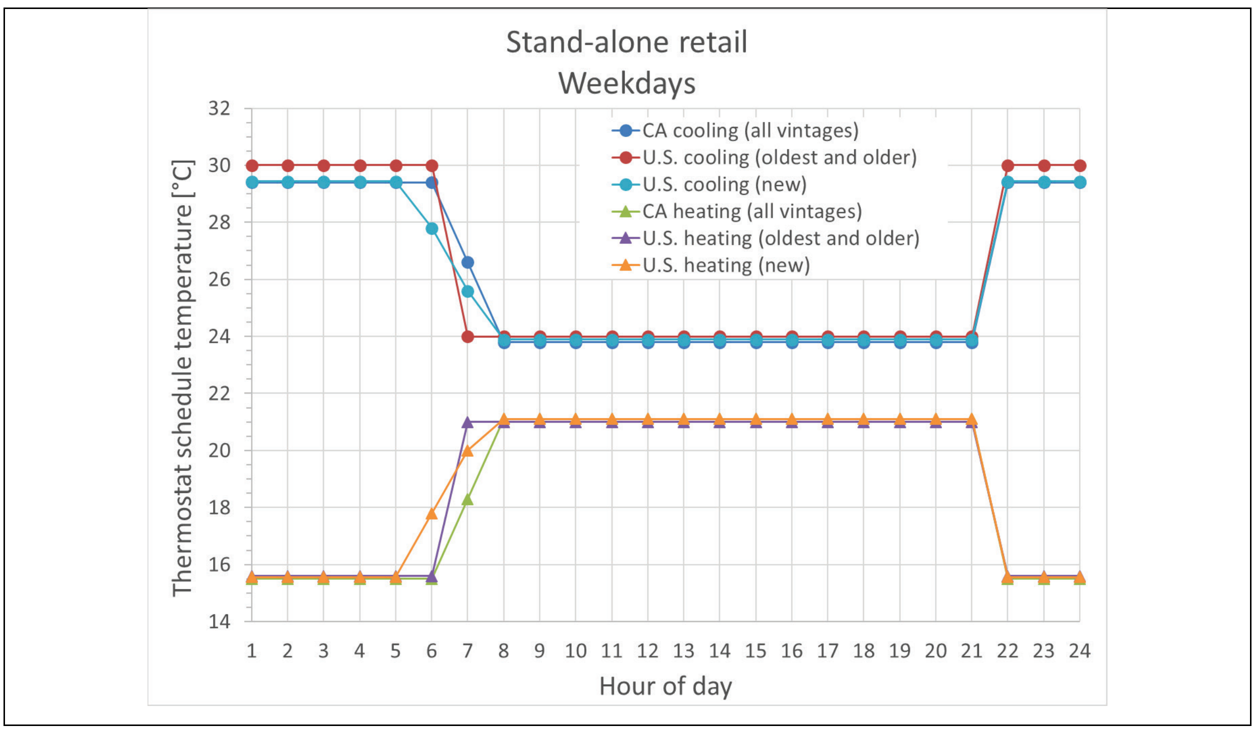

Figure 5. Cooling and heating thermostat schedules for weekdays in the stand-alone retail for California and United States.

2.4 Building energy simulation

2.4.1 Simulation tools

All building energy simulations were performed with EnergyPlus (EnergyPlus 2003), a program designed to model the energy uses of a building, including those for cooling, heating, and ventilation. We used jEPlus (jEPlus 2015), a parametric EnergyPlus simulation manager, to vary wall albedo, roof albedo, and building orientation. All simulations were run on the jEPlus Simulation Server, or JESS, cloud service (JESS 2015).

2.4.2 Parametric analysis

For California, we developed 96 residential building prototypes (2 building categories × 16 California climate zones × 3 vintages) and 384 commercial building prototypes (8 building categories × 16 California climate zones × 3 vintages). Similarly, we developed 270 residential building prototypes (2 building categories × 3 heating systems × 15 U.S. climate zones × 3 vintages) and 360 commercial building prototypes (8 building categories × 15 U.S. climate zones × 3 vintages) for the United States.

We parametrically varied wall and roof albedos to assess changes in annual building cooling, heating, and fan energy consumption. For each building category, climate zone, and vintage, we simulated the following cases.

(a) Base case: base wall albedo 0.25, and base roof albedo 0.10 (residential) or 0.20 (commercial). These base values represent albedos typical of walls and roofs in existing buildings.

(b) Alternative wall cases: a series of alternative albedos (0.10, 0.40, and 0.60) for the modified walls, leaving roof albedo unchanged. This was done for each of the 15 wall combinations in Table 14.

(c) Alternative roof cases: a series of alternative albedos for the roof, leaving wall albedo unchanged. In residential prototypes, the alternative albedos were 0.25, 0.40, and 0.60; in commercial prototypes, the alternative albedos were 0.10, 0.25, 0.40, and 0.60.

Each of these cases was simulated once with the building oriented long axis east-west, and again with the building oriented long axis north-south. Thus, for a given location and vintage, there were 98 simulations per residential prototype [(1 base case + 3 alternative roof albedos + 3 alternative wall albedos × 15 wall combinations) × 2 building orientations] and 100 simulations per commercial prototype [(1 base case + 4 alternative roof albedos + 3 alternative wall albedos × 15 wall combinations) × 2 building orientations].

Table 14. List of simulated wall combinations, taken 1, 2, 3, or 4 walls at a time.

Number of walls modified	Possible wall combinations
1	North (N), East (E), South (S), West (W)
2	NE, ES, EW, NS, NW, SW
3	NES, NEW, ESW, NSW
4	NESW

Therefore, in California we performed 96 residential prototypes × 98 simulations per residential prototype = 9,408 residential simulations, and 384 commercial prototypes × 100 simulations per commercial prototype = 38,400 commercial simulations, for a total of 47,808 California simulations. For the U.S. we performed 270 residential prototypes × 98 simulations per residential prototype = 26,460 residential simulations, and 360 commercial prototypes × 100 simulations per commercial prototype = 36,000 commercial simulations, for a total of 62,460 U.S. simulations.

2.4.3 Weather files

The California simulations were executed with the most recent weather files developed for use in Title 24 compliance simulations. This set of California weather files, called CZ2010, was developed by White Box Technologies (WBT 2011) with funding from the California Energy Commission. CZ2010 replaces the previous set of California weather files, known as CTZ2. The CZ2010 set represents better than CTZ2 the current annual weather in California (Huang 2013), as it includes current actual weather records that span 1998 to 2009, while the CTZ2 set characterized weather records from the 1950s to the 1980s. From the entire CZ2010 set of 85 weather files, we chose the 16 files generated from weather stations located in the 16 representative cities and towns listed in Table 1.

The U.S. simulations were performed using Typical Meteorological Year 3 (TMY3) weather files, which are the latest edition of the typical meteorological year weather files produced by NREL (Wilcox and Marion 2008) and distributed with EnergyPlus. We used the weather files associated with the commercial and residential prototypes from BECP. These were 17 weather files, one per city simulated (Table 2).

2.5 Degree days and annual solar radiation

Cooling degree days at 18°C (CDD18C) and heating degree days at 18°C (HDD18C) can be used to predict cooling load and heating load, respectively (EIA 2017). Cool surface energy savings also depend on solar radiation, since changes in cooling and heating loads induced by raising albedo are proportional to incident sunlight. Section 3.1 shows annual CDD18C, annual HDD18C, and annual global horizontal solar radiation (incident solar energy per unit area) computed from the weather files used in the California and U.S. simulations.

2.6 Monthly and seasonal daily sunlight by surface

To understand how daily solar radiation varies by location, season, and orientation, the PVWatts Calculator (NREL 2017) was used to compute for each California and U.S. representative city the monthly and seasonal average values of daily sunlight (solar energy per unit area) incident on a horizontal roof or on a north, east, south, or west exterior wall. We will refer to these five exterior envelope surfaces—roof, north wall, east wall, south wall, and west wall—as building "faces".

Section 3.2 summarizes for each representative city in California and the U.S., respectively, the daily sunlight received by the five building faces in summer and in winter. Task Report Appendix D further summarizes for each simulated location in California and U.S., the monthly and seasonal daily solar radiation intercepted by the five faces. The tables in Task Report Appendix D also show for each face the ratio of sunlight received in winter to that received in summer.

2.7 Energy, peak power, pollution, and energy cost savings

2.7.1 Site energy savings

Consider a building prototype representing a building category, vintage, and location simulated with a given orientation (long axis north-south or east-west). Let E_c, E_h, and E_f represent annual whole-building cooling, heating, and fan site electricity uses, and let G_h represent annual whole-building site gas use, each term evaluated in the base case (i.e., with wall and roof albedos set to prototype-specific base values). When the albedo of the roof or the albedo of one or more walls is raised to an alternative value, the annual whole-building cooling site electricity savings (e_c), heating site electricity *penalty* (e_h), fan site electricity savings (e_f), and heating site gas *penalty* (g_h) are calculated respectively as

$$e_{\mathrm{c}} = E_{\mathrm{c,base}} - E_{\mathrm{c,alternative}} \,, \tag{1}$$

$$e_{\mathrm{h}} = E_{\mathrm{h,alternative}} - E_{\mathrm{h,base}} \,, \tag{2}$$

$$e_{\mathrm{f}} = E_{\mathrm{f,base}} - E_{\mathrm{f,alternative}} \,, \tag{3}$$

and

$$g_{\mathrm{h}} = G_{\mathrm{h,alternative}} - G_{\mathrm{h,base}} \,, \tag{4}$$

where the subscript "alternative" refers to one of the alternative cases of a prototype (see 2.4.2, and the subscript "base" refers to the base case of the same prototype.

2.7.2 Source energy savings

The annual HVAC (cooling + heating + fan) source energy savings is calculated as

$$h_{\mathrm{HVAC}} = s_{\mathrm{e}} \times (e_{\mathrm{c}} + e_{\mathrm{f}} - e_{\mathrm{h}}) - s_{\mathrm{g}} \times g_{\mathrm{h}} \,, \tag{5}$$

where s_e is a state-specific site-to-source conversion factor for electricity, and s_g is a non-regional site-to-source conversion factor for natural gas. These site-to-source conversion factors were obtained from the Source Energy and Emissions Analysis Tool, or SEEAT (GTI 2017). The tool uses current and previous eGRID databases[2] to determine state-specific source energy consumption and greenhouse gas (GHG) emissions associated with annual site electricity consumption and site fuel (natural gas, oil, propane) used. The site-to-source factors for electricity incorporate transmission losses and the gas factors include distribution losses.

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[2] The Emissions & Generation Resource Integrated Database (eGRID) is a data source that provides characteristics (e.g., net generation, emission rates, and resource mix) of nearly all electric power generated in the United States (eGRID 2014).

Table 15. Site-to-source electric and natural gas conversion factors (GTI 2017).

	Site-to-source conversion factors	
State	**Electric [BTU/BTU]**	**Natural gas [BTU/BTU]**
Florida	2.94	1.09
Texas	3.25	
Arizona	3.34	
Tennessee	3.18	
Texas	3.25	
California	3.31	
Maryland	3.47	
New Mexico	3.40	
Oregon	2.05	
Washington	1.87	
Illinois	3.44	
Idaho	2.10	
Vermont	3.14	
Montana	2.79	
Minnesota	3.57	
Alaska	2.55	

2.7.3 HVAC peak power demand reduction

In this study, we define *peak hours* as those between 12:00 to 18:00 Clock Time (CT) during the weekdays (Monday to Friday) of June through September. For any given peak hour *i*, the site HVAC peak power demand reduction is calculated as

$$d_{\mathrm{HVAC},i} = \frac{(e_{\mathrm{c},i} + e_{\mathrm{f},i} - e_{\mathrm{h},i})}{1 \text{ hour}}, \quad (6)$$

where $e_{\mathrm{c},i}$, $e_{\mathrm{f},i}$, and $e_{\mathrm{h},i}$ are the peak hour whole-building site cooling energy savings, fan energy savings, and electric heating energy penalty, respectively. Let T be the total number of peak hours in a given year. The annual-average HVAC peak power demand reduction, d_{HVAC}, is calculated by averaging the HVAC power demand over all annual peak hours:

$$d_{\mathrm{HVAC}} = \frac{\sum_{i=1}^{T} d_{\mathrm{HVAC},i}}{T}. \quad (7)$$

2.7.4 Pollution savings

The annual reduction in emission of air pollutant a is calculated as

$$p_a = f_{e,a} \times (e_c + e_f - e_h) - f_{g,a} \times g_h \,. \tag{8}$$

where site electricity emission factor $f_{e,a}$ is the mass of pollutant emitted by power plants per unit of site electricity consumed, and site gas emission factor $f_{g,a}$ is the mass of pollutant emitted by the building's furnace per unit of site gas consumed. This study considers reductions in emission of carbon dioxide (CO_2), carbon dioxide equivalent[3] (CO_2e), nitrogen oxides (NO_x), and sulfur dioxide (SO_2). The emission factors of these four air-pollutants are listed in Table 16 (for site electricity) and in Table 17 (for site gas). These emission factors were also obtained using SEEAT and incorporate transmission and distribution losses.

[3] Carbon dioxide equivalent (CO_2e) is a measure that allows for greenhouse gas emissions other than CO_2 to be expressed in terms of CO_2 based on their global warming potential (GWP) relative to CO_2. Thus, emissions expressed as CO_2e represent the GWP of all greenhouse gases expressed in terms of CO_2 (SBT 2017).

Table 16. State-specific air-pollutant emission factors for site electricity use (GTI 2017).

	Air-pollutant emission rates from generated electricity			
State	**CO_2 [kg/kWh]**	**CO_2e [kg/kWh]**	**NO_x [g/kWh]**	**SO_2 [g/kWh]**
Florida	0.553	0.590	0.435	0.481
Texas	0.631	0.675	0.522	0.844
Arizona	0.553	0.582	0.535	0.272
Tennessee	0.557	0.579	0.354	0.789
California	0.312	0.342	0.308	0.086
Maryland	0.587	0.611	0.562	0.934
New Mexico	0.824	0.868	1.479	0.431
Oregon	0.159	0.172	0.154	0.150
Washington	0.120	0.128	0.109	0.050
Illinois	0.501	0.523	0.327	0.807
Idaho	0.086	0.094	0.086	0.086
Vermont	0.036	0.040	0.109	0.077
Montana	0.646	0.674	0.753	0.540
Minnesota	0.593	0.621	0.549	0.540
Alaska	0.459	0.492	1.878	0.422

Table 17. Non-regional air-pollutant emission factors from site gas use (GTI 2017).

Air-pollutant emission rates from consumed natural gas			
CO_2 [kg/therm]	**CO_2e [kg/therm]**	**NO_X [g/therm]**	**SO_2 [g/therm]**
5.908	6.681	7.802	1.315

2.7.5 Energy cost savings

Annual HVAC energy cost savings are calculated as

$$c = z_e \times (e_c + e_f - e_h) - z_g \times g_h \,, \tag{9}$$

where z_e and z_g are the state-specific annual average prices of electricity and natural gas, respectively. These prices are also dependent on type of building (residential or commercial). The annual average electricity and gas prices used in the study are in Table 18. These prices represent the state-average prices charged to residential and commercial customers in 2015 (EIA 2016a, EIA 2016b).

Table 18. State-specific average price of electricity (EIA 2016a) and natural gas sold to residential and commercial customers in 2015 (EIA 2016b).

	2015 price of electricity [$/kWh]		2015 price of natural gas [$/therm]	
State	**Residential customers**	**Commercial customers**	**Residential customers**	**Commercial customers**
Florida	0.116	0.095	1.955	1.092
Texas	0.116	0.082	1.062	0.695
Arizona	0.121	0.104	1.704	1.053
Tennessee	0.103	0.102	0.962	0.846
California	0.170	0.157	1.139	0.804
Maryland	0.138	0.110	1.203	0.980
New Mexico	0.125	0.103	0.863	0.632
Oregon	0.107	0.088	1.243	1.009
Washington	0.091	0.082	1.180	0.977
Illinois	0.125	0.090	0.797	0.729
Idaho	0.099	0.078	0.859	0.759
Vermont	0.171	0.145	1.456	0.789
Montana	0.109	0.102	0.826	0.813
Minnesota	0.121	0.094	0.879	0.731
Alaska	0.198	0.174	0.964	0.801

2.7.6 Savings intensity

The savings intensity (savings per unit of modified surface area) for site energy, source energy, emission, or energy cost savings j is calculated as

$$j' = j / A_{\mathrm{m}} \ , \tag{10}$$

where A_{m} is the total surface area modified. For example, if the east and west walls were modified, A_{m} is the sum of the east and west net wall areas.

2.7.7 Averaged savings and savings intensity over two building orientations

Each savings or savings intensity calculated using Eqs. (1) to (10) is for a single building orientation (long axis east-west or north-south). Two-orientation mean savings are calculated as

$$j_{\mathrm{mean}} = (j_{\mathrm{EW}} + j_{\mathrm{NS}})/2 \ , \tag{11}$$

where EW and NS refer to the long axis of the building running east-west and north-south, respectively. Two-orientation mean savings intensity is calculated as

$$j'_{\mathrm{mean}} = (j_{\mathrm{EW}} + j_{\mathrm{NS}})/(A_{\mathrm{m,EW}} + A_{\mathrm{m,NS}}). \quad (12)$$

2.8 Tabulating all computed savings

For each prototype and building orientation, the simulations included the base case, alternative wall cases, and alternative roof cases described in Section 2.4.2. These simulations were used to calculate for each prototype the annual whole-building savings in site energy, source energy, emission, energy cost, and site HVAC peak power demand using Eqs. (1) to (9). All saving intensities were calculated using Eq. (10). Savings and savings intensities averaged over the two building orientations were computed using Eqs. (11) and (12), respectively.

All computed savings and savings intensities from every simulated prototype were combined into a savings database, detailed in Task Report Appendix E.

3 Results

3.1 Degree days and annual solar irradiation

Figure 6 and Figure 7 show CDD18C, HDD18C, and annual global horizontal solar radiation (incident solar energy per unit area) calculated from the weather files used in the California and U.S. simulations.

In California (Figure 6), the warmest climate zone is CACZ15 (Imperial; 2,700 CDD18C), which represents the state's southeastern deserts. California climate zones located in the state's Central Valley (CACZs 11, 12, 13, and 14) have warm summers as well as cool winters. The coastal climates zones (CACZs 1, 2, 3, and 5) have cool climates and have high HDD18C. The coldest climate zone is CACZ 16 (Mount Shasta; 3,400 HDD18C), which represents the mountainous regions of the state.

California has limited variation in annual global horizontal solar radiation, ranging from 1.45 MWh/m² (Arcata; CACZ 1) to 2.1 MWh/m² (China Lake; CACZ 14).

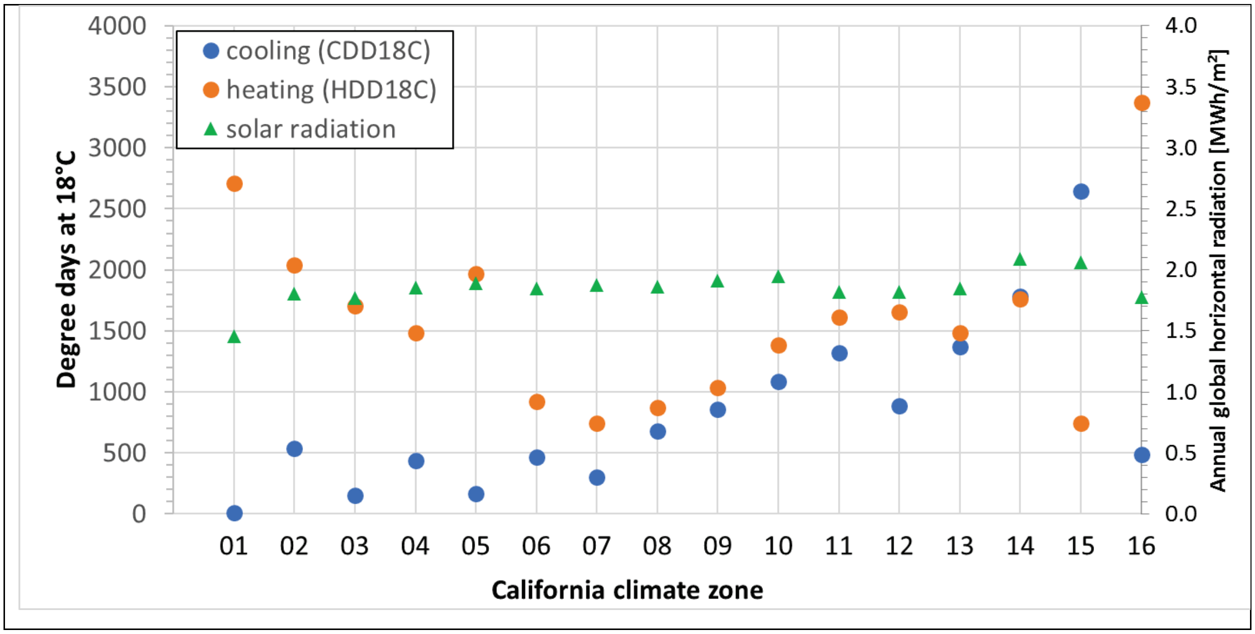
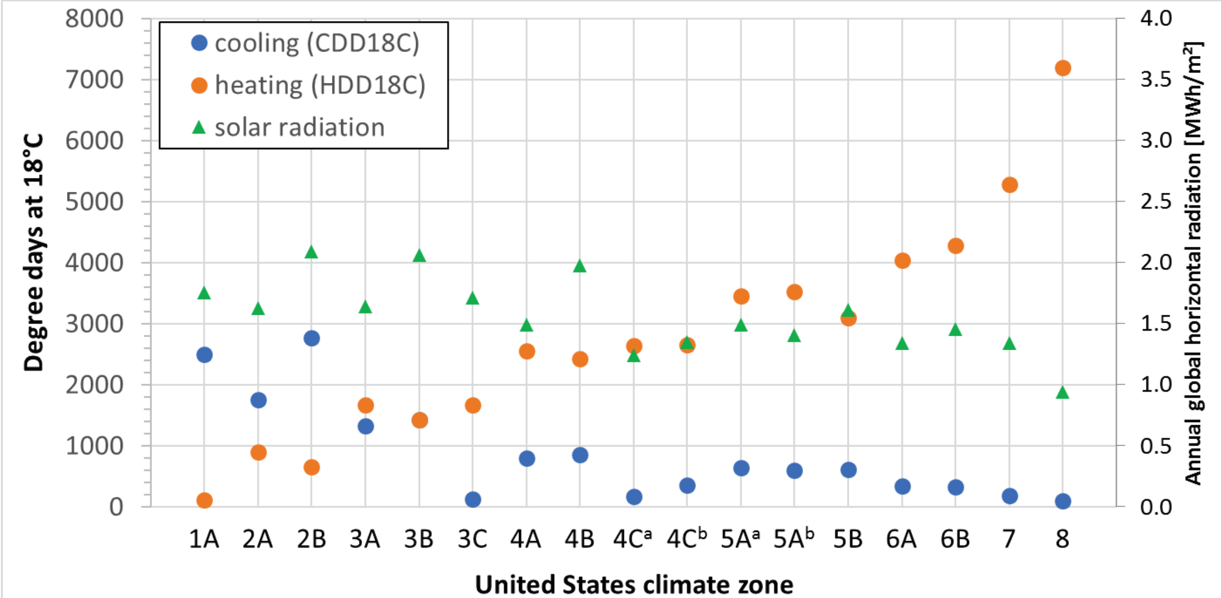


Figure 6. Cooling degree days at 18°C (CDD18C), heating degree days at 18°C (HDD18C), and annual global horizontal solar radiation by California climate zone, computed from CZ2010 weather files.

In the U.S. (Figure 7) the U.S. climate zone with the greatest CDD18C is 2B (Phoenix; 2,800 CDD18C) followed by USCZ 1A (Miami; 2,500 CDD18C). All U.S. climate zones from 3C onward had CDD18C below 1,000. HDD18C increased with U.S. climate zone number, ranging from 140 HDD18C (Miami; USCZ 1A) to 7,200 HDD18C (Fairbanks; USCZ 8).

USCZs 3B (El Paso) and 4B (Albuquerque) receive the most sunlight, getting nearly 2.1 MWh/m² annually. USCZ 8 (Fairbanks) receives the least sunlight (950 MWh/m²).



[a] From weather files used for residential prototypes.

[b] From weather files used for commercial prototypes.

Figure 7. Cooling degree days at 18°C (CDD18C), heating degree days at 18°C (HDD18C), and annual global horizontal solar radiation by United States climate zone, computed from TMY3 weather files.

3.2 Monthly and seasonal daily sunlight by face

Table 19 and Table 20 give for the representative cities in California and the U.S., respectively, the ratios of daily sunlight on each vertical face (north, east, south, or west) to that on the horizontal roof. Each ratio is evaluated in summer (June-July-August) and winter (December-January-February) as seasonal-average vertical sunlight to seasonal-average horizontal sunlight.

During the summer in all California locations, the roof receives the most sunlight, followed in descending order by the west, east, south, and north walls. During summer, the west-to-horizontal ratios range from 53 percent to 65 percent; the east-to-horizontal ratios range from 43 percent to 58 percent; the south-to-horizontal ratios range from 34 percent to 46 percent; and the north-to-horizontal ratios range from 23 percent to 31 percent (Table 19).

During winter in California, the south wall always receives more sunlight than all other faces, while the north wall once again receives the least solar radiation. During winter, the west-to-horizontal ratios range from 62 percent to 75 percent; the east-to-horizontal ratios range from 59 percent to 71 percent; the south-to-horizontal ratios range from 129 percent to 169 percent; and the north-to-horizontal ratios range from 22 percent to 32 percent (Table 19).

Table 19. Ratios of daily sunlight over a surface facing north (N), east (E), south (S), or west (W) to daily sunlight over a horizontal (H) roof. The table includes ratios computed for summer days and winter days in each of California's representative cities.

City or town in California	CAC Z	Summer (Jun, Jul, and Aug)				Winter (Dec, Jan, and Feb)			
		N-to-H ratio	E-to-H ratio	S-to-H ratio	W-to-H ratio	N-to-H ratio	E-to-H ratio	S-to-H ratio	W-to-H ratio
Arcata	1	31%	44%	46%	65%	32%	68%	148%	66%
Santa Rosa	2	23%	49%	40%	55%	32%	64%	136%	66%
Oakland	3	24%	45%	40%	55%	29%	61%	139%	65%
San Jose	4	23%	51%	39%	54%	28%	66%	146%	67%
Santa Maria	5	24%	42%	37%	59%	24%	65%	144%	65%
Long Beach	6	25%	43%	36%	59%	25%	59%	134%	62%
San Diego	7	24%	43%	34%	56%	22%	60%	138%	63%
Fullerton	8	25%	47%	36%	56%	26%	61%	137%	64%
Burbank	9	24%	52%	35%	53%	24%	63%	139%	63%
Riverside	10	25%	52%	35%	54%	25%	63%	141%	66%
Beale (for Red bluff) [a]	11	24%	56%	41%	54%	31%	63%	144%	69%
Sacramento	12	23%	57%	39%	54%	32%	61%	139%	68%
Fresno	13	24%	56%	37%	56%	32%	64%	129%	64%
China Lake	14	23%	58%	34%	55%	23%	71%	158%	69%
Palm Springs (for Imperial) [a]	15	26%	57%	34%	57%	24%	66%	148%	68%
Montague (for Mount Shasta) [a]	16	23%	58%	42%	55%	26%	67%	169%	75%
Minimum		**23%**	**43%**	**34%**	**53%**	**22%**	**59%**	**129%**	**62%**
Maximum		**31%**	**58%**	**46%**	**65%**	**32%**	**71%**	**169%**	**75%**

[a] Calculated for town that is near the climate zone's representative city.

During the summer in all U.S. locations, the roof receives the most sunlight, followed in descending order by the east, west, south, and north walls. In lower-latitude cities, such as Miami and Houston, the surfaces facing N and S receive similar solar radiation. The solar radiation received by the south wall increases with latitude. During summer and excluding Fairbanks, the west-to-horizontal ratios range from 46 percent to 61 percent; the east-to-horizontal ratios range from 46 percent to 62 percent; the south-to-horizontal ratios range from 31 percent to 53 percent; and the north-to-horizontal ratios range from 19 percent to 31 percent (Table 20).

In winter across the U.S., the south wall always receives more sunlight than the horizontal surface. The north wall once again receives the least sunlight. During winter and excluding

Fairbanks, the west-to-horizontal ratios range from 56 percent to 86 percent; the east-to-horizontal ratios range from 57 percent to 79 percent; the south-to-horizontal ratios range from 107 percent to 195 percent; and the north-to-horizontal ratios range from 21 percent to 37 percent (Table 20).

Table 20. Ratios of daily sunlight over a surface facing north (N), east (E), south (S), or west (W) to daily sunlight over a horizontal (H) roof. The table includes ratios computed for summer days and winter days in each of the U.S. representative cities.

City, State	USCZ	Summer (Jun, Jul, and Aug)				Winter (Dec, Jan, and Feb)			
		N-to-H ratio	E-to-H ratio	S-to-H ratio	W-to-H ratio	N-to-H ratio	E-to-H ratio	S-to-H ratio	W-to-H ratio
Miami, FL	1A	31%	52%	31%	48%	25%	58%	107%	58%
Houston, TX	2A	29%	54%	33%	50%	29%	57%	114%	64%
Phoenix, AZ	2B	25%	54%	34%	54%	23%	65%	144%	68%
Memphis, TN	3A	27%	53%	39%	54%	27%	64%	136%	64%
El Paso, TX	3B	25%	54%	32%	52%	24%	66%	138%	64%
San Francisco, CA	3C	25%	49%	40%	56%	29%	64%	144%	66%
Baltimore, MD	4A	29%	56%	43%	53%	29%	69%	150%	67%
Albuquerque, NM	4B	26%	58%	36%	50%	22%	65%	153%	69%
Salem, OR	4C	28%	56%	50%	61%	36%	65%	144%	70%
Seattle, WA	4C	28%	55%	53%	57%	37%	68%	157%	70%
Chicago, IL	5A	31%	57%	48%	56%	33%	67%	152%	68%
Peoria, IL	5A	19%	46%	36%	46%	21%	59%	141%	56%
Boise, ID	5B	25%	58%	46%	57%	32%	68%	159%	71%
Burlington, VT	6A	31%	58%	51%	58%	34%	68%	147%	66%
Helena, MT	6B	28%	62%	52%	57%	36%	79%	195%	86%
Duluth, MN	7	28%	55%	51%	58%	32%	72%	176%	72%
Fairbanks, AK	8	42%	79%	77%	61%	38%	131%	323%	69%
Minimum [a]		**19%**	**46%**	**31%**	**46%**	**21%**	**57%**	**107%**	**56%**
Maximum [a]		**31%**	**62%**	**53%**	**61%**	**37%**	**79%**	**195%**	**86%**

[a] Excluding USCZ 8 (Fairbanks, AK).

Table 21 and Table 22 give for the representative cities in California and U.S., respectively, the ratio of winter to summer daily sunlight for each of the five surfaces (roof, north wall, east wall, south wall, and west wall) and for the four-wall average. In California as well as the U.S., the roof, north wall, east wall, and west wall always receive more sunlight in summer than in winter. Changes to cooling and heating loads from modifying the albedo of an exterior surface are proportional to the sunlight intercepted by the modified surface. Therefore, since the roof, north wall, east wall, and west wall receive more sunlight during summer than in winter, we expect that modifying any of these four surfaces would yield cooling load changes in summer that are greater than the heating load changes in winter.

In the northern hemisphere, the sun in summer rises in the northeast and sets in the northwest. The solar altitude peaks close to zenith from the south. During winter, the sun rises in the southeast and sets in the southwest; the solar altitude peaks in the southern sky at a low elevation (Abood 2015; Schroeder 2011). As an example, in Fresno, the peak solar altitude at the summer solstice is 77˚, and the peak solar altitude in the winter solstice is 30˚ (Figure 8). Thus, the south wall in summer receives direct solar irradiation only from mid-morning to mid-afternoon and at a large incidence angle. In winter, the south wall is exposed to beam solar irradiation all day, and at a smaller incidence angle than in summer. At a surface, the beam solar irradiation increases inversely with incidence angle. Therefore, under clear skies the south wall receives more solar irradiation in winter than in summer. In China Lake, CA; Palm Springs, CA; Miami, FL; Phoenix, AZ; El Paso, TX; and Albuquerque, NM the south wall receives twice or more sunlight in winter than in summer. Since the south wall receives more sunlight in winter than in summer, we expect heating load changes in winter from a cool wall to be greater than the cooling load changes in summer.

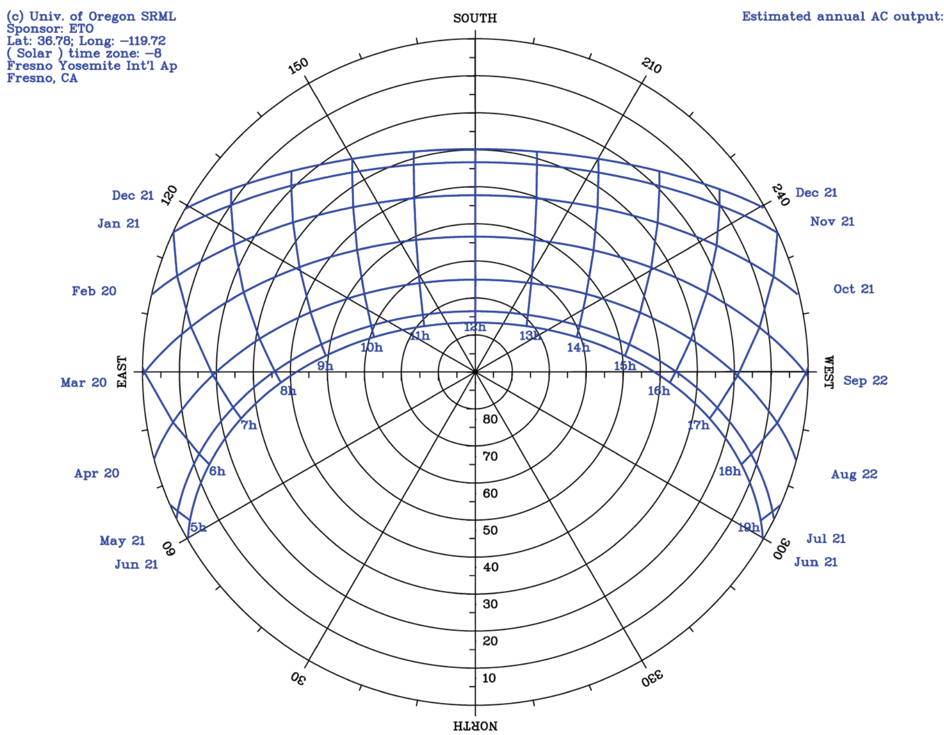


Figure 8. Sun path chart for Fresno, California (UO SRML 2008).

Table 21. Ratios of sunlight striking a face during a winter day to that of a summer day for each representative city in California. The table include ratios for a horizontal (H) roof, north (N) wall, east (E) wall, south (S) wall, west (W) wall, and the four-wall average.

City or town in California	CACZ	Winter to summer ratio					
		H	**N**	**E**	**S**	**W**	**Four-wall average**
Arcata	1	35%	36%	53%	110%	35%	58%
Santa Rosa	2	27%	37%	36%	94%	33%	49%
Oakland	3	33%	40%	45%	116%	39%	60%
San Jose	4	32%	40%	42%	123%	40%	60%
Santa Maria	5	43%	41%	66%	166%	47%	78%
Long Beach	6	41%	41%	57%	154%	44%	71%
San Diego	7	47%	43%	65%	188%	52%	84%
Fullerton	8	43%	45%	56%	162%	49%	76%
Burbank	9	39%	40%	47%	157%	46%	69%
Riverside	10	42%	43%	51%	169%	51%	75%
Beale (for Red Bluff) [a]	11	30%	39%	34%	104%	38%	52%
Sacramento	12	27%	37%	29%	96%	34%	47%
Fresno	13	30%	39%	34%	103%	34%	50%
China Lake	14	42%	42%	51%	194%	53%	79%
Palm Springs (for Imperial) [a]	15	46%	41%	53%	197%	54%	80%
Montague (for Mount Shasta) [a]	16	30%	35%	35%	120%	41%	57%
Minimum		**27%**	**35%**	**29%**	**94%**	**33%**	**47%**
Maximum		**47%**	**45%**	**66%**	**194%**	**54%**	**84%**

[a] Calculated for town that is near the climate zone's representative city.

Table 22. Ratios of sunlight striking a face during a winter day to that of a summer day for each U.S. representative city. The table include ratios for a horizontal (H) roof, north (N) wall, east (E) wall, south (S) wall, west (W) wall, and the four-wall average.

City, State	USCZ	Winter to summer ratio					
		H	**N**	**E**	**S**	**W**	**Four-wall average**
Miami, FL	1A	64%	52%	71%	221%	78%	98%
Houston, TX	2A	50%	50%	52%	172%	64%	79%
Phoenix, AZ	2B	46%	42%	55%	192%	58%	82%
Memphis, TN	3A	38%	37%	45%	131%	45%	63%
El Paso, TX	3B	51%	48%	62%	220%	64%	91%
San Francisco, CA	3C	36%	42%	46%	130%	43%	64%
Baltimore, MD	4A	37%	38%	46%	130%	47%	65%
Albuquerque, NM	4B	47%	41%	52%	197%	64%	85%
Salem, OR	4C	23%	30%	27%	67%	27%	38%
Seattle, WA	4C	22%	29%	27%	64%	27%	37%
Chicago, IL	5A	33%	35%	38%	104%	40%	54%
Peoria, IL	5A	35%	37%	45%	135%	42%	65%
Boise, ID	5B	26%	33%	30%	89%	32%	46%
Burlington, VT	6A	31%	34%	36%	88%	34%	48%
Helena, MT	6B	26%	35%	33%	99%	40%	52%
Duluth, MN	7	32%	36%	41%	108%	39%	58%
Fairbanks, AK	8	6%	6%	10%	27%	7%	14%
Minimum [a]		**22%**	**33%**	**27%**	**64%**	**27%**	**37%**
Maximum [a]		**64%**	**52%**	**71%**	**221%**	**78%**	**98%**

[a] Excluding USCZ 8 (Fairbanks, AK).

Task Report Appendix D further summarizes for each simulated location in California and U.S., the monthly and seasonal daily solar radiation intercepted by the five faces. In addition to the monthly and seasonal solar radiation, the tables in Task Report Appendix D show for each face the ratio of sunlight received in winter to that received in summer.

3.3 California case studies

This section uses some of the California simulations to evaluate the effects of raising wall albedo. We use the simulations from the single-family home to represent residential buildings, and those of the medium office building and stand-alone retail building to represent commercial buildings.

Cool roofing products for pitched roofs on homes (e.g., concrete tiles, clay tiles, and high-performance asphalt shingles) are typically rated with an aged albedo around 0.40, while cool roofing products for low-slope roofs on commercial buildings are typically rated with an aged albedo of at least 0.60 (Sleiman et al. 2011). In the case of walls, an aged albedo of at least 0.60 can be currently obtained with light-colored paints (Task 4.2 report: *Natural exposure of wall products*). We assume that a conventional residential roofing product (e.g., a dark asphalt shingle) has an aged albedo of about 0.10; that a conventional commercial roofing product (e.g., a dark gray membrane) has an aged albedo of about 0.20; and that a conventional wall coating (e.g., a dark to medium color paint) has an aged albedo of about 0.25. Thus, in these case studies, we present cool wall savings from increasing wall albedo by 0.35 (to 0.60 from 0.25) in both residential and commercial buildings, and from increasing roof albedo by 0.30 (to 0.40 from 0.10) in residential buildings and by 0.40 (to 0.60 from 0.20) in commercial buildings.

We compare savings between cool walls and cool roofs, and explore how the cool wall savings vary by location, vintage, and combination of modified walls. Finally, we investigate whether the sum of savings from walls modified one at a time equals the savings from modifying the same set of walls simultaneously.

All savings and penalties shown here are average values from the two building orientations (east-west and north-south). Values by orientation are available in the savings database.

3.3.1 California source energy savings intensity (per unit surface area modified) of the new single-family home by climate zone and modified surface

This section shows the annual source cooling, fan, and HVAC savings intensity and heating penalty intensity of the new single-family home by California climate zone from individually increasing the albedo by 0.35 (to 0.60 from 0.25) of the north wall, east wall, south wall, west wall, and roof, and of the roof by 0.30 (to 0.40 from 0.10). We choose to present the savings in the single-family home because it is the most common building type in California and has the most floor area in the state (Section 6.7.5 in Rosado 2016). Savings from the older and oldest single-family home show similar behavior to those from the new vintage but of different magnitudes.

3.3.1.1 Source energy changes by California climate zone

Figure 9 shows annual source values of cooling savings intensity, heating penalty intensity, fan savings intensity, and HVAC savings intensity for the new single-family home in California. In every California climate zone, raising wall or roof albedo reduced cooling and fan energy uses and increased heating energy use. However, every face (walls or roof) yielded source energy savings from cooling and fan that exceeded the heating penalties, leading to HVAC source energy savings in every California climate zone. CACZs 1 (Arcata) and 16 (Mount Shasta) had the smallest HVAC source energy savings intensities. The first (CACZ 1), was the location with the smallest source cooling savings intensities; it is also the location with the fewest CDD18C

(8). Arcata also yielded large heating penalties when compared to most other locations; it was the location with the second highest HDD18C (2,700). Mount Shasta (CACZ 16) experienced the most HDD18C in all California (nearly 3,400 HDD18C), yielding large heating source penalties.

The greatest HVAC source energy savings intensities were in CACZs 6 (Long Beach), 7 (San Diego), and 15 (Imperial). The first two (CACZs 6 and 7) were locations with small CDD18C and HDD18C when compared to the other California locations. However, low requirements for roof and wall insulation in the single-family home helped make annual HVAC source energy savings intensities in CACZs 6 and 7 larger than those in the other California climate zones. Specifically, the new single-family prototypes from CACZs 6 and 7 were simulated with less wall insulation than all other CACZs; the wall assembly thermal resistance in CACZs 6 and 7 was R-15.4 (Table 10), which is 79 percent of the R-19.6 that was used in all other CACZs (R-15.4 / R-19.6 = 79 percent). The roof assembly thermal resistance in CACZs 6 and 7 was R-30.3 (Table 12), which is 66 percent of the R-46.2 that what was used in many other CACZs (4, 8-16).

The third location (CACZ 15) is the location with the most CDD18C (2,650) and fewest HDD18C (740); it is also one of the most sunlit locations in California (Figure 9d). This CACZ 15 climate led to the largest HVAC source energy savings intensities.

3.3.1.2 Source energy changes by face

Changes in HVAC energy use are proportional to changes in heat conducted through the building envelope, which in turn scale with changes in wall solar heat gain. Wall solar heat gain depends on orientation. Thus, all else being equal, we expect changes in HVAC energy use to be greater from modified external surfaces that receive more sunlight (solar energy per unit area).

Of all four walls, the north wall was the one that yielded in all California climate zones the lowest annual cooling and fan source energy savings intensities (Figure 9a,c) because it received the least sunlight. As an example, consider CACZ 13 (Fresno), in which the north wall yields annual cooling source energy savings intensity 9.5 MJ/m², or 42 percent of that from the east wall (22.5 MJ/m²). From Table D-13 in Task Report Appendix D, we find that the summer daily solar irradiation on the north wall was 1.89 kWh/m², which is 44 percent of that from the east wall (4.33 kWh/m²). During winter, the north wall again received the least sunlight, yielding the smallest annual heating source energy penalty intensity (Figure 9b).

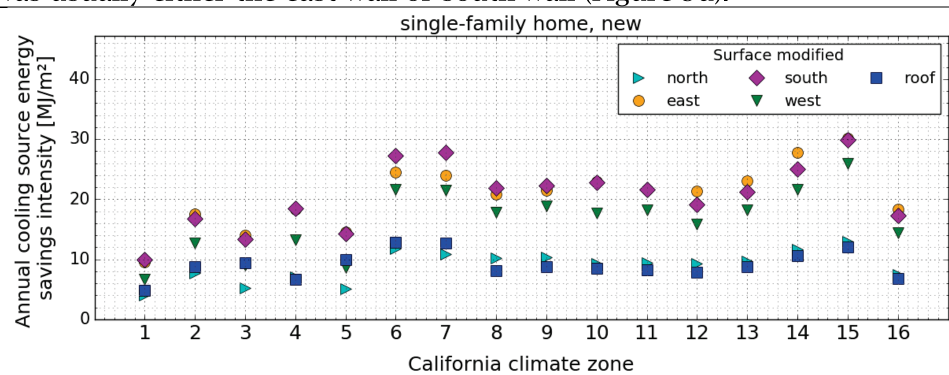
In all California climate zones, the annual cooling and fan source energy savings intensities from the roof were generally as small as those from the north wall. The roof and north wall savings intensities were in turn smaller than those from the east, south, and west walls. However, the roof (if assumed to be horizontal) was the face that received the most summer daily solar irradiation (Table D-13). The key is that the thermal resistance of the wall is less than half that of the roof. For example, in CACZs 4 and 8-16, the thermal resistance of the wall assembly was R-19.6, which is 42 percent of the roof thermal resistance in the roof of the same California climate zones (Table 10 and Table 12).

During winter, the annual heating source energy penalties from the roof were once again smaller than those from the east, south, and west walls, and similar to those from the north wall.

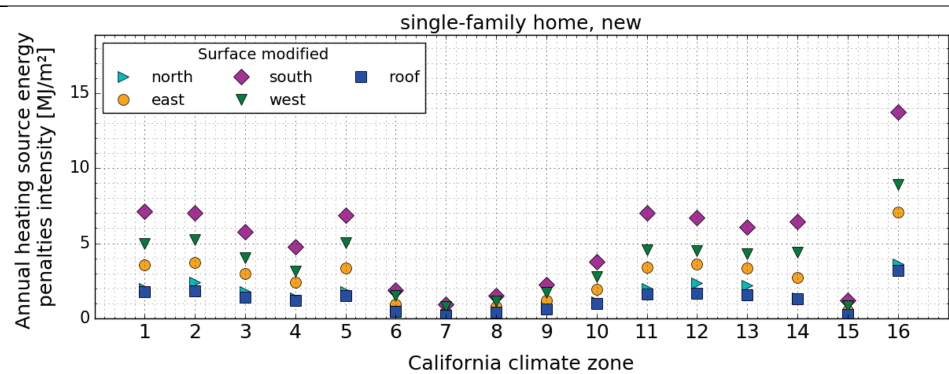
The wall that receives the most summer daily solar radiation is the west wall, followed by the east wall (Table 19). However, in many California climate zones the south wall yielded the greatest annual cooling and fan source energy savings intensities. In the remaining California climate zones, the greatest annual cooling and fan energy savings intensities were from the east wall. The savings intensities from the west wall were always 70 percent to 90 percent of those from the east wall.

In all California climate zones, the south wall received more sunlight during winter than any of the other surfaces (including the roof). Thus, in all locations, the south wall yielded annual heating source energy penalty intensities greater than those from any of the other surfaces (Table 21). In most locations, the south wall received more sunlight during winter than in summer, causing its heating penalties to be in some locations nearly as much as its cooling savings. The face yielding the largest annual HVAC source energy savings intensities varied by location, but was usually either the east wall or south wall (Figure 9d).

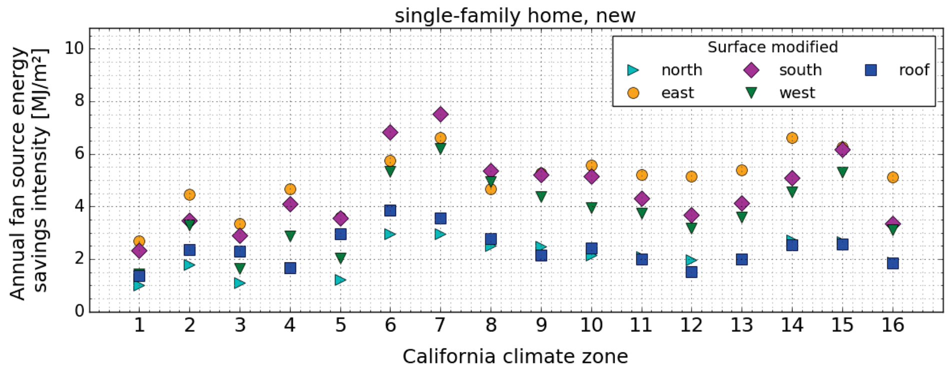
(a)



(b)



(c)



(d)

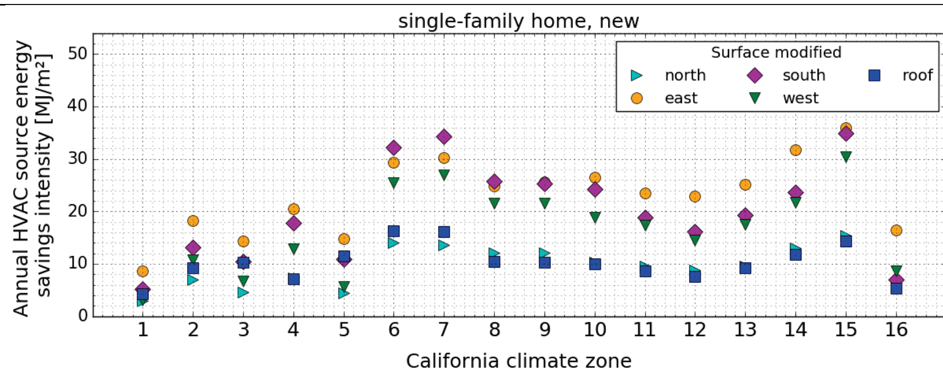


Figure 9. Annual source energy savings and penalty intensities of the new single-family home by California climate zone. The plots show (a) cooling savings, (b) heating penalties, (c) fan savings, and (d) HVAC savings.

3.3.2 Correlation of savings in California to outdoor air temperature and to changes in solar absorptance

Annual cooling savings and heating penalties vary by location, which is in part due to differences in climate between locations. This section investigates for the oldest single-family home the correlation of the annual cooling savings or heating penalties to two drivers: (a) change in absorbed solar radiation and (b) annual degree days. We used the coefficient of determination (R^2) to assess the fractions of variation in savings and penalties that can be explained by either driver.

Figure 10a and Figure 10b show how annual cooling site energy savings intensity from each modified face vary with changes in absorbed summer solar radiation and with annual CDD18C, respectively, in the oldest single-family home. Since the insulation in the building envelope and the efficiency of the AC system often vary by location, the changes in absorbed radiation were normalized by the face's thermal resistance and by the cooling efficiency (Figure 10a). annual CDD18C were normalized in the same manner (Figure 10b).

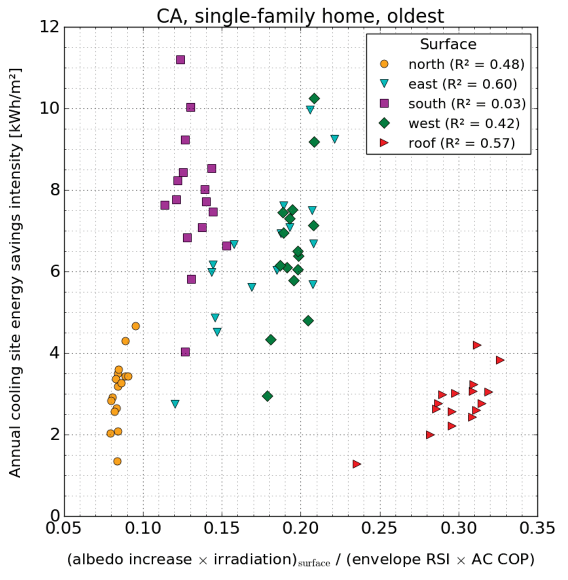
The annual site cooling savings from the south wall were essentially uncorrelated (R^2=0.03) with the change in absorbed irradiation (Figure 10a). Annual cooling savings for the other four faces—north wall (R^2=0.48), east wall (R^2=0.60), west wall (R^2=0.42), and roof (R^2=0.57)—showed considerably better correlation with change in absorbed irradiation. Figure 10b shows that for every modified face, the annual cooling savings intensity correlates very well with annual CDD18C (from R^2=0.76 for south wall to R^2=0.86 for east wall). The graph clearly shows how cooling savings intensity increases with annual CDD18C.

Figure 10c and Figure 10d show the correlation of annual site gas heating energy penalty intensity to changes in absorbed solar radiation to annual HDD18C, respectively, for the oldest single-family home. The changes in winter solar radiation and annual HDD18C were normalized by the envelope's thermal resistance and the heating efficiency.

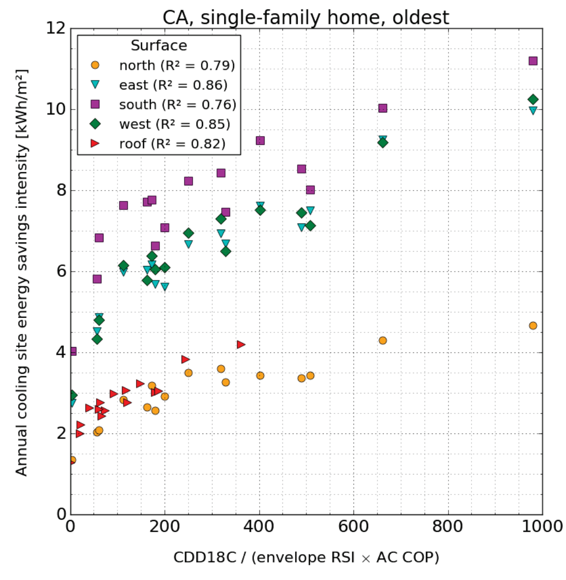
Annual site gas heating energy penalty intensities correlated poorly with changes in winter solar radiation (R^2=0.02 for east wall, west wall, and roof; R^2=0.11 for north wall). However, the annual site gas heating energy penalty intensities correlated very well with annual HDD18C (from R^2=0.90 for north wall to R^2=0.98 for west wall). Thus, annual heating penalty intensity increases with annual HDD18C.

	Changes in site energy vs changes in absorbed sunlight	Changes in site energy vs degree days
	(a)	(b)
Cooling		
	(c)	(d)
Heating		

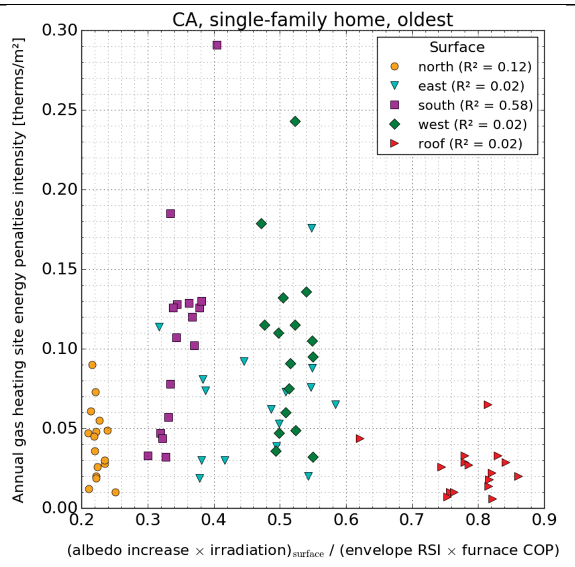
(a)



(b)



(c)



(d)

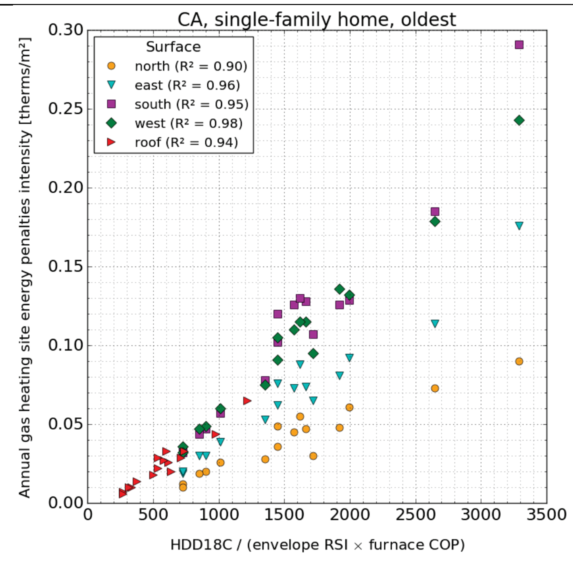


Figure 10. Correlation of changes in site energy use in California to changes in absorbed sunlight and to degree days, including (a) correlation of annual cooling site energy savings to change in absorbed sunlight during summer; (b) correlation of annual cooling site energy savings to annual CDD18C; (c) correlation of annual heating site energy penalties to change in absorbed sunlight during winter; and (d) correlation of annual heating site energy penalties to annual HDD18C.

We applied a multivariate linear regression analysis to investigate whether the correlations of cooling energy savings to either changes in absorbed sunlight or to annual CDD18C improved when both drivers (change in absorbed sunlight and annual CDD18C) were considered simultaneously.

Table 23 shows for all modified faces of the single-family home, medium office, and retail stand-alone the coefficient of determination from the correlation analysis of annual site cooling savings (a) to annual cooling degree days (CDD18C), (b) to change in absorbed summer sunlight, and (c) simultaneously to annual CDD18C and change in absorbed summer sunlight. For all buildings and faces, cooling savings correlated better with cooling degree days than with change in absorbed summer sunlight. When both metrics were considered simultaneously, the correlation improved the most—compared to the individual correlations to both drivers (change in absorbed summer sunlight and annual CDD18C)—for the south wall and the roof in the new vintage of the three building categories. The multivariate linear regression yielded little to no improvement—compared to the individual correlations to each driver—for the north wall, east wall, and west wall.

We repeated this analysis to investigate whether the correlation of annual site heating energy penalties to changes in absorbed winter sunlight or to heating degree days heating improved when both metrics are considered simultaneously. Table 24 shows for all modified faces of the single-family home, medium office, and retail stand-alone, the coefficient of determination from the correlation analysis of annual site heating penalties (a) to heating degree days, (b) to change in absorbed winter sunlight, and (c) simultaneously to heating degree days and change in absorbed winter sunlight. Heating penalties usually correlated better with heating degree days than with change in absorbed winter sunlight. When both metrics were considered simultaneously, the correlations improved significantly (increased by > 0.20) only in some vintages of the medium office, specifically for the north wall, east wall, and roof. This improvement of more than 0.20 was relative to the largest correlation to the individual metrics.

Table 23. Coefficient of determination (R^2) from the correlations of annual cooling savings to annual cooling degree days at 18°C ("cdd"), annual cooling savings to change in absorbed summer sunlight ("sun"), and annual cooling savings to cdd and sun. The coefficients of determination are for all vintages in California of the single-family home, medium office, and retail stand-alone.

		Coefficient of determination (R^2)														
		north wall			east wall			south wall			west wall			roof		
Building	**Vintage**	cdd	sun	cdd + sun	cdd	sun	cdd + sun	cdd	sun	cdd + sun	cdd	sun	cdd + sun	cdd	sun	cdd + sun
single-family home	oldest	0.79	0.48	0.80	0.86	0.60	0.88	0.76	0.03	0.79	0.85	0.42	0.86	0.82	0.57	0.89
	older	0.21	0.09	0.23	0.32	0.31	0.36	0.12	0.03	0.15	0.23	0.09	0.23	0.35	0.66	0.96
	new	0.51	0.28	0.53	0.66	0.38	0.66	0.43	0.16	0.60 [a]	0.55	0.24	0.55	0.17	0.42	0.87 [a]
medium office	oldest	0.89	0.60	0.89	0.86	0.43	0.86	0.83	0.03	0.87	0.85	0.39	0.85	0.70	0.41	0.82
	older	0.85	0.53	0.85	0.82	0.47	0.82	0.72	0.06	0.80	0.83	0.35	0.83	0.43	0.47	0.79
	new	0.69	0.42	0.70	0.63	0.32	0.63	0.41	0.20	0.63 [a]	0.62	0.21	0.62	0.32	0.72	0.94 [a]
retail stand-alone	oldest	0.89	0.59	0.89	0.88	0.51	0.88	0.84	0.01	0.85	0.84	0.42	0.85	0.75	0.44	0.88
	older	0.77	0.48	0.78	0.84	0.49	0.84	0.72	0.03	0.76	0.78	0.37	0.78	0.60	0.40	0.88
	new	0.42	0.31	0.42	0.70	0.20	0.76	0.31	0.20	0.53 [a]	0.50	0.22	0.50	0.43	0.64	0.95 [a]

[a] Coefficient of determination that significantly improved in the multivariate linear regression.

Table 24. Coefficient of determination (R^2) from the correlations of annual heating penalty to annual heating degree days at 18°C ("hdd"), annual heating penalty to change in absorbed winter sunlight ("sun"), and annual heating penalty to hdd and sun. The coefficients of determination are for all vintages in California of the single-family home, medium office, and retail stand-alone.

		Coefficient of determination (R^2)														
		north wall			east wall			south wall			west wall			roof		
Building	**Vintage**	hdd	sun	hdd + sun	hdd	sun	hdd + sun	hdd	sun	hdd + sun	hdd	sun	hdd + sun	hdd	sun	hdd + sun
single-family home	oldest	0.90	0.12	0.91	0.96	0.02	0.97	0.95	0.58	0.97	0.98	0.02	0.98	0.94	0.02	0.94
	older	0.64	0.09	0.64	0.83	0.05	0.86	0.86	0.74	0.97	0.78	0.00	0.80	0.74	0.35	0.79
	new	0.81	0.08	0.81	0.88	0.06	0.93	0.89	0.69	0.97	0.90	0.00	0.92	0.66	0.05	0.78
medium office	oldest	0.79	0.16	0.81	0.06	0.36	0.43	0.14	0.16	0.18	0.40	0.07	0.43	0.16	0.08	0.39 [a]
	older	0.66	0.24	0.73	0.26	0.47	0.71 [a]	0.16	0.31	0.32	0.02	0.38	0.38	0.19	0.23	0.34
	new	0.44	0.43	0.67 [a]	0.26	0.36	0.60 [a]	0.18	0.22	0.24	0.00	0.49	0.49	0.47	0.23	0.50
retail stand-alone	oldest	0.85	0.03	0.86	0.84	0.04	0.87	0.84	0.33	0.84	0.85	0.00	0.85	0.96	0.17	0.96
	older	0.87	0.04	0.88	0.93	0.05	0.97	0.93	0.51	0.94	0.91	0.00	0.92	0.95	0.04	0.95
	new	0.11	0.02	0.11	0.72	0.09	0.79	0.90	0.44	0.90	0.88	0.00	0.89	0.89	0.16	0.89

[a] Coefficient of determination that significantly improved in the multivariate linear regression.

3.3.3 Savings in California by climate zone and vintage

This section reports annual HVAC source energy, energy cost, CO_2e, NO_x, SO_2, and peak power demand savings for the single-family home, the medium office, and the stand-alone retail buildings upon (a) increasing the albedo of all four walls simultaneously by 0.35 (to 0.60 from 0.25) or (b) increasing the albedo of the roof to 0.40 from 0.10 (single-family home) or to 0.60 from 0.20 (medium office and retail stand-alone). Each metric is compared by vintage and by California climate zone.

3.3.3.1 Annual HVAC source energy savings

Figure 11 shows annual HVAC source energy savings intensity by vintage and by California climate zone for the single-family home (Figure 11a), medium office (Figure 11b), and stand-alone retail (Figure 11c).

In the single-family home (Figure 11a) the increase in roof albedo (0.30) was 86 percent of that of walls (0.35). In each vintage, the thermal resistance of the roof assembly was much greater than that of the wall assembly; in older and oldest vintages, the thermal resistance of the roof assembly was 2.7 times greater than that of the wall assembly, and in the new vintage, the thermal resistance of the roof assembly insulation was 1.5 to 2.4 times greater than that of walls (Table 10 and Table 12). Hence, these differences between roof and wall thermal resistance are a major reason why the four-walls annual HVAC source energy savings intensities were generally at least twice than those from the roof.

In the single-family home (Figure 11a), the thermal resistance of the wall assembly in the new vintage was 3.4 times that in the oldest vintage, while the cooling efficiency in the new vintage was 1.4 times that in the oldest vintage. Thus, we would expect the HVAC savings intensity from cool walls in the oldest single-family home to be about $3.4 \times 1.4 = 4.75$ times that of the new home. This estimate matches well with what we observe in Figure 11a and calculated in Table 25, where the cool wall savings intensity from the oldest vintage is about 5 times that of the new vintage. In the case of older single-family home, the HVAC savings intensity were about 2.5 times that of the new vintage (Table 26).

The medium-office savings (Figure 11b) were from increasing the wall albedo by 0.35 (to 0.60 from 0.25), and from increasing the roof albedo by 0.40 (to 0.60 from 0.20). Thus, the increase in roof albedo was 1.14 times that of walls. The thermal resistance of the roof assembly in the oldest medium office was from 1.2 to 1.4 times that of the wall assembly in CACZs 2-5 and 8-13; however, the thermal resistance of the roof assembly was 2.0 to 2.6 times that of the wall assembly in the remaining CACZs (1, 6-7, and 14-16) (Table 10 and Table 12). In these California climate zones with large ratio of roof thermal resistance to wall thermal resistance, annual HVAC savings intensity from the walls were greater than those from the roof (Figure 11b).

In the medium office (Figure 11b), the ratio of wall thermal resistances of new to oldest vintage varies by location but ranges from 3.8 to 6.4. Additionally, the cooling efficiency in the new vintage was only 1.1 times that of the oldest vintage. Thus, we would expect the HVAC savings from cool walls in the oldest single-family home to be between 4.2 (3.8 × 1.1) to 7.0 (6.4 × 1.1) times that of the new medium office. This estimate matches well with what we observe in Figure 11a and calculated in Table 25, where the cool walls savings intensity from the oldest vintage were on average, 5.2 times that of the new vintage. In the case of older medium office, the annual HVAC savings intensity were on average, 2.0 times that of the new vintage (Table 26)

In the retail stand-alone, the cool wall savings throughout California from the oldest vintage were on average 5.8 times that of the new vintage (Figure 11c; Table 25); the wall savings from the older vintage were on average 2.6 times that of the new vintage (Figure 11c; Table 26). These oldest-to-new and older-to-new savings ratios of the stand-alone retail were greater than those of the medium office even though the thermal resistance of the retail stand-alone and medium office were very similar (identical in most cases). That is because the air conditioner efficiency in the stand-alone retail increased 23 percent (to 3.49 from 2.84) between the old vintages and the new vintage, while in the medium office, the air conditioner efficiency increased only 5.0 percent (to 3.96 from 3.78) (Table 5).

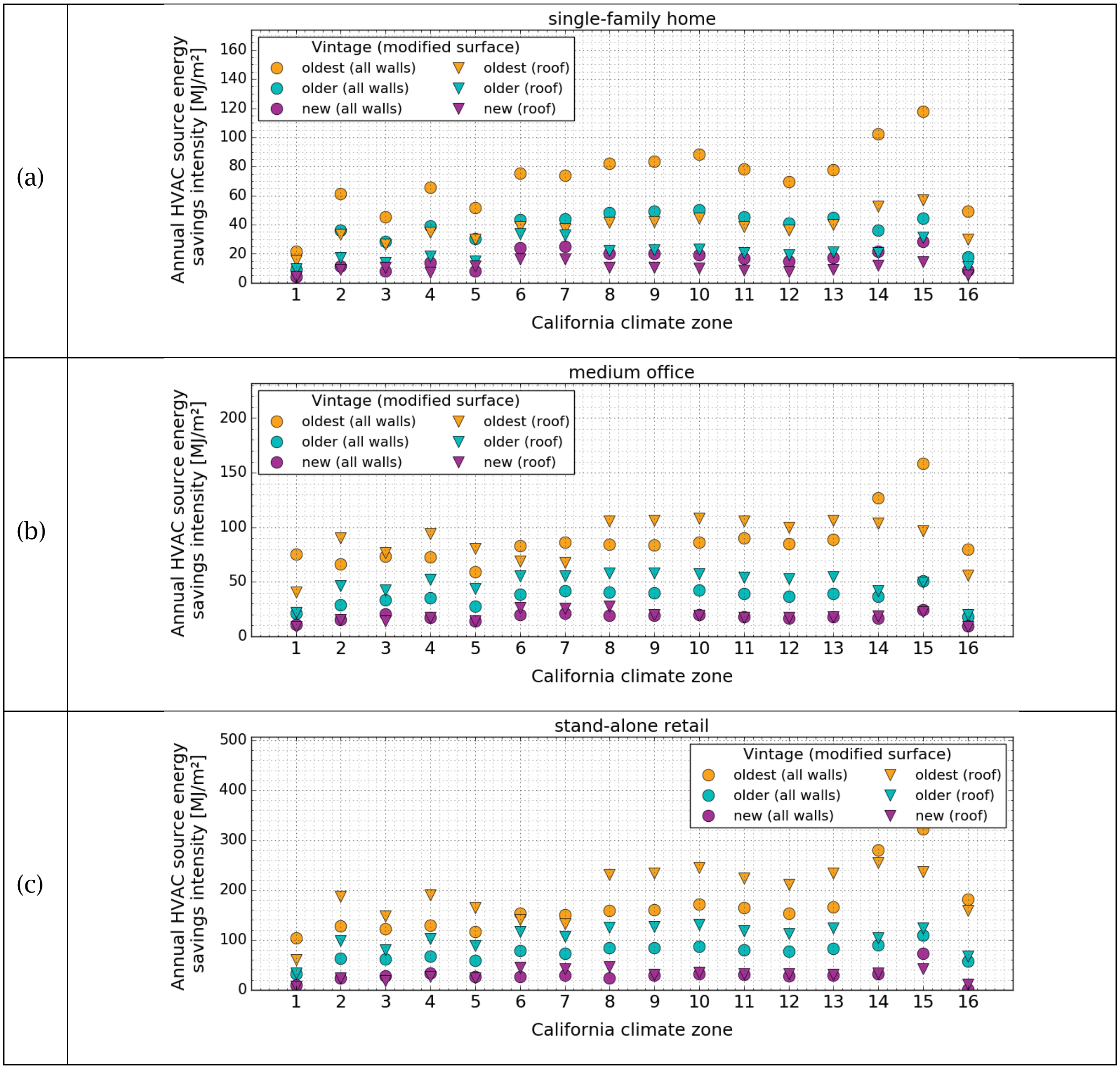


Figure 11. Annual HVAC source energy savings intensity by vintage and by California climate zone for the (a) single-family home, (b) medium office, and (c) retail stand-alone. The plots compare the savings intensity from increasing the albedo of all walls by 0.35 tothat from increasing the roof albedo by 0.30 (residential) or 0.40 (commercial).

The fractional savings (absolute savings / base value) of the energy, energy cost, and emission metrics were influenced not only by the absolute savings but also by the energy consumed in the base case. When comparing cool walls to a cool roof, the differences in fractional savings were driven by the envelope characteristics (e.g., differences in surface albedo change and in insulation) as well as by the envelope geometry (e.g., ratio of roof area to net wall area).

Figure 12 shows the annual HVAC source energy fractional savings by vintage and by California climate zone for the single-family home (Figure 12a), medium office (Figure 12b), and stand-alone retail (Figure 12c). For the single-family home (Figure 12a), CACZ 7 (San Diego) had the greatest cool walls and cool roof fractional savings in all vintages, reaching up to 25 percent (oldest vintage) when all walls were made cool and 8.0 percent (oldest vintage) when the roof was made cool. Low requirements for roof and wall insulation helped make annual HVAC source energy savings intensity in CACZ 7 larger than those in the other CACZs. San Diego also experienced fewer CDD18C and HDD18C than other locations, requiring lower-than-average baseline conditioning energy consumption. CACZs 14 (China Lake) and 15 (Imperial) were the locations with the greatest annual HVAC source energy savings intensity, but yielded less than the CA-average annual HVAC energy fractional savings; savings in CACZs 14 and 15 were up to 12 percent (oldest vintage) from when all walls were made cool and 4.0 percent (oldest vintage) when the roof was made cool.

In the single-family home, annual HVAC source energy savings intensity from the walls were about 2 times that of the roof (Figure 11a). However, the HVAC fractional savings from the walls were from 2.2 to 3.3 times that of the roof. The walls-to-roof ratio in fractional savings was greater than the ratio in savings intensity because the net wall area is greater than the roof area. From Table 4, we gather that the net wall area is 1.6 times that of the roof area. Thus, the ratio of wall savings intensity to roof savings intensity adjusted by the wall-to-roof area ratio is $2 \times 1.6 = 3.2$. This adjusted wall-to-roof savings ratio is similar to the ratio of 2.2 to 3.5 we observed for HVAC energy fractional savings Figure 12a.

For the medium office (Figure 12b), we saw once again that CACZ 15 (Imperial), which was the location with greatest annual HVAC energy savings intensity, yielded fractional savings that were close to the average fractional savings for California; fractional savings in CACZ 15 were 3.7 percent (oldest vintage) when all walls were made cool and 3.0 percent (older and oldest vintage) when the roof was made cool.

When analyzing the annual HVAC source energy savings intensity of the medium office (Figure 11b), we observed that in most California climate zones and vintages, the savings intensity from the roof were slightly greater than those from the walls. In the case of fractional savings (Figure 12b) the ratio of roof-to-wall savings were greater than those from the savings intensity. This difference is due in part because the modified roof area is 1.3 times that of the modified net wall area. Although the medium office is three stories high, its large window area (ratio of window to gross wall area = 0.33) gives it more roof area than net wall area.

In the case of retail stand-alone (Figure 12c), the roof-to-wall ratios of annual HVAC fractional savings were even greater than those observed in the medium office. That is because the stand-alone retail is a single-story building with a large footprint (2,290 m^2), and has more than twice as much roof area as wall area (roof area to net wall area ratio = 2.1) (Table 4). Hence, the difference in cool roof fractional savings to those from the cool walls was significantly influenced by the large ratio of roof area to net wall area.

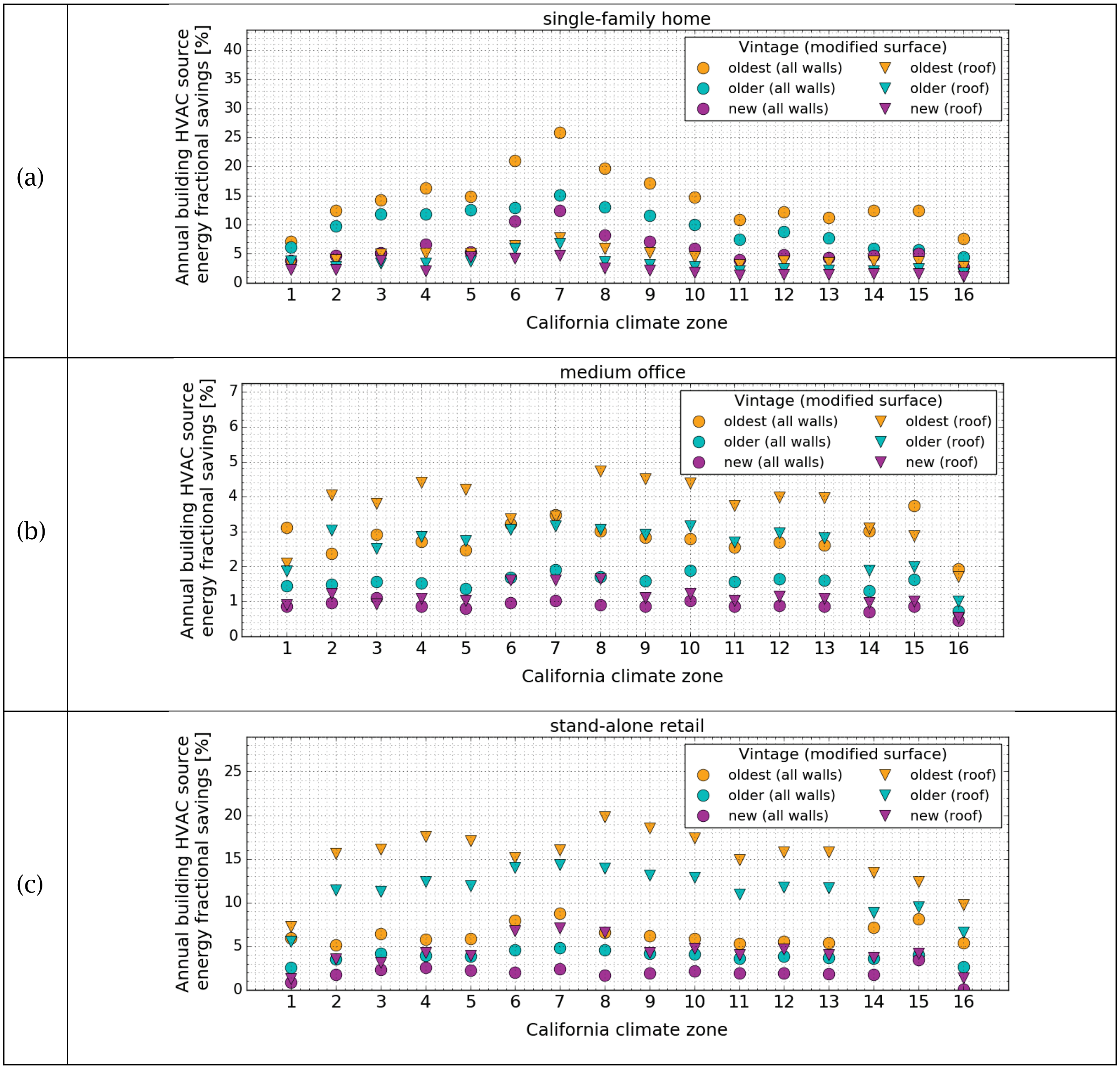


Figure 12. Annual HVAC source energy fractional savings by vintage and by California climate zone for the (a) single-family home, (b) medium office, and (c) retail stand-alone. The plots compare the fractional savings from increasing the albedo of all walls by 0.35 to that from increasing the roof albedo by 0.30 (residential) or 0.40 (commercial).

3.3.3.2 Annual HVAC energy cost savings

Figure 13 shows annual HVAC energy cost savings intensity by vintage and by California climate zone for the single-family home (Figure 13a), medium office (Figure 13b), and stand-alone retail (Figure 13c). These annual HVAC energy cost savings intensities were computed using Eq. (9) and California's electricity and gas prices from Table 18. For the single-family home, we used the prices for residential buildings; for the medium office and retail stand-alone, we used the prices for commercial buildings.

The annual HVAC energy cost savings intensities show the same trend between California climate zones and between vintages that those we observed for the HVAC source energy savings intensities. The proportions of cool roof energy cost savings intensities to those from cool walls were very similar to those we observed for annual HVAC energy savings intensities. These similarities happen because HVAC energy cost savings intensities and HVAC energy savings intensities are affected equally by climate (i.e., solar radiation, CDD18C, and HDD18C) and building properties (i.e., envelope insulation).
In the single-family home (Figure 13a), cool walls generated greater annual HVAC energy cost savings intensities than did cool roof. The greatest annual HVAC energy cost savings intensities when all walls were made cool were \$1.7/m² (oldest, CACZ 15, Imperial) and \$1.5/m² (oldest; CACZ 14, China Lake). CACZ 1 (Arcata) yielded the smallest annual HVAC energy cost savings intensities. The cool wall HVAC energy cost savings intensity from the oldest vintage were on average, 4.5 times that those of the new vintage (Table 25). In the case of older single-family home, the HVAC energy cost savings intensity were about 2.4 times that of the new vintage (Table 26).

Note that for a given building category and vintage, the only difference between locations in wall construction is the climate-specific insulation requirements. Thus, the variations in wall thermal resistance between locations stem from the insulation requirements. In the oldest medium office (Figure 13b), the wall thermal resistance was smaller in CACZs 1, 6-7, and 14-16 than in the other California climate zones. These locations with lower wall thermal resistance yielded wall annual HVAC energy cost savings intensities greater than those from the roof. For the medium office, the cool wall annual HVAC energy cost savings intensity from the oldest vintage was on average 5.1 times those of the new vintage (Table 25). The annual HVAC energy cost savings intensity from the older vintage was on average, 2.0 times that of the new vintage (Table 26).

Trends for the stand-alone retail (Figure 13c) were similar to those observed for the medium office because the roof and wall thermal resistances of these two buildings were nearly identical. However, the wall annual HVAC energy cost savings throughout California from the oldest vintage were on average 5.8 times that of the new vintage (Table 25); the wall savings from the older vintage were on average 3.6 times that of the new vintage (Table 26). Oldest-to-new and older-to-new savings ratios of the stand-alone retail were greater than those of the medium office even though the insulation between the retail stand-alone and medium office were mostly identical. That is because the air conditioner efficiency in the stand-alone retail increased 23 percent between the old vintages and the new vintage, while in the medium office, the air conditioner efficiency increased only 5.0 percent (Table 5).

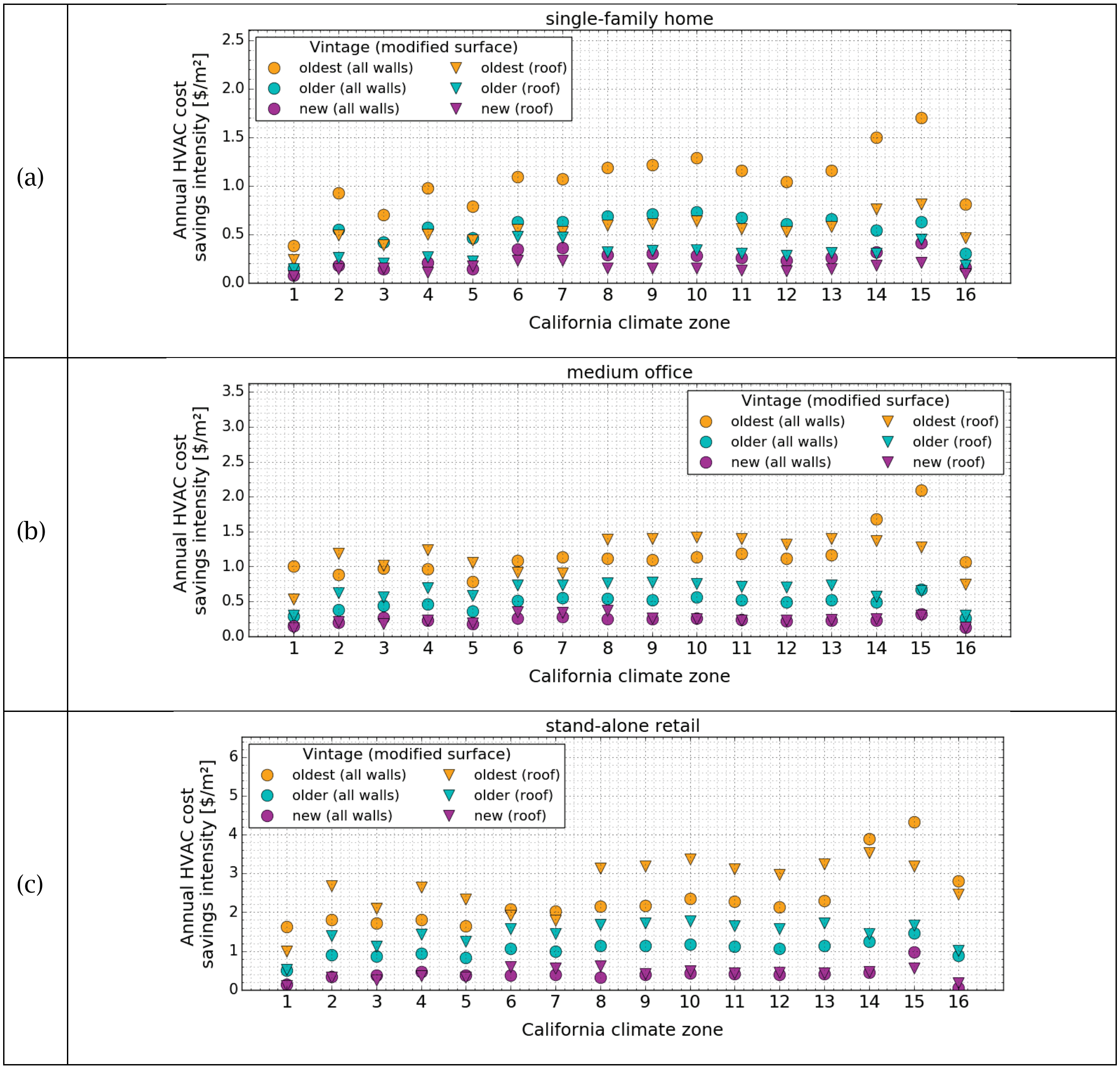


Figure 13. Annual HVAC energy cost savings intensity by vintage and by California climate zone for the (a) single-family home, (b) medium office, and (c) retail stand-alone. The plots compare the savings intensity from increasing the albedo of all walls by 0.35 to that from increasing the roof albedo by 0.30 (residential) or 0.40 (commercial).

Figure 14 shows HVAC energy cost fractional savings by vintage and by California climate zone for the single-family home (Figure 14a), medium office (Figure 14b), and stand-alone retail (Figure 14c). Similar to what we observed between annual HVAC source energy and energy cost savings intensities, the annual HVAC source energy and energy cost savings intensities are affected equally by climate and building properties (Section 3.3.3.1).

For the single-family home (Figure 14a), CACZ 7 (San Diego) had the greatest cool walls and cool roof fractional savings in all vintages, reaching up to 27 percent (oldest vintage) when all walls were made cool and 8.5 percent (oldest vintage) when the roof was made cool. Low requirements for roof and wall insulation and small base HVAC energy cost helped make annual HVAC energy cost fractional savings in CACZ 7 larger than those in the other California climate zones. CACZs 14 (China Lake) and 15 (Imperial) were the locations with the greatest annual HVAC energy cost savings intensities, but yielded less than CA-averaged energy cost fractional savings; savings in CACZs 14 and 15 were up to 14 percent (oldest vintage) from when all walls were made cool and 4.0 percent (oldest vintage) when the roof was made cool.

In the single-family home (Figure 14a), the annual HVAC energy cost fractional savings from the walls were from 2.0 to 3.3 times that of the roof. These wall-to-roof ratios of fractional savings were greater than those of savings intensities due to the wall area being 1.64 times that of the roof.

In the oldest medium office (Figure 14b), the wall thermal resistance was greater in CACZs 2-5 and 8-13, when compared to the other California climate zones. These locations with more wall thermal resistance yielded roof annual HVAC energy cost fractional savings that were greater than those from the walls. This three-story building has more roof area than net wall area (ratio 1.3), which further increased the roof-to-wall ratio of annual HVAC energy cost fractional savings.

For the medium office (Figure 14b), the greatest cool roof annual HVAC energy cost fractional savings was 4.8 percent and occurred from the oldest vintage in CACZ 8 (Fullerton). In the case of walls, the greatest annual HVAC energy cost fractional savings was 3.8 percent and occurred from the oldest vintage in CACZ 15 (Imperial).

As discussed earlier, the roof-to-wall ratios of HVAC fractional savings in the retail stand-alone (Figure 14c) were even greater than those observed in the medium office, even though both buildings have nearly identical envelope thermal resistances in all locations. That is because the stand-alone retail is a single-story building with a very large footprint (2,290 m^2), and has more than twice as much roof area as wall area (ratio of roof area to net wall area = 2.1) (Table 4).

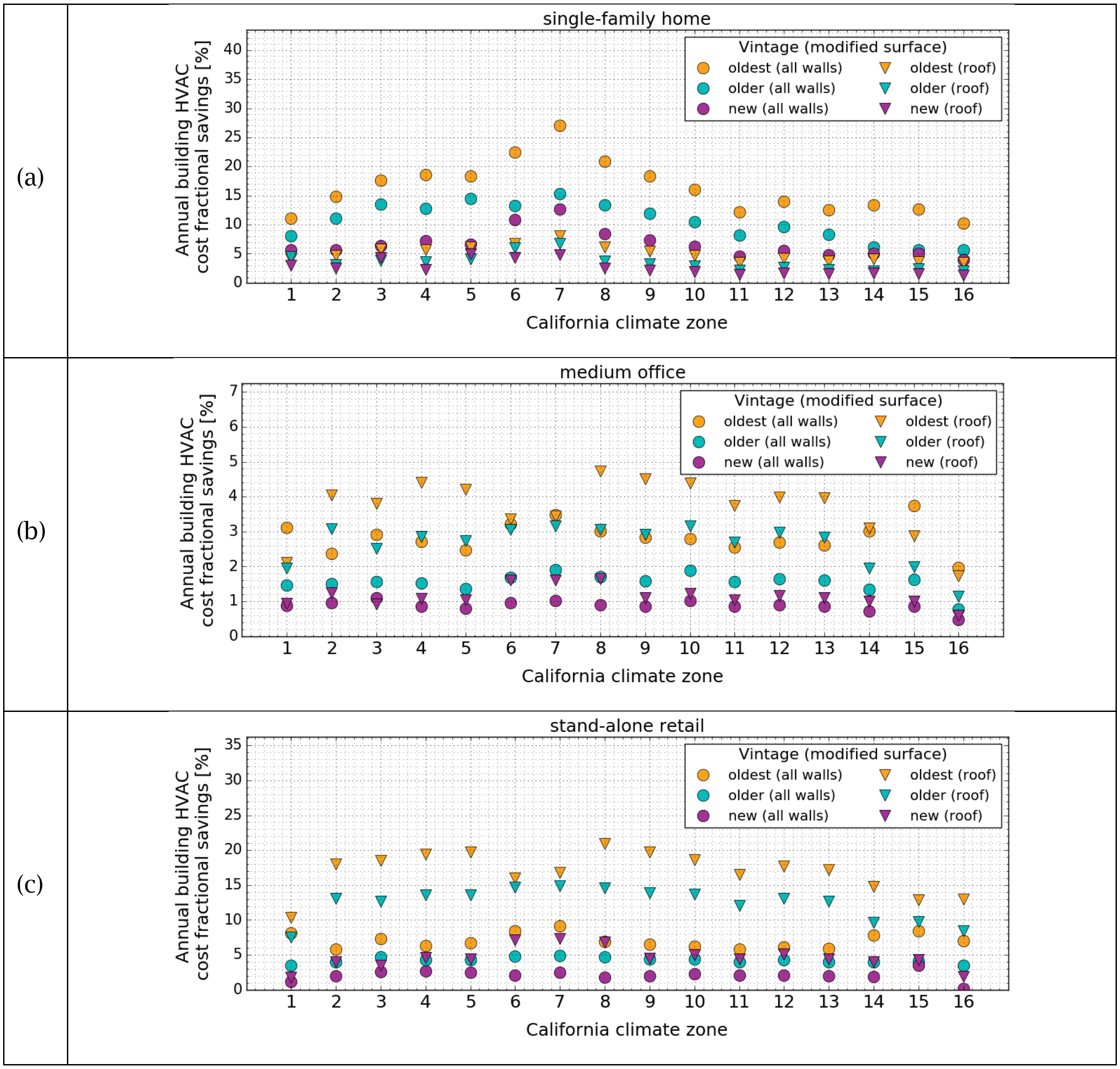


Figure 14. Annual HVAC energy cost fractional savings by vintage and by California climate zone for the (a) single-family home, (b) medium office, and (c) retail stand-alone. The plots compare the fractional savings from increasing the albedo of all walls by 0.35 to that from increasing the roof albedo by 0.30 (residential) or 0.40 (commercial).

3.3.3.3 Annual CO_2e emissions reduction

Figure 15 shows annual CO_2e emissions reduction intensities by vintage and by California climate zone for the single-family home (Figure 15a), medium office (Figure 15b), and stand-alone retail (Figure 15c). These emissions reduction intensities were computed using Eq. (8) and California's CO_2e emissions rate of generated electricity (Table 16) and of consumed gas (Table 17). This study included calculations of CO_2, which are available in the savings database.

The annual CO_2e emissions reduction intensities exhibit the same trend between California climate zones and between vintages that those we observed for the annual HVAC source energy and energy cost savings intensities. The ratios of cool roof CO_2e reduction intensities to those from cool walls were very similar to those we observed for annual HVAC energy and energy cost savings intensities. These similarities happen because emissions reduction intensities, HVAC source energy savings intensity, and energy cost savings intensities are affected equally by climate (i.e., solar radiation, CDD18C, and HDD18C) and building properties (i.e. envelope insulation) (see Section 3.3.3.1).

In the single-family home (Figure 15a), the walls generated higher annual CO_2e emissions reduction intensities than did the roof. The greatest CO_2e emissions reduction intensities were 3.3 kg/m² (oldest, CACZ 15, Imperial) and 2.6 kg/m² (oldest; CACZ 14, China Lake). CACZ 1 (Arcata) and CACZ 16 (Mount Shasta) yielded the smallest annual CO_2e emissions reduction intensities. In California, the four-wall CO_2e emissions reduction intensity from the oldest vintage was on average, 5.4 times that of the new vintage (Table 25). In the case of older single-family home in California, the CO_2e emissions reduction intensity was on average, 3.1 times that of the new vintage (Table 26).

As noted earlier, the wall thermal resistance in the oldest medium office was smaller in CACZs 1, 6-7, and 14-16 than in the other CACZs (Figure 15b). These locations with less wall thermal resistance yielded wall CO_2e emissions reduction intensities greater than those from the roof. For the medium office in California, the wall CO_2e emissions reduction intensity from the oldest vintage were on average, 5.1 times that of the new vintage (Table 25). The CO_2e emissions reduction intensity from the older vintage were on average, 2.0 times that of the new vintage (Table 26).

In the stand-alone retail (Figure 15c), the greatest annual CO_2e emissions reduction intensities were 9.3 kg/m² (oldest, CACZ 15, Imperial) and 7.5 kg/m² (oldest; CACZ 14, China Lake). CACZ 1 (Arcata) and CACZ 16 (Mount Shasta) yielded the smallest annual CO_2e emissions reduction intensities. For the stand-alone retail in California, the wall CO_2e emissions reduction intensities from the oldest vintage were 6.0 times that of the new vintage (Table 25); the wall emissions reduction from the older vintage were on average, 2.7 times that of the new vintage (Table 26).

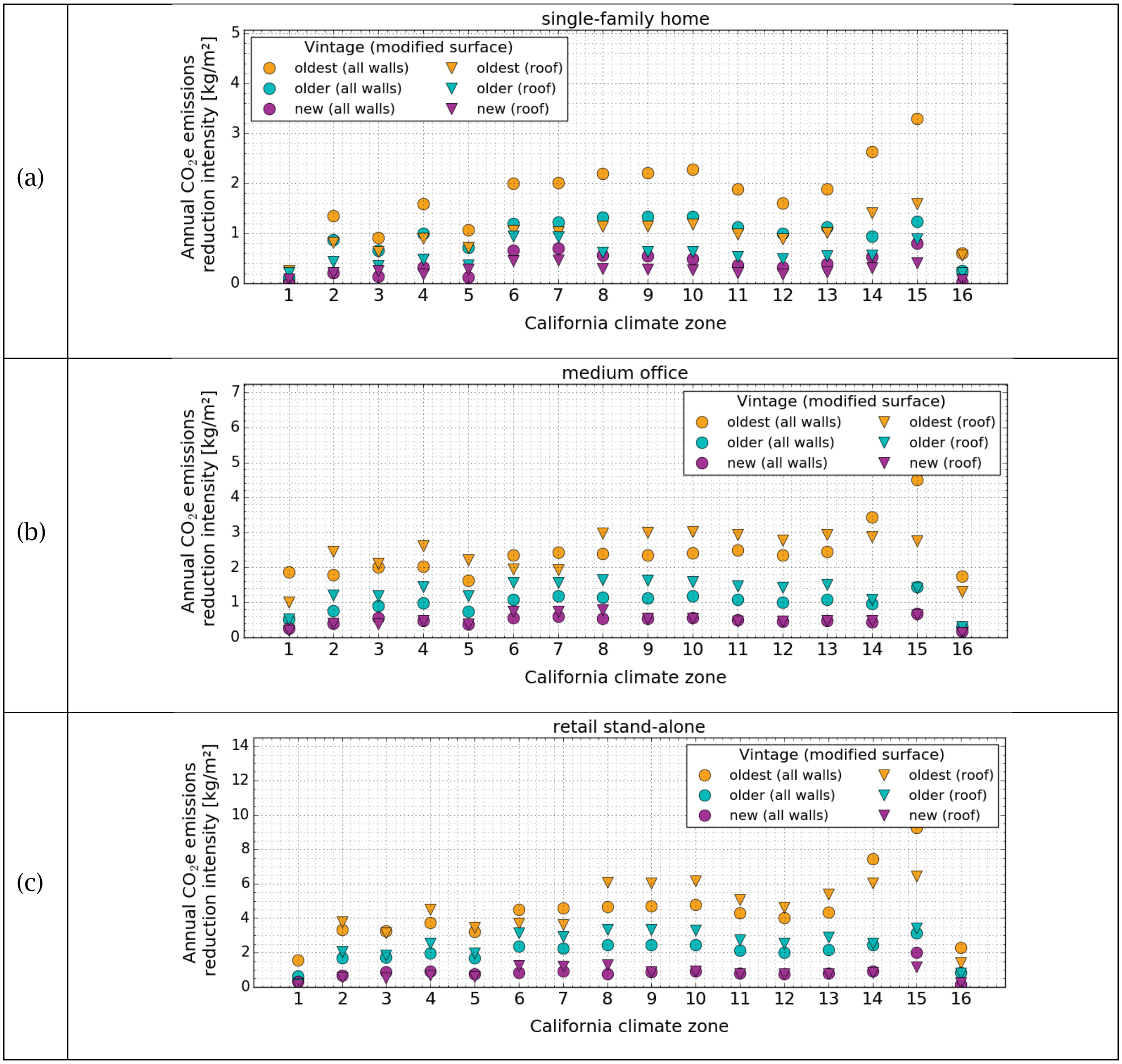


Figure 15. Annual CO_2e emissions reduction intensity by vintage and by California climate zone for the (a) single-family home, (b) medium office, and (c) retail stand-alone. The plots compare the reduction intensity from increasing the albedo of all walls by 0.35 to that from increasing the roof albedo by 0.30 (residential) or 0.40 (commercial).

Figure 16 shows fractional reductions in CO_2e emissions by vintage and by California climate zone for the single-family home (Figure 16a), medium office (Figure 16b), and stand-alone retail (Figure 16c). The annual CO_2e emission fractional reductions have the same trend between California climate zones and between vintages that those we observed for the annual HVAC source energy and energy cost fractional savings. The ratios of cool roof CO_2e fractional reductions to those from cool walls were very similar to those we observed for annual HVAC energy and energy cost fractional savings. These similarities happen because emissions fractional reduction, HVAC source energy fractional savings, and HVAC energy cost fractional savings are affected equally by climate (i.e., solar radiation, CDD18C, and HDD18C) and building properties (i.e. envelope insulation, envelope geometry) (see in Section 3.3.3.1).

In all vintages of the single-family home (Figure 16a), CACZ 7 (San Diego) had the greatest cool walls and cool roof fractional savings of annual CO_2e emissions, reaching up to 23 percent (oldest vintage) when all walls were made cool and 7.0 percent (oldest vintage) when the roof was made cool. Low requirements for roof and wall insulation and small base whole-building CO_2e emissions helped make annual fractional savings of CO_2e emissions in CACZ 7 larger than those in the other California climate zones.

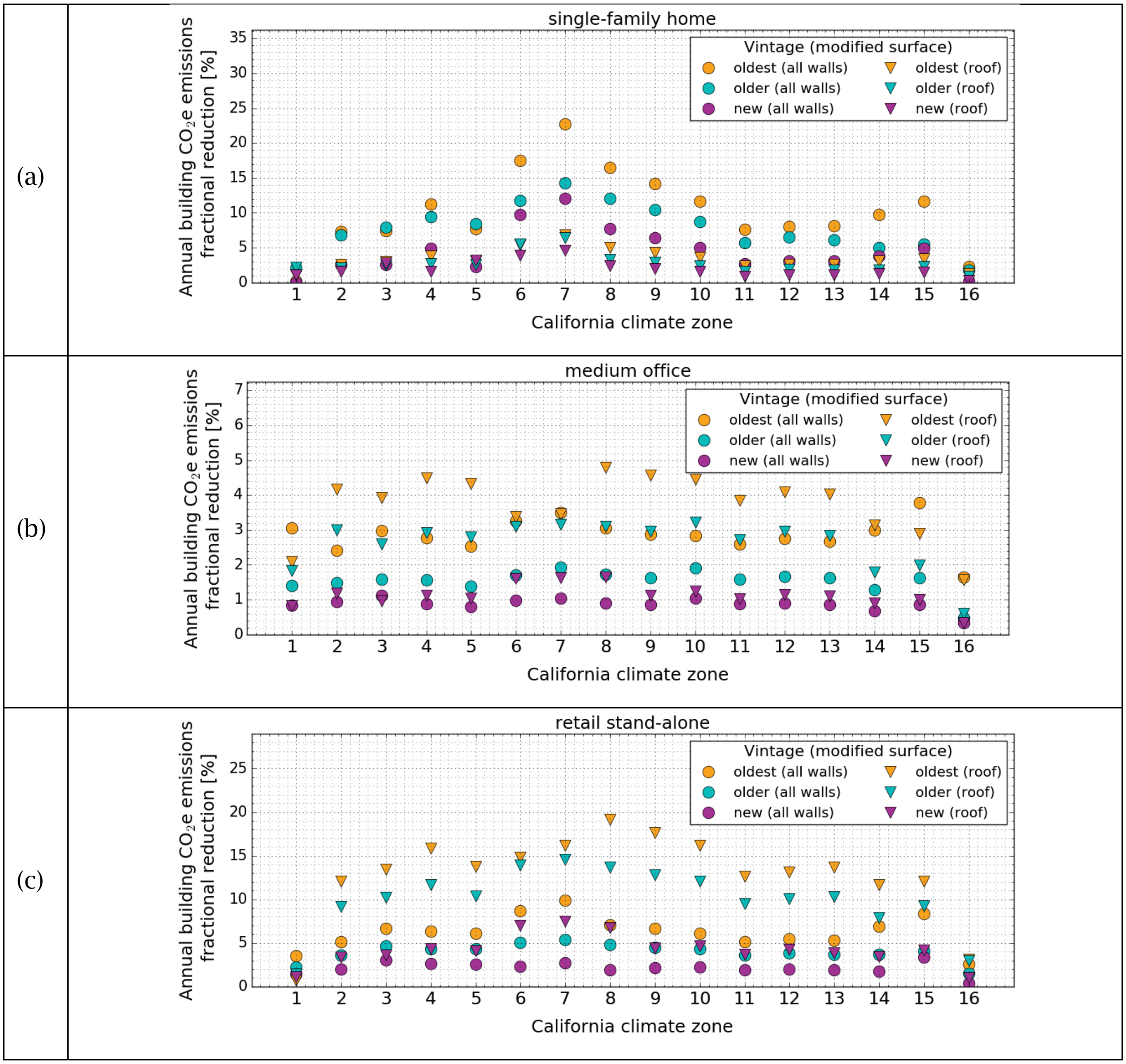


Figure 16. Annual CO_2e emissions fractional reduction by vintage and by California climate zone for the (a) single-family home, (b) medium office, and (c) retail stand-alone. The plots compare the fractional reduction from increasing the albedo of all walls by 0.35 to that from increasing the roof albedo by 0.30 (residential) or 0.40 (commercial).

3.3.3.4 Annual NO_x emissions reduction

Figure 17 and Figure 18 show annual NO_X emissions reduction intensities and fractional reductions, respectively, by vintage and by California climate zone for the single-family home (Figure 17a and Figure 18a), medium office (Figure 17b and Figure 18b), and stand-alone retail (Figure 17c and Figure 18c). These emissions reduction intensities were computed using Eq. (8) and (10), and the fractional reductions were computed using Eq. (8). These emission reductions were calculated using California's NO_x emissions rate of generated electricity (Table 16) and of consumed gas (Table 17).

The annual NO_x emissions reduction intensities and fractional reductions exhibit the same trend between California climate zones and between vintages that those we observed for the annual savings intensity and fractional savings of annual CO_2e emissions. The ratios of cool roof NO_x reductions to those from cool walls were very similar to those we observed for annual CO_2e emissions reductions. These similarities happen because NO_x and CO_2e emission reductions are affected equally by climate (i.e., solar radiation, CDD18C, and HDD18C) and building properties (i.e. envelope thermal resistance) (see Section 3.3.3.1). Fractional savings are also affected by building geometry (e.g., net wall area and roof area).

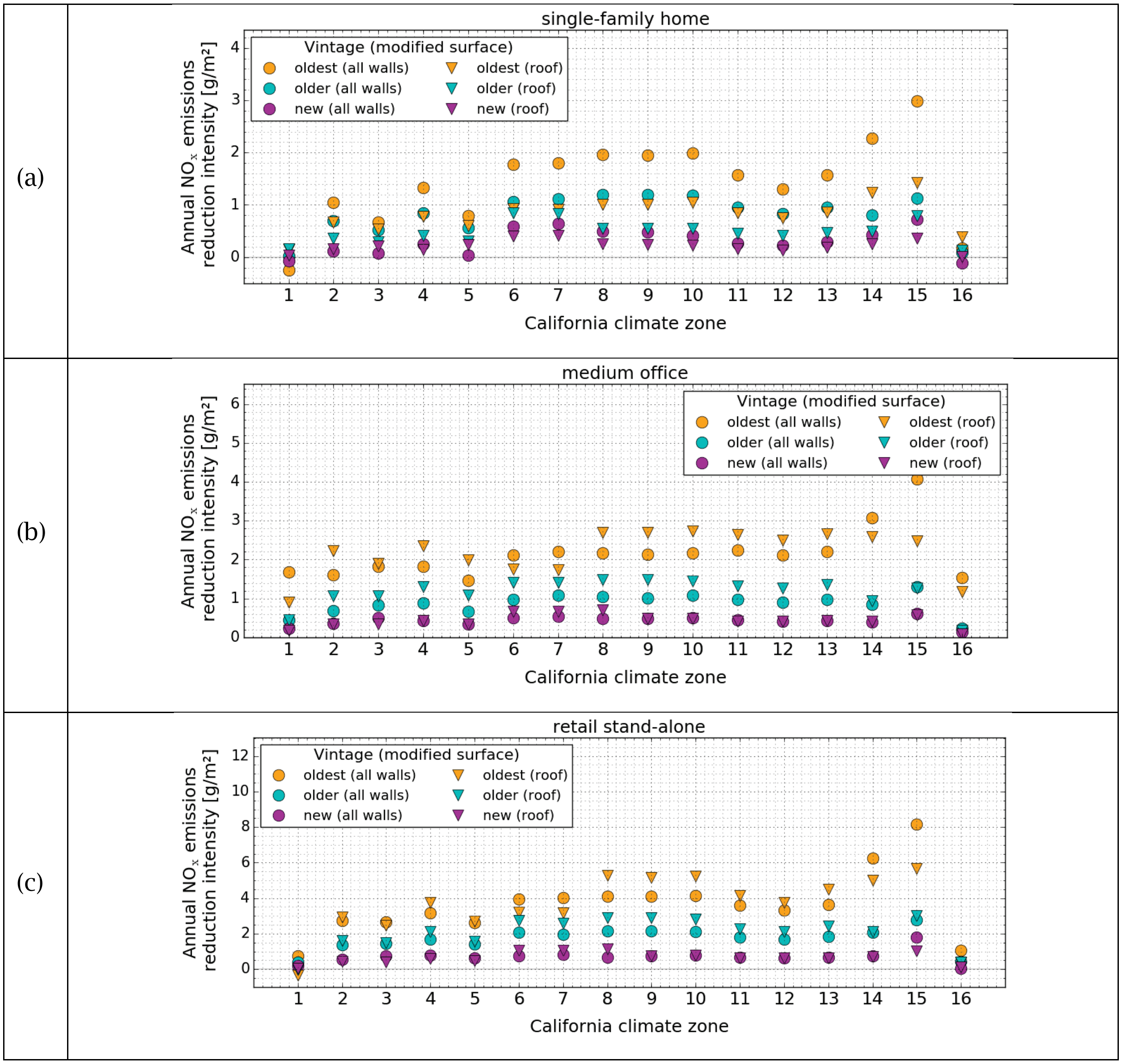


Figure 17. Annual NO_X emissions reduction intensity by vintage and by California climate zone for the (a) single-family home, (b) medium office, and (c) retail stand-alone. The plots compare the reduction intensity from increasing the albedo of all walls by 0.35 to that from increasing the roof albedo by 0.30 (residential) or 0.40 (commercial).

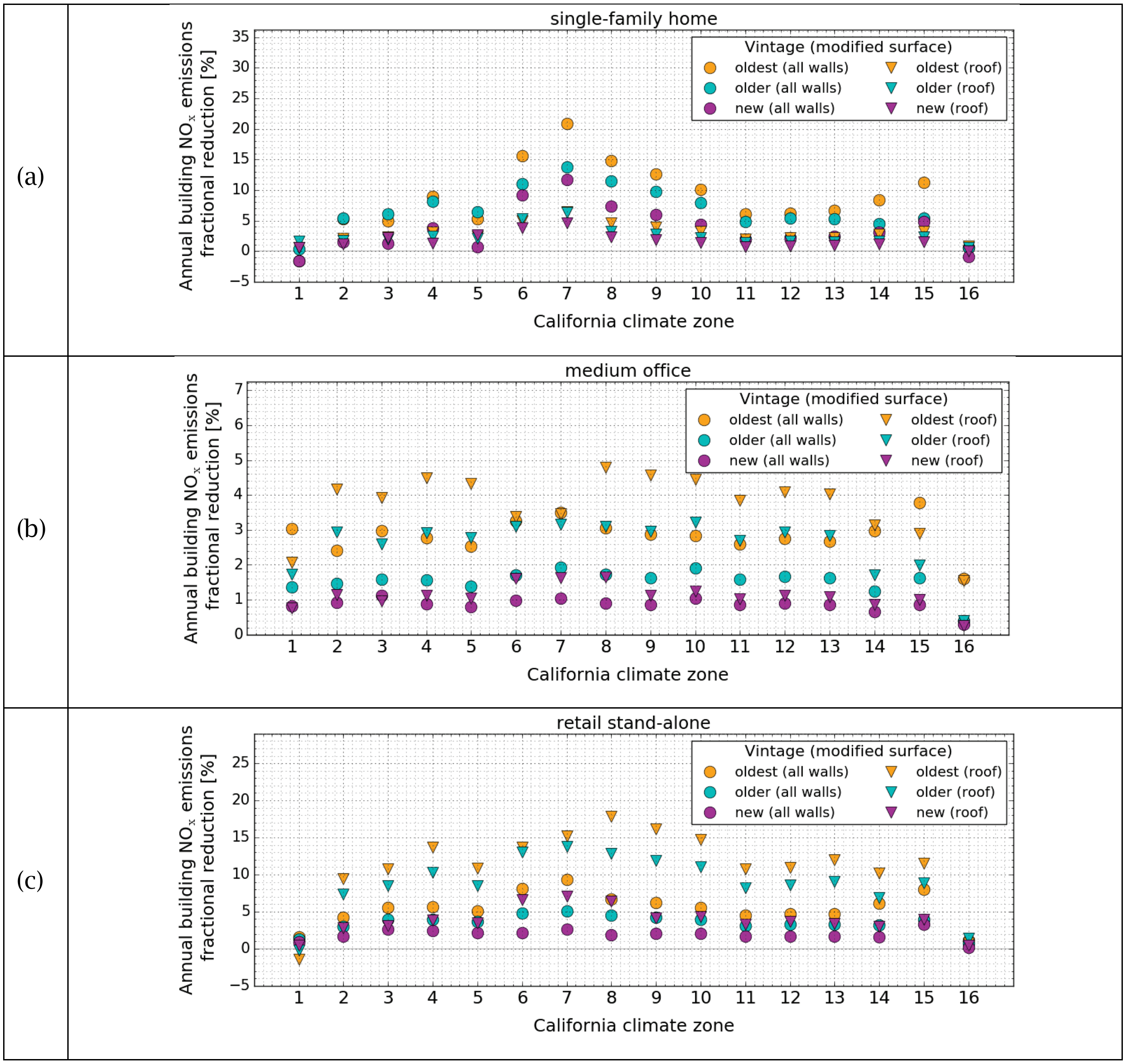


Figure 18. Annual NO_X emissions fractional reduction by vintage and by California climate zone for the (a) single-family home, (b) medium office, and (c) retail stand-alone. The plots compare the fractional reduction from increasing the albedo of all walls by 0.35 to that from increasing the roof albedo by 0.30 (residential) or 0.40 (commercial).

3.3.3.5 Annual SO_2 emissions reduction

Figure 19 and Figure 20 show annual SO_2 emissions reduction intensities and fractional reductions, respectively, by vintage and by California climate zone for the single-family home (Figure 19a and Figure 20a), medium office (Figure 19b and Figure 20b), and stand-alone retail (Figure 19c and Figure 20c). These emissions reduction intensities were computed using Eq. (8) and (10), and the fractional reductions were computed using Eq. (8). These emission reductions were calculated using California's SO_2 emissions rate of generated electricity (Table 16) and of consumed gas (Table 17).

The annual SO_2 emissions reduction intensities and fractional reductions have the same trend between California climate zones and between vintages that those we observed for the annual savings intensity and fractional savings of annual CO_2e emissions. The ratios of cool roof SO_2 reductions to those from cool walls were very similar to those we observed for annual CO_2e emissions reductions. These similarities happen because SO_2 and CO_2e emissions reductions are affected equally by climate (i.e., solar radiation, CDD18C, and HDD18C) and building properties (i.e. envelope thermal resistance) (see Section 3.3.3.1). Fractional savings are also affected by building geometry (e.g., net wall area and roof area).

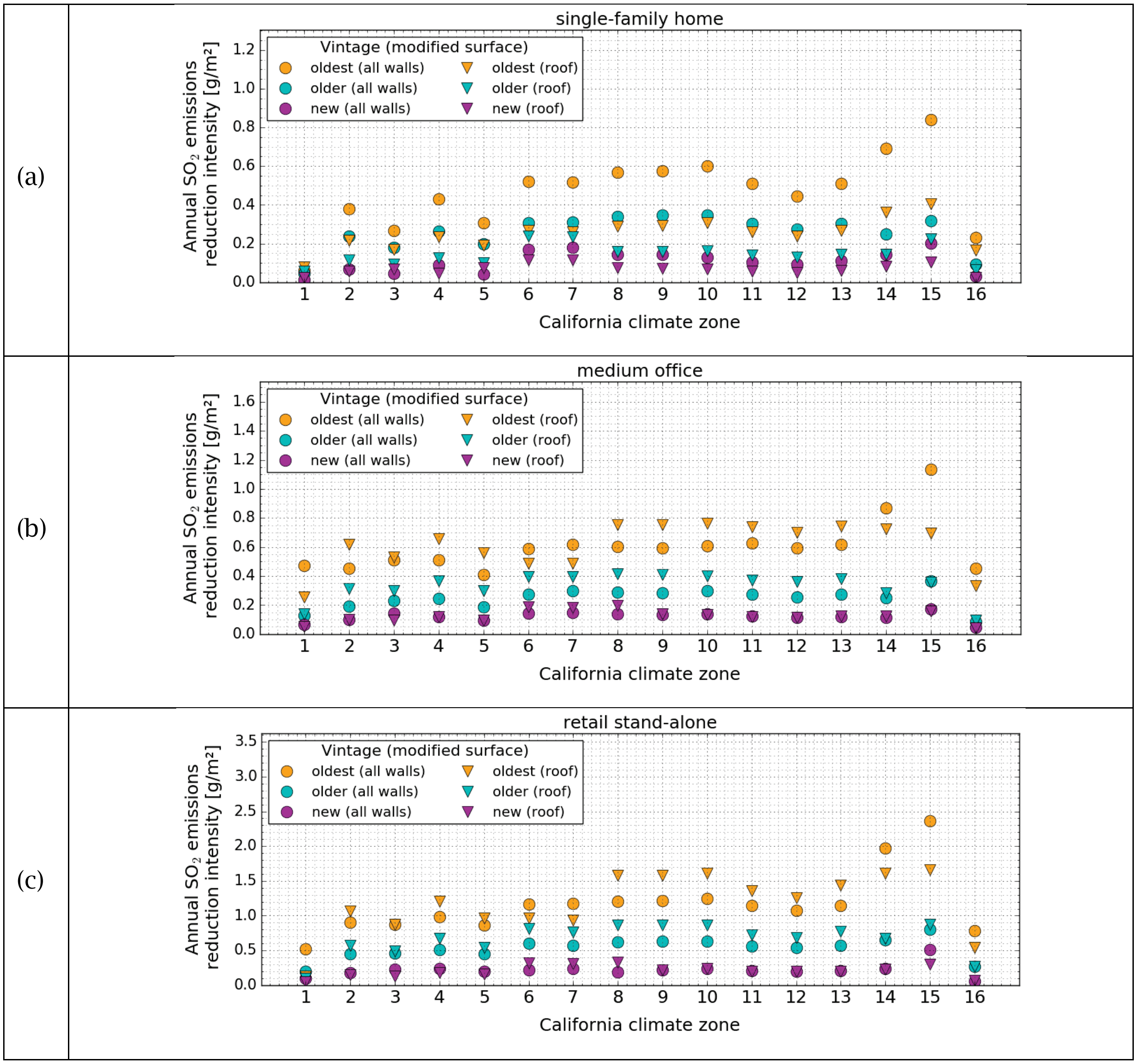


Figure 19. Annual SO_2 emissions reduction intensity by vintage and by California climate zone for the (a) single-family home, (b) medium office, and (c) retail stand-alone. The plots compare the reduction intensity from increasing the albedo of all walls by 0.35 to that from increasing the roof albedo by 0.30 (residential) or 0.40 (commercial).

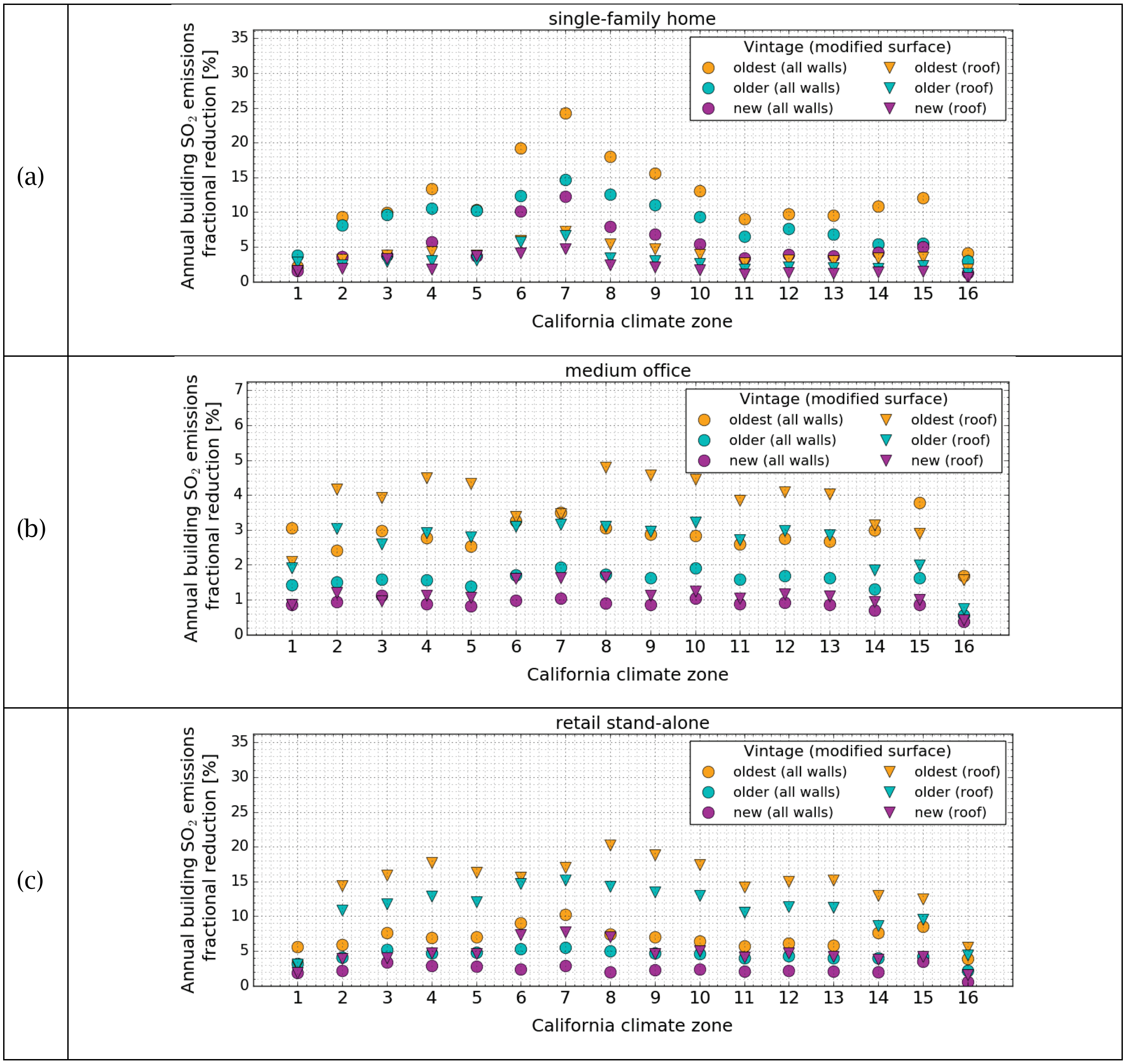


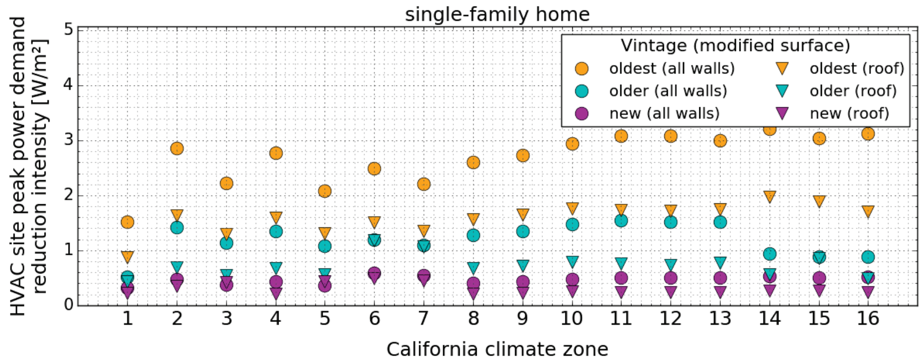
Figure 20. Annual SO_2 emissions fractional reduction by vintage and by California climate zone for the (a) single-family home, (b) medium office, and (c) retail stand-alone. The plots compare the fractional reduction from increasing the albedo of all walls by 0.35 to that from increasing the roof albedo by 0.30 (residential) or 0.40 (commercial).

3.3.3.6 HVAC peak power demand reduction

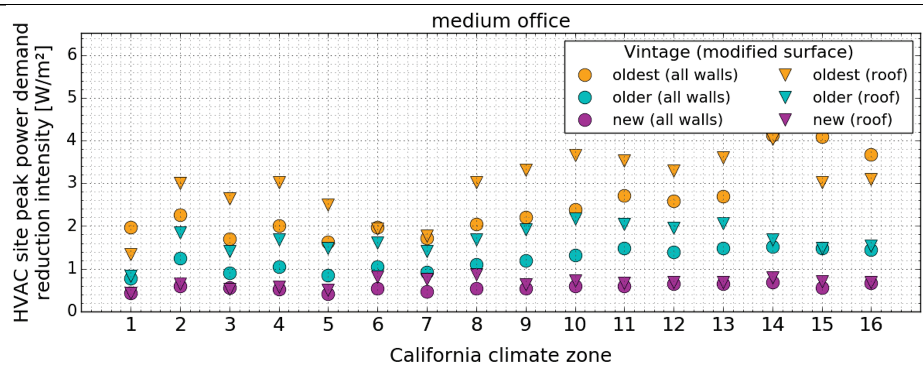
Figure 21 and Figure 22 show annual-average HVAC peak power demand reduction intensity and fractional reduction, respectively, by vintage and by California climate zone for the single-family home (Figure 21a and Figure 22a), medium office (Figure 21b and Figure 22b), and stand-alone retail (Figure 21c and Figure 22c). The peak power demand reduction intensity were computed using Eqs. (7), (10), and (12).

The annual-average HVAC peak power demand reduction intensity and fractional reduction show a similar trend between vintages that those observed for HVAC source energy, energy cost, and emissions. When comparing between California climate zones, the trends observed for peak power demand reduction intensity and fractional reduction are somewhat different than those of HVAC source energy, energy cost, and emissions. These differences in trends happen because HVAC peak power demand is affected only by the summer climate (i.e. peak hours solar radiation and CDD18C), while HVAC source energy, energy cost, and emissions are affected by the annual climate (i.e. solar radiation, CDD18C, and HDD18C).

(a)



(b)



(c)

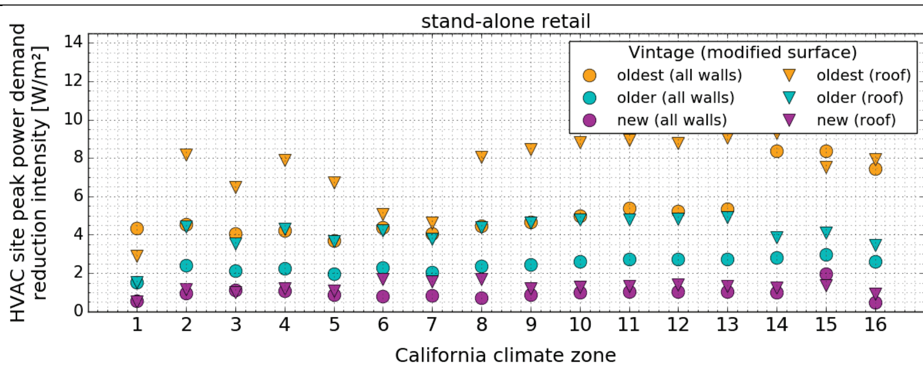


Figure 21. Annual-average HVAC peak power demand reduction intensity by vintage and by California climate zone for the (a) single-family home, (b) medium office, and (c) retail stand-alone. The plots compare the reduction intensity from increasing the albedo of all walls by 0.35 to that from increasing the roof albedo by 0.30 (residential) or 0.40 (commercial).

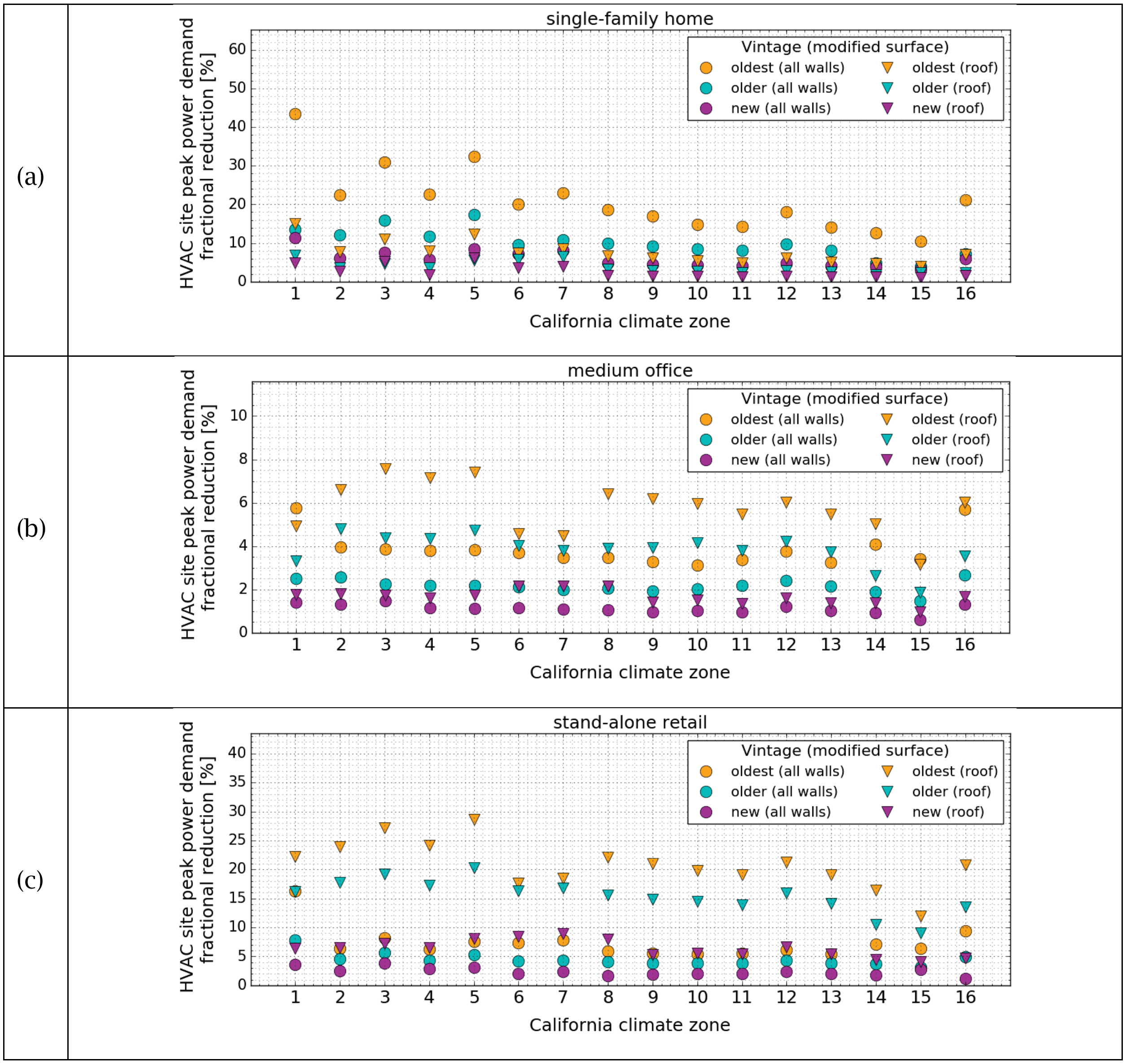


Figure 22. Annual-average HVAC peak power demand fractional reduction by vintage and by California climate zone for the (a) single-family home, (b) medium office, and (c) retail stand-alone. The plots compare the fractional reduction from increasing the albedo of all walls by 0.35 to that from increasing the roof albedo by 0.30 (residential) or 0.40 (commercial).

3.3.3.7 Comparing savings between vintages

Table 25 and Table 26 report oldest-to-new vintage and older-to-new vintage ratios respectively, of annual HVAC source energy savings, emissions reductions, and HVAC energy cost savings. The savings were from increasing the albedo of all walls by 0.35 (to 0.60 from 0.25). The ratios are given by building type and are the mean of both building orientations. The calculations omit ratios that were negative to exclude the few instances where the new vintage generated small annual penalties, while the older and oldest vintages generated annual savings.

In the case of oldest-to-new vintage (Table 25), savings from the oldest vintage were usually between 3.0 to 6.0 times that of the new vintage. In the case of older-to-new vintage (Table 26), savings from the older vintage were typically between 2.0 to 3.0 times that of the new vintage.

Table 25. California average ratios of oldest vintage to new vintage savings by building type and metric. Values are the mean from the two building orientations (east-west and north-south).

	CA average annual savings ratios (oldest-to-new)				
Prototype building	**HVAC source energy [MJ/MJ]**	**CO_2e [kg/kg]**	**NOx [g/g]**	**SO_2 [g/g]**	**HVAC energy cost [$/$]**
Single-family home	4.6	5.4	5.5	5.3	4.5
Apartment building	3.3	3.1	3.1	3.1	3.4
Large hotel	1.7	1.9	1.5	1.7	1.8
Large office	5.2	5.3	5.4	5.3	5.1
Medium office	5.2	5.3	5.3	5.2	5.1
Small office	5.0	4.9	4.9	5.0	5.0
Fast-food restaurant	7.0	5.8	5.8	6.3	7.9
Retail stand-alone	5.8	6.0	5.3	5.9	5.8
Strip mall retail	5.0	5.3	5.2	5.1	5.0
Sit-down restaurant	5.3	6.1	7.6	5.4	5.6

Table 26. California average ratios of older vintage to new vintage savings by building type and metric. Values are the mean from the two building orientations (east-west and north-south).

Prototype building	CA average annual saving ratios (older-to-new)				
	HVAC source energy [MJ/MJ]	CO_2e [kg/kg]	NOx [g/g]	SO_2 [g/g]	HVAC energy cost [$/$]
Single-family home	2.5	3.1	3.5	2.9	2.4
Apartment building	2.0	2.1	2.2	2.1	2.0
Large hotel	1.2	1.2	1.3	1.1	1.2
Large office	2.4	2.4	2.5	2.4	2.4
Medium office	2.0	2.0	2.0	2.0	2.0
Small office	2.2	2.2	2.2	2.2	2.2
Fast-food restaurant	3.0	2.4	2.5	2.6	2.9
Retail stand-alone	2.6	2.7	3.0	2.7	3.6
Strip mall retail	2.5	2.6	2.5	2.5	2.5
Sit-down restaurant	2.4	2.8	4.1	2.5	2.3

3.3.4 Savings from modifying multiple walls simultaneously to sum of savings from modifying same set of walls one at a time (California)

This section compares the savings obtained from modifying a group of walls simultaneously (e.g., east and west) to the sum of the savings from modifying the walls one at a time. These comparisons are presented for whole-building annual values of (a) source cooling savings, (b) heating penalties, (c) fan savings, and (d) HVAC savings. Energy savings and penalties are shown for the new single-family home (Figure 23), new medium office (Figure 24), and new stand-alone retail (Figure 25). The plots include all the 15 wall combinations simulated in each California climate zone; the values are the average of the two building orientations (east-west and north-south).

If the energy savings from simultaneously modifying a group of walls equals the sum of the individual contributions from each wall, we refer to this behavior as the savings being linearly *additive* (hereafter, simply "additive"). These plots help visualize for each prototype and energy metric whether the additive behavior holds for all wall combinations and climate zones. In the plots, the savings of a prototype are additive in all locations if the slope of the linear regression and the coefficient of determination, or R^2, equal unity and the intercept of the regression is zero. (Visually, this means all savings fall along the y=x line.)

In the single-family home, the annual cooling source energy savings were nearly perfectly additive (Figure 23a). In some cases, savings from adding individual walls were slightly smaller than those from a group of walls. In the case of annual heating source energy, the penalties from adding individual walls were typically smaller than those from a modifying a group of walls (Figure 23b). As the number of combined walls increases (e.g., modifying all four walls), the heating savings get less additive. In the case of annual fan source energy, the savings were not additive for just some wall combinations in some of the California climate zones (Figure 23c). The annual HVAC source energy savings were nearly perfectly additive (Figure 23d).

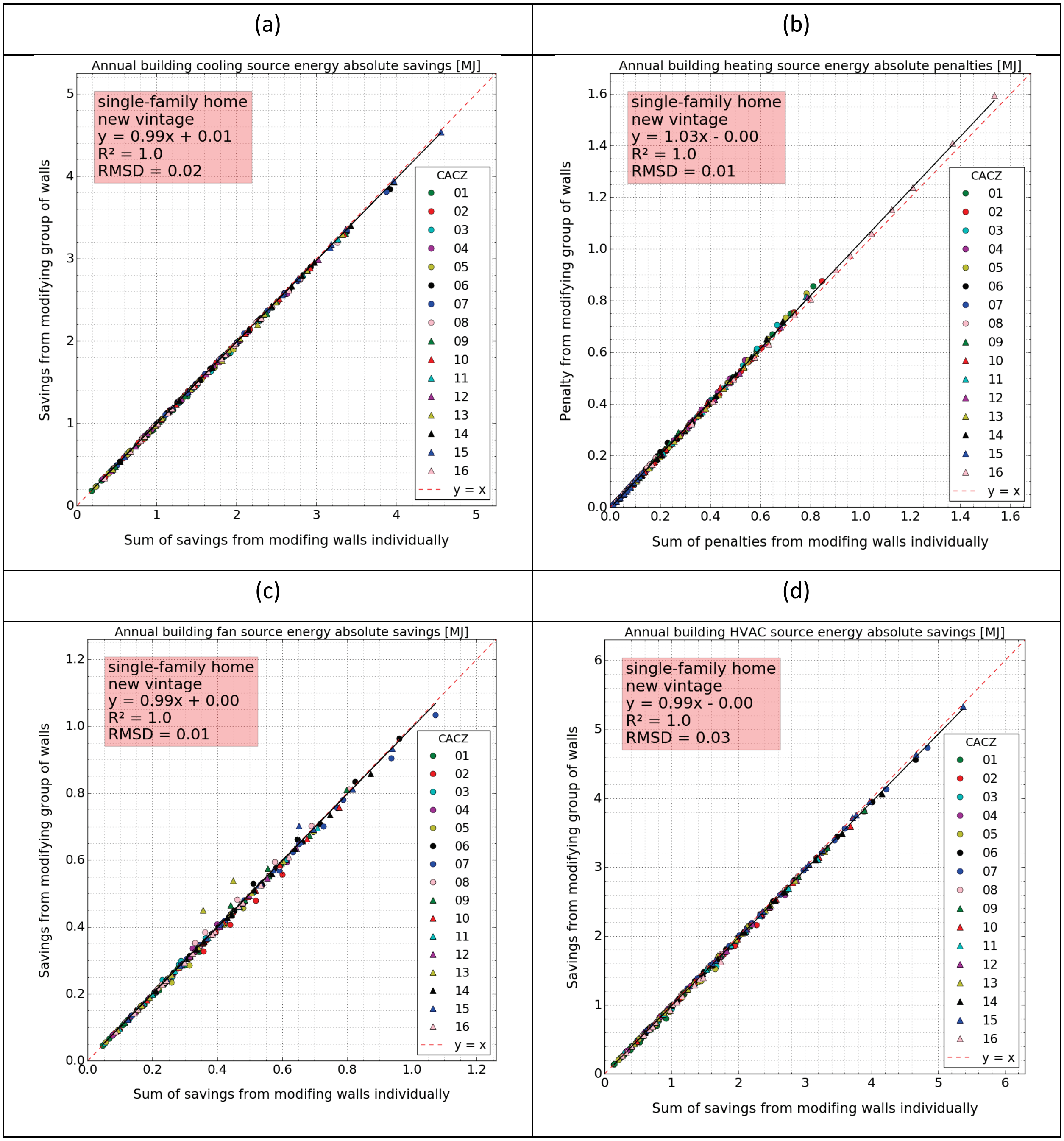


Figure 23. Comparing changes in annual whole-building source energies for the new vintage of single-family home in California climate zones from walls modified one at a time to savings from modifying multiple walls simultaneously. The plots show (a) cooling savings, (b) heating penalties, (c) fan savings, and (d) HVAC savings.

The regressions in the additive test of the medium office were very similar to those of the single-family home. In all California climate zones, the annual cooling source energy savings of the medium office were almost perfectly additive (Figure 24a). In the case of annual heating source energy, the savings and penalties from adding individual walls were close to additive in most California climate zones, except in some wall combinations in CACZ 16 (Mount Shasta) (Figure 24b). Annual fan source energy savings were mostly additive except for a few wall combinations in a few climate zones, most noticeably in CACZ 1 (Figure 24c). The annual HVAC source energy savings were nearly perfectly additive (Figure 24d).

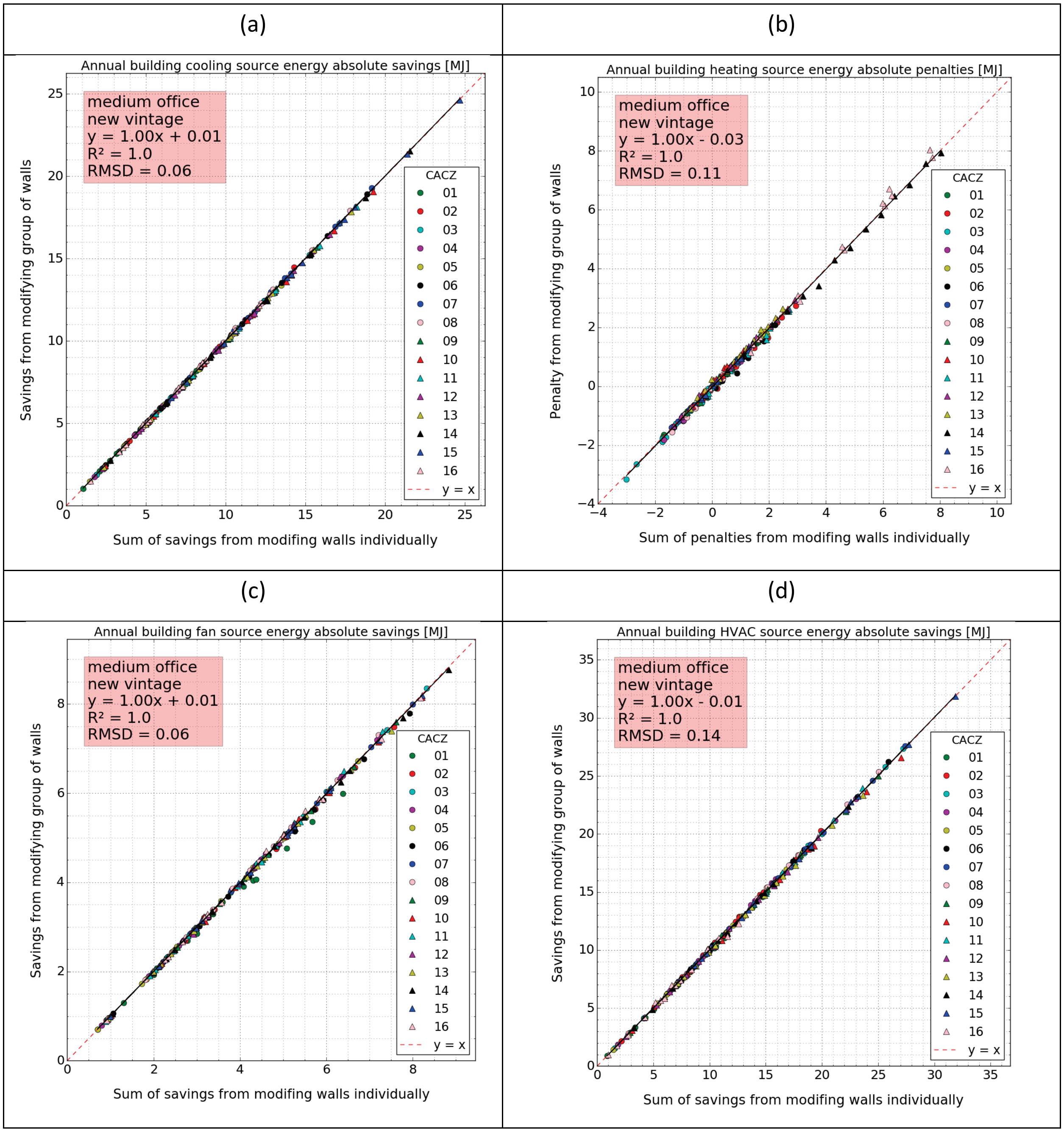


Figure 24. Comparing changes in annual whole-building source energies for the new vintage of medium office in California climate zones from walls modified one at a time to savings from modifying multiple walls simultaneously. The plots show (a) cooling savings, (b) heating penalties, (c) fan savings, and (d) HVAC savings.

Like the medium office, the annual cooling source energy savings of the stand-alone retail were additive, except for two instances of wall combinations in CACZ 8 (Figure 25a). In the case of annual heating source energy, the penalties from adding individual walls were often slightly less than those from modifying a group of walls (Figure 25b). For the case of annual fan source energy savings, some California climate zones were more additive than others; CACZs 4, 5, 6, and 15 had wall combinations that were less additive than in the other California climate zones (Figure 25c).

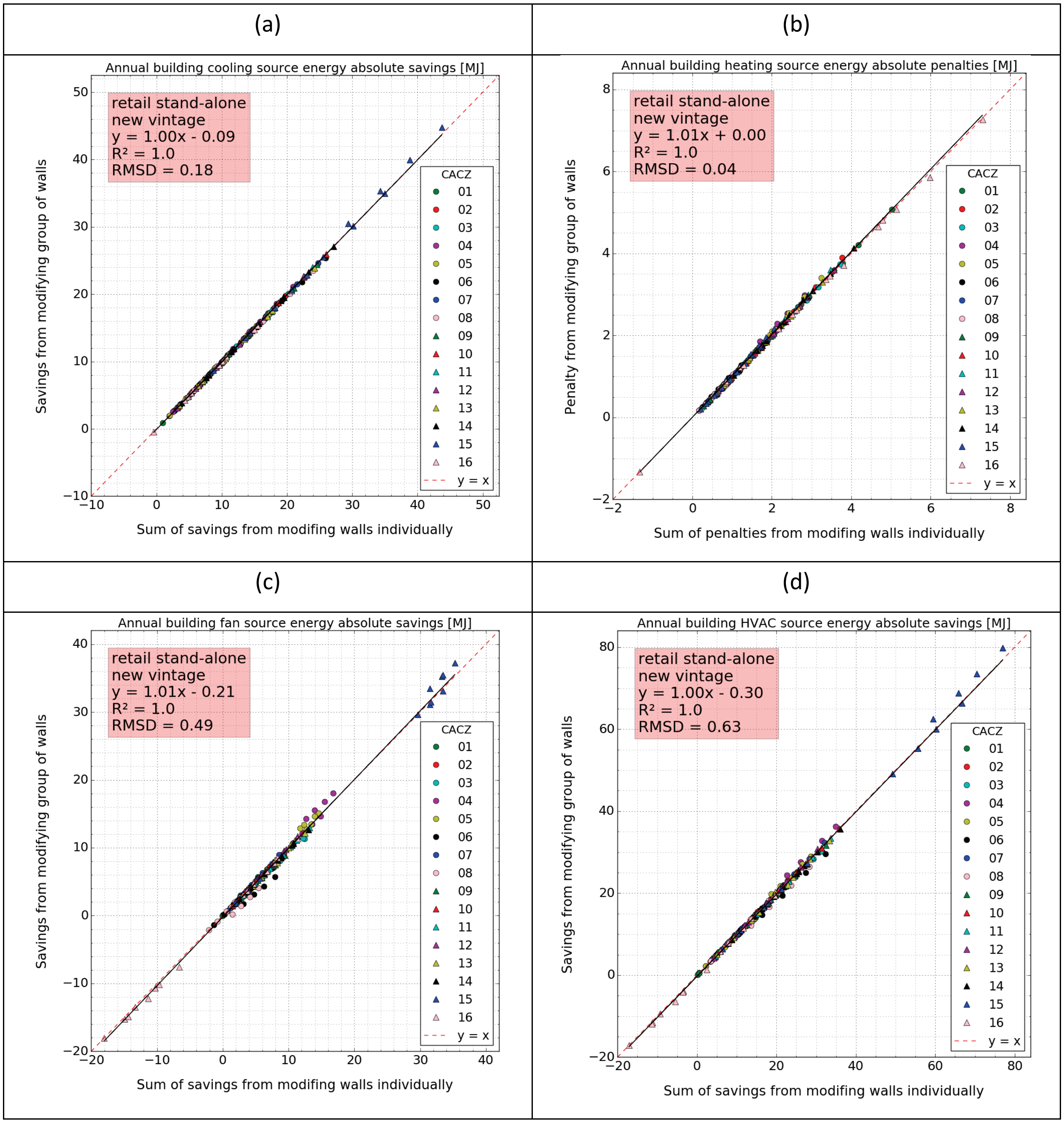


Figure 25. Comparing changes in annual whole-building source energies for the new vintage of stand-alone retail in California climate zones from walls modified one at a time to savings from modifying multiple walls simultaneously. The plots show (a) cooling savings, (b) heating penalties, (c) fan savings, and (d) HVAC savings.

Table 27 summarizes for the California prototypes, the slope, intercept, coefficient of determination (R^2), and root mean square difference (RMSD) of linear regression comparing HVAC source energy savings from modifying multiple walls simultaneously (dependent variable) to the sum of savings from walls modified one at a time (independent variable). The HVAC source energy savings from a given building category are perfectly additive in all locations when the slope = 1, R^2 = 1, and intercept = 0. There was no building category in any vintage in which the HVAC savings were perfectly additive for every wall combination and climate zone.

For almost all prototypes and climate zones in California, annual cooling energy savings were additive. However, for most prototypes, annual heating (electric or gas) energy savings and fan energy savings were additive only in some climate zones and for some wall orientations. Thus, when combining the savings from the different HVAC components (cooling, heating, and fan), there is no prototype in any vintage in which the HVAC system is perfectly additive in all locations and for all wall combinations.

In many prototypes, the fan drew constant load irrespective of changes to cooling or heating load. Therefore, fan energy use lacked any sensitivity to changes in cooling and heating energy changes, which resulted in the fan being non-additive. In these cases, annual HVAC energy changes were close to additive when fan energy was not included.

Table 27. Slope, intercept, coefficient of determination (R^2), and root mean square difference (RMSD) of linear regression comparing HVAC source energy savings from modifying multiple walls simultaneously (dependent variable) to the sum of savings from walls modified one at a time (independent variable). These results include all California climate zones and wall combinations of each prototype, and are the average values from both building orientations (E-W and N-S).

	Regression slope [MJ/MJ]			Regression intercept [MJ]			Coefficient of determination (R^2)			RMSD [MJ]		
Prototype building	**oldest**	**older**	**new**	**oldest**	**older**	**new**	**oldest**	**older**	**new**	**oldest**	**older**	**new**
Single-family home	0.96	0.99	0.99	0.12	0.01	0.00	0.97	1.00	1.00	0.80	0.07	0.03
Apartment building	1.00	1.00	1.00	-0.11	-0.06	-0.02	1.00	1.00	1.00	0.25	0.12	0.05
Large hotel	1.06	1.00	1.00	-3.65	-2.63	-2.88	1.00	1.00	0.99	14.5	7.33	11.4
Large office	1.01	0.99	0.97	1.78	1.60	2.95	1.00	0.99	0.98	12.5	6.60	5.16
Medium office	1.00	0.99	1.00	-0.05	0.11	-0.01	1.00	1.00	1.00	0.65	0.45	0.14
Small office	1.00	0.99	0.99	0.09	0.04	0.02	1.00	1.00	1.00	0.20	0.10	0.06
Fast-food restaurant	0.98	1.00	1.00	0.10	0.03	0.00	0.99	0.99	0.99	0.66	0.18	0.11
Retail stand-alone	1.00	1.00	1.00	-0.12	-0.07	-0.30	1.00	1.00	1.00	1.10	0.39	0.63
Strip mall retail	1.00	1.00	1.01	-0.46	0.05	0.35	1.00	1.00	0.99	1.62	1.41	1.09
Sit-down restaurant	0.98	0.98	1.00	0.15	0.06	0.04	1.00	1.00	0.99	0.54	0.21	0.14

3.4 United States case studies

This section uses some of the U.S. simulations to evaluate the effects of cool walls. As in the California case studies, we discuss outcomes for a single-family home, a medium office building, and a stand-alone retail building, each with a gas furnace. We present cool wall savings from increasing wall albedo by 0.35 (to 0.60 from 0.25) in both residential and commercial buildings, and from increasing roof albedo by 0.30 (to 0.40 from 0.10) in residential buildings and by 0.40 (to 0.60 from 0.20) in commercial buildings.

We compare savings between cool walls and cool roofs, and show how the cool wall savings vary by location, vintage, and combination of modified walls. Finally, we investigate where the sum of savings from walls modified one at a time equals the savings from modifying the same set of walls simultaneously. All savings and penalties shown here are the average values from the two building orientations (east-west and north-south).

3.4.1 United States source energy savings intensity (per unit surface area modified) of the new single-family home by climate zone and modified surface

This section shows the annual source cooling, fan, and HVAC savings intensity and heating penalty intensity of the new single-family home by U.S. climate zone from individually increasing the albedo by 0.35 (to 0.60 from 0.25) of the north wall, east wall, south wall, west wall, and roof, and of the roof by 0.30 (to 0.40 from 0.10). We chose to present the savings of the new single-family home because it is the most common building type in the U.S. and with the most floor area in the country (EIA 2009, EIA 2012). Savings from the older and oldest single-family home show similar behavior to those from the new vintage but of different magnitudes.

3.4.1.1 Source energy changes by United States climate zone

First, note that in the new single-family home, the wall assembly thermal resistance in USCZs 1A, 2A, 2B, 3A, and 4B was R-11.5 (Table 11), which is 71 percent of the R-16.3 that was used in all other U.S. climate zones (R-11.5 / R-16.3 = 71 percent). The roof assembly thermal resistance in USCZs 1A, 2B, and 3A was R-27.6 (Table 13), which is 85 percent of the R-32.4 that was used in USCZs 2A, 3B, 3C, 4B, and 5B (R-27.6 / R-32.4 = 85 percent), and which is 73 percent of the R-37.6 that was used in USCZs 4A, 4C, 5A, 6A, 6B, 7, and 8 (R-27.6 / R-37.6 = 73 percent).

Figure 26 shows annual source values of cooling savings intensity, heating penalty intensity, fan savings intensity, and HVAC savings intensity for the new single-family home in U.S. In every U.S. climate zone, raising wall or roof albedo reduced cooling and fan energy uses (Figure 26a,b) and increased heating energy use (Figure 26b). However, 9 out of 15 U.S. climate zones (USCZs 1A, 2A, 2B, 3A, 3B, 3C, 4A, 4B and 5A) yielded annual HVAC source energy savings intensities from each of the five surfaces (Figure 26d). From these 9 U.S. climate zones, USCZ 2B (Phoenix) benefited the most from cool walls and cool roofs, yielding significantly greater HVAC savings intensities than all other climate zones. USCZ 2B was the climate zone with the most CDD18C (2,800), received the most sunlight, and had few HDD18C (700). Additionally, Phoenix was one of the locations with the lowest wall and roof thermal resistances. USCZ 1A (Miami) had the second largest HVAC savings intensities; it had large CDD18C (2,500) and the fewest HDD18C (100) (Figure 7). In Miami, wall and roof thermal resistances were as low as those from Phoenix. From these 9 U.S. climate zones, USCZ 5A (Peoria) had the smallest HVAC source energy savings intensities; in this location, CDD18C were 5 times that of HDD18C, and had more wall and roof thermal resistances than the other 8 USCZs yielding HVAC savings intensities. USCZs 4C (Seattle), 5B (Boise), and 6A (Burlington) yielded small annual HVAC source energy savings intensities from some surfaces and HVAC source energy penalty intensities from the other surfaces. USCZs 6B (Helena), 7 (Duluth), and 8 (Fairbanks) yielded HVAC source energy penalty intensities from all five surfaces (Figure 26d). All these USCZs that yield HVAC energy penalty intensities experienced significantly more HDD18C than CDD18C. Fairbanks, AK (USCZ 8) had the lowest CDD18C (50) and the highest HDD18C (7,100). Still, USCZ 8 yielded very similar

HVAC source energy penalty intensities than USCZ 6B (Helena), which had 4,150 HDD18C (42 percent less HDD18C than those in USCZ 8). However, the magnitudes of all HVAC source energy savings and penalty intensities from USCZs 4C, 5B, 6A, 6B, 7, and 8 were half or less than the magnitude of those from USCZs 1A (Miami), 2B (Phoenix), 3A (Memphis), and 3B (El Paso) (Figure 26d).

3.4.1.2 Source energy changes by face

As described in Section 3.3.1.2, changes in HVAC energy use are proportional to changes in heat conducted through the building envelope, which in turn scale with changes in wall solar heat gain. Wall solar heat gain depends on orientation. Thus, all else being equal, we expect changes in HVAC energy use to be greater from modified external surfaces that receive more sunlight (solar energy per unit area).

Of all four walls, the north wall was the one that yielded in all U.S. climate zones the lowest annual cooling and fan source energy savings intensities (Figure 26a,c) due to being the face that received the least sunlight. As an example, let us consider USCZ 2B (Phoenix), in which the north wall yields annual cooling source energy savings intensity 30 MJ/m², or 41 percent of that from the east wall (68 MJ/m²). From Table D-19 in Task Report Appendix D, we gather that the summer daily solar irradiation on the north wall was 1.95 kWh/m², which is 47 percent of that from the east wall (4.13 kWh/m²). During winter, the north wall again received the least sunlight, yielding the smallest annual heating source energy penalty intensity (Figure 26b).

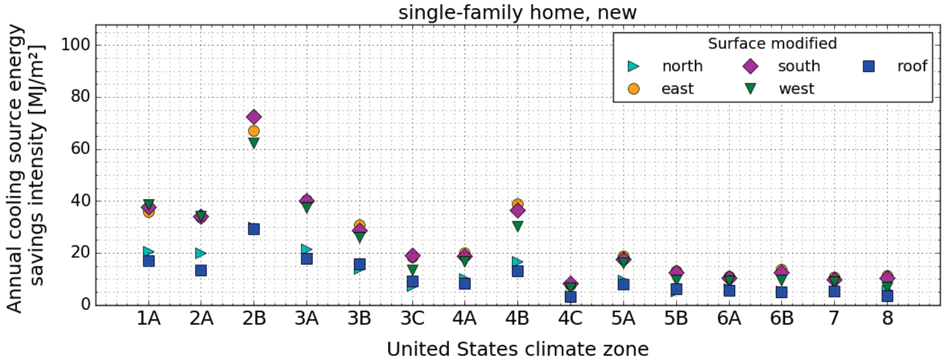
The annual source cooling energy savings intensities from the roof were never greater than those from any of the four walls, and in most cases, were less than those from the east, south, and west walls. However, in all U.S. climate zones, the roof (if assumed to be horizontal) was the face that received the most summer daily solar irradiation (Table 20). The key is that the thermal resistance of the roof is at least twice that of the wall. For example, in USCZs 1A, 3B, and 3A, the thermal resistance of the wall assembly was R-11.5, which is 42 percent of the roof thermal resistance in the roof of the same U.S. climate zones (Table 11 and Table 13). During winter, the annual heating source energy penalties from the roof were once again smaller than those from the east, south, and west walls, and slightly greater than those from the north wall.

The wall that receives the most summer daily solar radiation varied by U.S. climate zone, but was either the east wall or the west wall (Table 20). However, in some locations, the south wall yielded the greatest annual cooling energy savings intensities. In the rest of the U.S. climate zones, either the east or the west wall yielded the greatest annual cooling energy savings intensities. Still, in all locations, the annual cooling energy savings intensities from the east, south, and west walls were very similar.

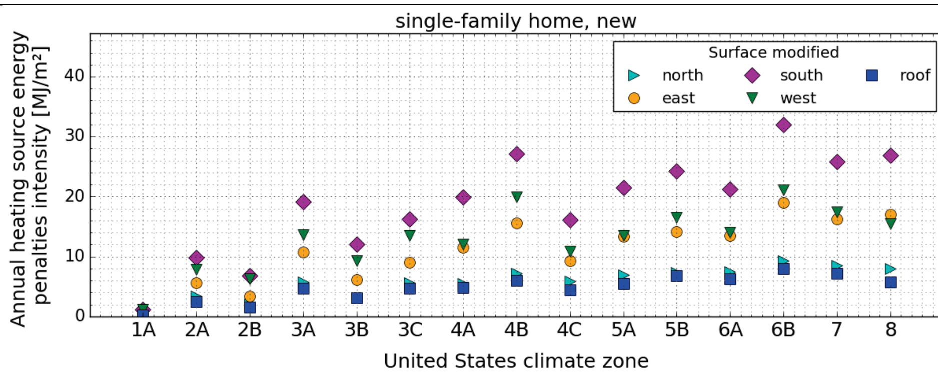
In all U.S. climate zones, the south wall received more sunlight during winter than any of the other surfaces (including the roof) (Table 20). Thus, in all locations, the south wall yielded annual heating source energy penalty intensities greater than those from any of the other faces (Figure 26b).

In the majority of U.S. locations, the south wall received at least as much sunlight in winter as in summer (Table 22). Additionally, from USCZ 4C onward, each location experienced significantly more HDD18C than CDD18C. Thus, the magnitude of the annual heating penalties from the south wall were up to twice as much as the magnitude of the annual cooling savings in locations with cold climates (Figure 26a,b).

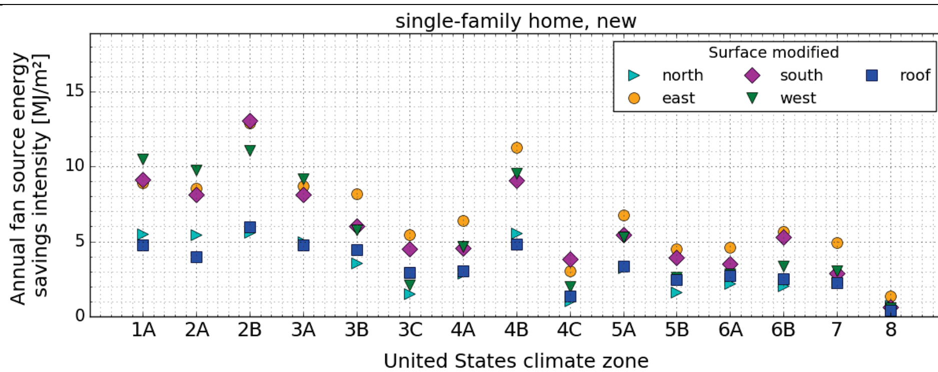
(a)


single-family home, new
Annual cooling source energy savings intensity [MJ/m²]
Surface modified
north
south
roof
east
west
0
20
40
60
80
100
1A 2A 2B 3A 3B 3C 4A 4B 4C 5A 5B 6A 6B 7 8
United States climate zone

(b)


single-family home, new
Annual heating source energy penalties intensity [MJ/m²]
Surface modified
north
south
roof
east
west
0
10
20
30
40
1A 2A 2B 3A 3B 3C 4A 4B 4C 5A 5B 6A 6B 7 8
United States climate zone

(c)


single-family home, new
Annual fan source energy savings intensity [MJ/m²]
Surface modified
north
south
roof
east
west
0
5
10
15
1A 2A 2B 3A 3B 3C 4A 4B 4C 5A 5B 6A 6B 7 8
United States climate zone

(d)

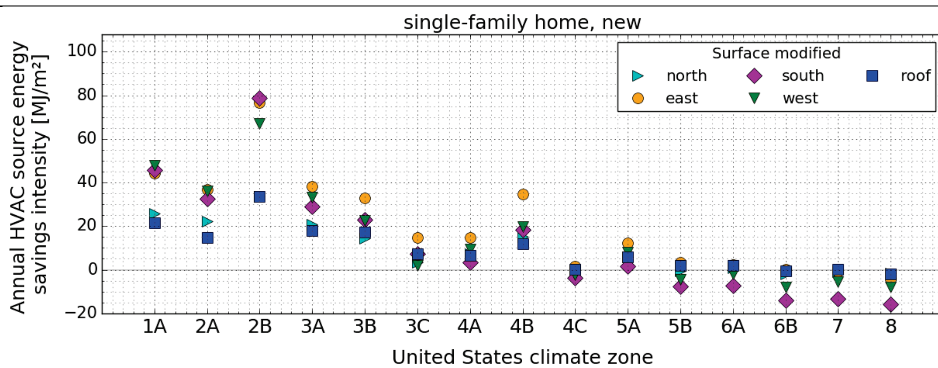

single-family home, new
Annual HVAC source energy savings intensity [MJ/m²]
Surface modified
north
south
roof
east
west
−20
0
20
40
60
80
100
1A 2A 2B 3A 3B 3C 4A 4B 4C 5A 5B 6A 6B 7 8
United States climate zone

Figure 26. Annual source energy savings and penalty intensities of the new single-family home by U.S. climate zone. The plots show (a) cooling savings, (b) heating penalties, (c) fan savings, and (d) HVAC savings.

3.4.2 Correlation of savings in United States to outdoor air temperature and to changes in solar absorptance

Annual cooling savings and heating penalties vary by location, which is in part due to the variation in climate between locations. This section investigates for the oldest single-family home the correlation of the annual cooling savings or heating penalties to two drivers: (a) change in absorbed solar radiation and (b) annual degree days. As done in the California case study, we used the coefficient of determination (R^2) to assess the fractions of variation in savings and penalties that can be explained by either driver.

Figure 27a and Figure 27b show how annual cooling site energy savings intensity from each modified face vary with changes in absorbed summer solar radiation and with annual CDD18C, respectively, in the oldest single-family home. Since the insulation in the building envelope and the efficiency of the air conditioner often vary by location, the changes in absorbed radiation were normalized by the face's thermal resistance and by the cooling efficiency (Figure 27a). Annual CDD18C were normalized in the same manner (Figure 27b).

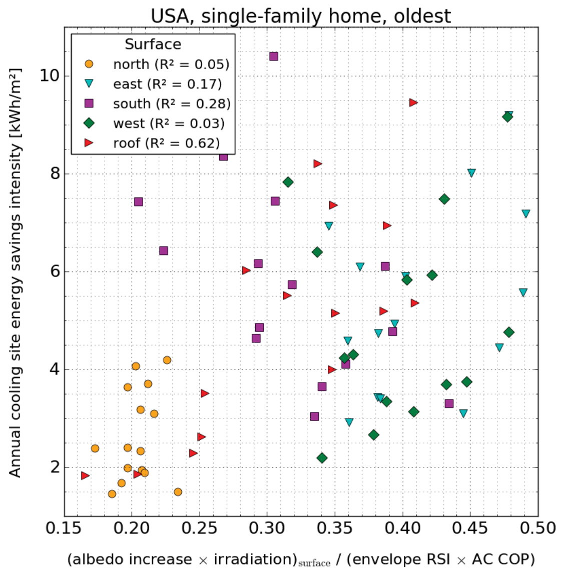
The annual site cooling savings from the north (R^2=0.05) and west (R^2=0.03) walls were essentially uncorrelated with the change in absorbed irradiation (Figure 27a). Annual cooling savings for the east (R^2=0.17) and south (R^2=0.28) walls correlated poorly with absorbed irradiation. Only the roof (R^2=0.62) had better correlation with change in absorbed irradiation. Figure 27b shows that for every modified surface, the annual cooling savings intensity correlates well with annual CDD18C (from R^2=0.70 for south wall to R^2=0.90 for north and west walls). The graph demonstrates how cooling savings intensity increases with annual CDD18C.

Figure 27c and Figure 27d show the correlation of annual site gas heating energy penalty intensity to changes in absorbed solar radiation to annual HDD18C, respectively, for the oldest single-family home. The changes in winter solar radiation and annual HDD18C were normalized by the envelope's thermal resistance and the heating efficiency.

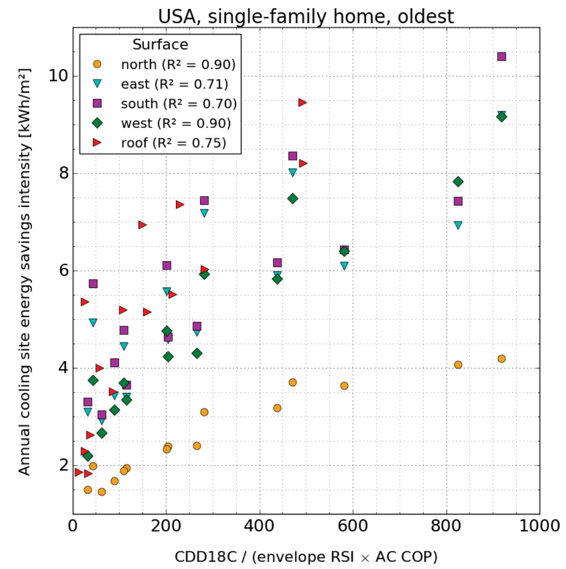
Annual site gas heating energy penalty intensities were essentially uncorrelated with changes in winter solar radiation for the north wall, east wall, west wall, and roof, ranging from R^2=0.00 (east wall) to R^2=0.06 (north wall). Only the south wall (R^2=0.58) showed considerably better correlation with change in absorbed irradiation. The annual site gas heating energy penalty intensities correlated well with annual HDD18C (from R^2=0.58 for west wall to R^2=0.84 for east wall). Thus, annual heating penalty intensity increased with annual HDD18C.

	Changes in site energy vs changes in absorbed sunlight	Changes in site energy vs degree days
	(a)	(b)
Cooling	see chart (a) below	see chart (b) below
	(c)	(d)
Heating	see chart (c) below	see chart (d) below

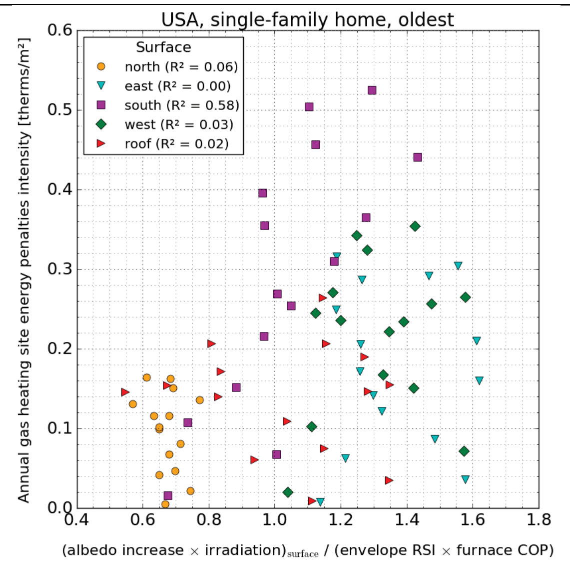
(a)



(b)



(c)



(d)

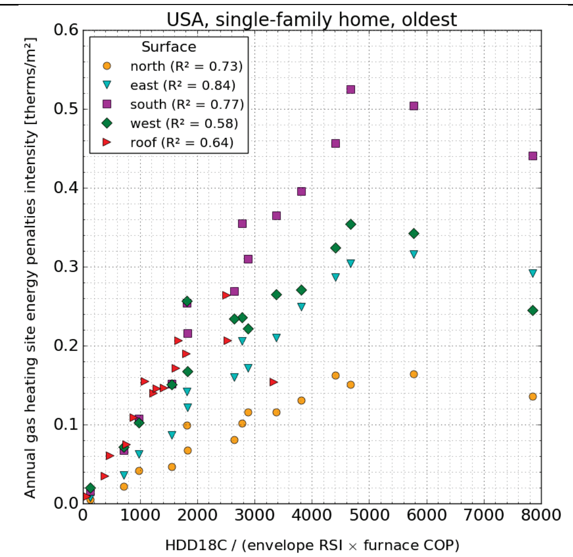


Figure 27. Correlation of changes in site energy use in United States to changes in absorbed sunlight and to degree days, including (a) correlation of annual cooling site energy savings to change in absorbed sunlight during summer; (b) correlation of annual cooling site energy savings to annual CDD18C; (c) correlation of annual heating site energy penalties to change in absorbed sunlight during winter; and (d) correlation of annual heating site energy penalties to annual HDD18C.

We applied a multivariate linear regression analysis to investigate if the correlations of cooling energy savings to either changes in absorbed sunlight or to annual CDD18C improved when both metrics (change in absorbed sunlight and annual CDD18C) were considered simultaneously.

Table 28 shows for all modified surfaces of the single-family home, medium office, and retail stand-alone, the coefficient of determination from the correlation analysis of annual site cooling savings (a) to cooling degree days (CDD18C), (b) to change in absorbed summer sunlight, and (c) simultaneously to annual CDD18C and change in absorbed summer sunlight. For all buildings and surfaces, cooling savings correlated better with cooling degree days than with change in absorbed sunlight. When both metrics were considered simultaneously, the correlation improved the most—compared to the individual correlations to both metrics (change in absorbed sunlight and annual CDD18C)—for the east wall and the roof in the oldest and older vintage of the single-family home. The multivariate linear regression caused little to no improvement—compared to the individual correlations to both metrics—in any of the other cases.

Similarly, we applied a multivariate linear regression analysis to investigate if the correlation of annual site heating energy penalties to changes in absorbed sunlight or to heating degree days heating improved when both metrics were considered simultaneously. Table 29 shows for all modified surfaces of the single-family home, medium office, and retail stand-alone, the coefficient of determination from the correlation analysis of annual site heating penalties (a) to heating degree days, (b) to change in absorbed winter sunlight, and (c) simultaneously to heating degree days and change in absorbed sunlight. Heating penalties always correlated better with heating degree days than with change in absorbed sunlight. When both metrics were considered simultaneously, the correlations improved by more than 0.10 only for the east wall in the new medium office and for the roof of the oldest and older retail stand-alone. This improvement of more than 0.10 was relative to the largest correlation from both individual metrics.

Table 28. Coefficient of determination (R^2) from the correlations of annual cooling savings to annual cooling degree days at 18°C (cdd), annual cooling savings to change in absorbed summer sunlight (sun), and annual cooling savings to cdd and sun. The coefficients of determination are for all vintages in U.S. of the single-family home, medium office, and retail stand-alone.

		Coefficient of determination (R^2)														
		north wall			east wall			south wall			west wall			roof		
Building	**vintage**	cdd	sun	cdd + sun	cdd	sun	cdd + sun	cdd	sun	cdd + sun	cdd	sun	cdd + sun	cdd	sun	cdd + sun
single-family home	oldest	0.90	0.05	0.89	0.71	0.17	0.84 [a]	0.70	0.28	0.66	0.90	0.03	0.93	0.75	0.62	0.95 [a]
	older	0.91	0.18	0.92	0.79	0.22	0.90 [a]	0.83	0.16	0.83	0.93	0.06	0.95	0.85	0.44	0.96 [a]
	new	0.94	0.71	0.95	0.89	0.72	0.94	0.92	0.18	0.93	0.96	0.66	0.97	0.93	0.79	0.97
medium office	oldest	0.96	0.71	0.96	0.96	0.53	0.96	0.94	0.06	0.94	0.95	0.46	0.97	0.95	0.52	0.96
	older	0.87	0.74	0.86	0.86	0.67	0.85	0.87	0.66	0.84	0.87	0.63	0.85	0.87	0.25	0.90
	new	0.98	0.68	0.98	0.99	0.53	0.99	0.99	0.29	0.99	0.99	0.51	0.99	0.96	0.57	0.98
retail stand-alone	oldest	0.94	0.65	0.93	0.97	0.50	0.97	0.97	0.05	0.97	0.97	0.34	0.97	0.98	0.50	0.99
	older	0.87	0.70	0.84	0.89	0.68	0.88	0.91	0.61	0.89	0.91	0.59	0.90	0.90	0.22	0.92
	new	0.99	0.97	0.99	1.00	0.97	1.00	0.95	0.97	0.99	0.72	0.86	0.87	0.98	0.52	0.99

[a] Coefficient of determination that improved in the multivariate linear regression by more than 0.10.

Table 29. Coefficient of determination (R^2) from the correlations of annual heating penalty to annual heating degree days at 18°C (hdd), heating penalty to change in absorbed winter sunlight (sun), and heating penalty to hdd and sun. The coefficients of determination are for all vintages in U.S. of the single-family home, medium office, and retail stand-alone.

Build-ing	vintage	Coefficient of determination (R^2)														
		north wall			east wall			south wall			west wall			roof		
		hdd	sun	hdd + sun	hdd	sun	hdd + sun	hdd	sun	hdd + sun	hdd	sun	hdd + sun	hdd	sun	hdd + sun
single-family home	oldest	0.73	0.06	0.81	0.84	0.00	0.81	0.77	0.58	0.75	0.58	0.03	0.62	0.64	0.02	0.62
	older	0.63	0.08	0.66	0.74	0.00	0.69	0.66	0.44	0.62	0.44	0.01	0.45	0.56	0.04	0.62
	new	0.72	0.27	0.73	0.77	0.05	0.74	0.70	0.16	0.66	0.54	0.02	0.53	0.62	0.19	0.57
medium office	oldest	0.75	0.80	0.81	0.76	0.66	0.79	0.85	0.19	0.87	0.68	0.52	0.66	0.52	0.37	0.44
	older	0.48	0.61	0.55	0.53	0.60	0.60	0.60	0.61	0.68	0.53	0.60	0.61	0.74	0.40	0.78
	new	0.25	0.61	0.64	0.70	0.29	0.82 [a]	0.58	0.03	0.60	0.71	0.36	0.81	0.55	0.15	0.56
retail stand-alone	oldest	0.48	0.37	0.39	0.45	0.09	0.45	0.58	0.00	0.54	0.17	0.01	0.36	0.16	0.02	0.49 [a]
	older	0.42	0.00	0.32	0.45	0.00	0.37	0.43	0.00	0.34	0.43	0.03	0.34	0.35	0.11	0.77 [a]
	new	0.04	0.03	-0.10	0.09	0.01	-0.01	0.03	0.04	-0.10	0.04	0.15	0.14	0.14	0.12	0.20

[a] Coefficient of determination that improved in the multivariate linear regression by more than 0.10.

3.4.3 Savings in United States by climate zone and vintage

This section reports annual HVAC source energy, energy cost, CO_2e, NO_x, SO_2, and peak power demand savings for the single-family home, the medium office, and the stand-alone retail buildings upon (a) increasing the albedo of all four walls simultaneously by 0.35 (to 0.60 from 0.25) or (b) increasing the albedo of the roof to 0.40 from 0.10 (single-family home) or to 0.60 from 0.20 (medium office and retail stand-alone). Each metric is compared by vintage and by U.S. climate zone.

We have omitted all results for the new stand-alone retail building in USCZ 1A (Miami) because modifying the albedo of its back wall yielded unrealistically large changes in annual fan energy use.

3.4.3.1 Annual HVAC source energy savings

First, note that in all locations except USCZ 8 (Fairbanks), the annual daily solar irradiation received by the roof was 1.7 to 2.0 times the four-wall average received solar irradiation.

Figure 28 shows annual HVAC source energy savings intensity by vintage and by U.S. climate zone for the single-family home (Figure 28a), medium office (Figure 28b), and stand-alone retail (Figure 28c). In the single-family home (Figure 28a) the increase in roof albedo (0.30) was 86 percent of that of walls (0.35). Additionally, in each vintage, the thermal resistance of the roof assembly was much greater than that of the wall assembly; in all vintages, the thermal resistance of the roof assembly was 1.7 to 3.4 times that of walls (Table 11 and Table 13). Hence, although the roof receives about twice more solar irradiation than the average of all walls, the large thermal resistance in roofs led to annual HVAC source energy savings intensities that were often similar or slightly greater than those from the average of all walls.

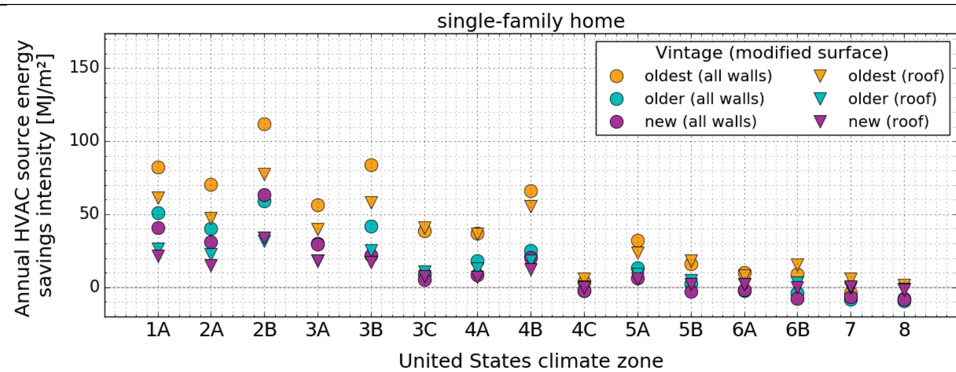
In the single-family home (Figure 28a), the differences in cool walls annual HVAC savings intensities between vintages is related to the differences in wall assembly thermal resistance and cooling efficiency between vintages. As an example, in USCZ 1A (Miami), the thermal resistance of the wall assembly in the new vintage was 1.8 times that in the oldest vintage; the ratio of cooling efficiency of new to oldest vintage was 1.3. Thus, we would expect the HVAC savings intensity from cool walls in the oldest single-family home to be about $1.8 \times 1.3 = 2.3$ times that of the new home. This estimate matches well with what we observe in Figure 28a, where the cool wall savings intensity from the oldest single-family home in USCZ 1A is about 2.1 times that of the new vintage. This ratio varied by U.S. location, but on average, the annual HVAC source energy savings intensities from the oldest home were 3.0 times that of the new home (Table 30). In the case of older single-family home, the annual HVAC savings intensity were on average 1.3 times that of the new home (Table 31).

The savings of the medium office (Figure 28b) were from increasing the wall albedo by 0.35 (to 0.60 from 0.25), and from increasing the roof albedo by 0.40 (to 0.60 from 0.20). Thus, the increase in roof albedo was 1.14 times that of walls. The thermal resistance of the roof assembly in the oldest medium office was about 2.0 to 2.4 times that of the wall assembly (Table 11 and Table 13). Hence, even though the roof receives about twice solar irradiation than the walls, the large thermal resistance in roofs led to annual HVAC source energy savings intensities that were equal or less than those from the average of all walls (Figure 28b).

In the medium office (Figure 28b), the thermal resistance of the wall assembly in the new vintage ranged from 1.5 to 3.0 times that in the oldest vintage, while the cooling efficiency ratio of wall thermal resistances of new to oldest vintage varies by location but ranges from 1.5 to 3.0. Additionally, the cooling efficiency in the new vintage was 1.1 to 1.2 times that in the oldest vintage. As an example, in USCZ 2B (Phoenix), the ratio of wall thermal resistance of new to oldest vintage was 1.9 and the ratio of cooling efficiency of new to oldest vintage was 1.1. Thus, we would expect the annual HVAC savings intensity from cool walls in the oldest medium office to be $1.9 \times 1.1 = 2.1$ times that of the new medium office. This estimate is similar to what we observe in Figure 28b where the cool walls savings intensity from the oldest vintage were 1.8 times that of the new vintage. This ratio varied by U.S. location, but on average, the annual HVAC source energy savings intensities from the oldest home were 1.5 to 8 times that of the new home in USCZs 1A to 4B and 5A, which were the U.S. climate zones that yielded annual HVAC source energy savings in both vintages. In the case of older medium office, the annual HVAC savings intensity were on average 4.1 times that of the new medium office in locations that yielded savings in both vintages (Table 31).

In the stand-alone retail (Figure 28c), the differences in annual HVAC source energy savings intensities from the walls to those of the roof were related to the differences in albedo change, thermal resistance and annual daily solar irradiation between walls and roof. However, in the stand-alone retail, the oldest vintage didn't present the largest annual HVAC source energy savings or penalty intensities. As an example, in USCZ 2B (Phoenix), the annual HVAC source energy savings intensity when all walls were made cool in the new vintage was 410 MJ/m², which is about 2.2 times that of the oldest vintage. The reason the new vintage in USCZ 2B yielded about twice the wall savings than those in the oldest vintage is that the wall thermal resistance in the new vintage was half of that in the oldest vintage. The oldest stand-alone retail was simulated with metal frame walls, while the new stand-alone retail was simulated with heavy mass walls. In warm climates (e.g., USCZ 2B) the walls of the new stand-alone retail were simulated with no additional wall insulation. Thus, in some locations, the resistance of the wall assembly in the new stand-alone retail was less than that of the oldest vintage. Note that the older stand-alone retail was also simulated with heavy mass walls.

(a)



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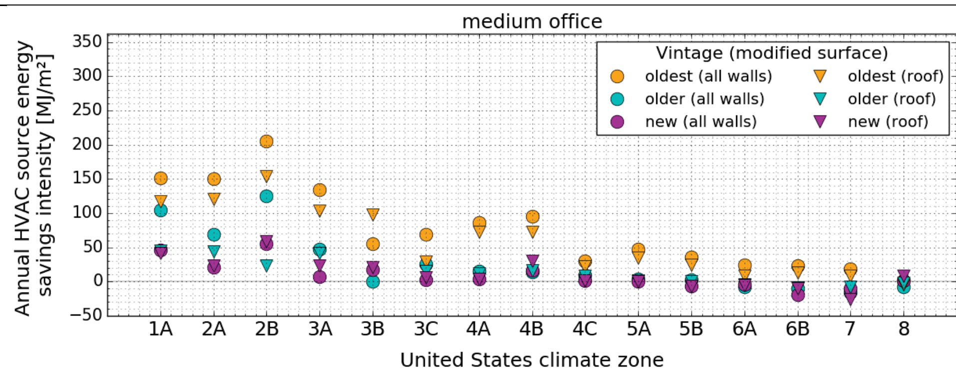


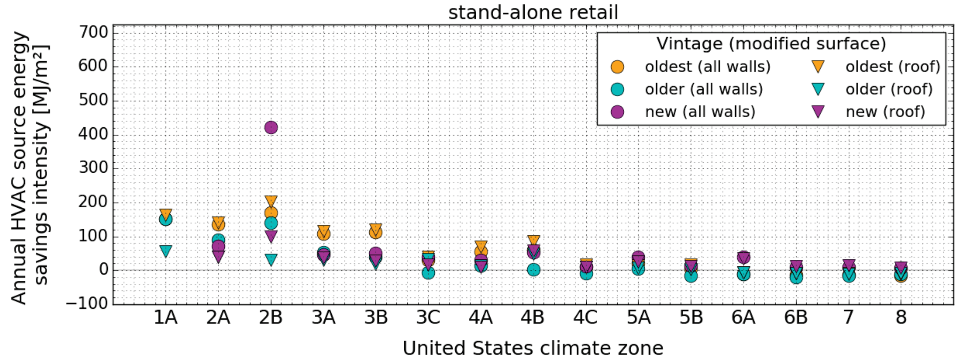
(c)	

Figure 28. Annual HVAC source energy savings intensity by vintage and by U.S. climate zone for the (a) single-family home, (b) medium office, and (c) retail stand-alone. The plots compare the savings intensity from increasing the albedo of all walls by 0.35 to that from increasing the roof albedo by 0.30 (residential) or 0.40 (commercial).

The fractional savings (absolute savings / base value) of the energy, energy cost, and emission metrics were influenced not only by the absolute savings but also by the energy consumed in the base case. When comparing cool walls to a cool roof, the differences in fractional savings were driven by the envelope characteristics (e.g., differences in surface albedo change and in insulation) as well as by the envelope geometry (e.g., ratio of roof area to net wall area).

Figure 29 shows the annual HVAC source energy fractional savings by vintage and by U.S. climate zone for the single-family home (Figure 29a), medium office (Figure 29b), and stand-alone retail (Figure 29c). For the single-family home (Figure 29a), the greatest HVAC source energy fractional savings when all walls were made cool were 8.3 percent (oldest, USCZ 3B, El Paso), followed in descending order by 7.7 percent (oldest, USCZ 2B, Phoenix), 7.5 percent (oldest and new, USCZ 1A, Miami), and 6.7 percent (oldest, USCZ 2A, Houston). The greatest cool roof fractional savings were from the oldest vintage in USCZ 3C (San Francisco), followed in descending order by the oldest vintages in USCZs 1A (Miami), 3B (El Paso), 2B (Phoenix), and 4B (Albuquerque). In U.S. climate zones 4C (Salem), 5B (Boise), 6A (Burlington), and 6B (Helena), the walls in the oldest home yielded fractional savings of 0.5 percent to 2.0 percent while the walls in the new home led to fractional penalties of 0.2 percent to 1.2 percent.

In the single-family home, the walls-to-roof ratio in fractional savings was always greater than 1.0, and often up to 2.0 (Figure 28a), because the net wall area is greater than the roof area. As an example, consider the oldest home in USCZ 2B (Phoenix). The annual HVAC source energy savings intensity from the walls were about 1.4 times that from the roof. From Table 4, we gather that the net wall area is 1.6 times that of the roof area. Thus, the ratio of wall savings intensity to roof savings intensity adjusted by the wall-to-roof area ratio is $1.4 \times 1.6 = 2.2$. This adjusted wall-to-roof savings ratio is close to the ratio of about 2.3 we observed for HVAC energy fractional savings Figure 29a for the oldest home in USCZ 2B.

For the medium office (Figure 29b), we see that USCZ 2B (Phoenix) was the location with greatest annual HVAC source energy savings intensity for roof and walls, and for all vintages. However, the largest HVAC source energy fractional savings were from the walls of the oldest medium office in USCZ 3C (San Francisco), yielding 4.5 percent savings. Although USCZ 3C had small HVAC source energy savings intensities for all vintages, it yielded large HVAC source energy fractional savings from having small base energy use compared to the other locations.

When analyzing annual HVAC source energy savings intensity of the medium office (Figure 28b), we observed that in most U.S. climate zones and vintages, the savings intensity from the walls were slightly greater than those from the roof. However, the roof area in the medium office is greater than the net wall area (roof area to net wall area ratio 1.3). Since fractional savings relate to the surface area modified, the fractional savings from the roof were often similar or greater than those from the walls (Figure 29b). The walls and roof fractional savings from the oldest vintage were greater than those from the older and new vintages, and yielded about 3.5 percent savings from USCZ 1A (Miami) to 3A (Memphis). The oldest vintage led to HVAC source energy fractional savings from walls and roof in all locations, but the fractional savings decreased as U.S. climate zones increased. The new medium office yielded HVAC source energy fractional savings from walls of up to 2 percent (USCZs 1A and 2B), but led to HVAC fractional penalties of up to 1.6 percent between USCZs 5B (Boise) to 7 (Duluth).

In the case of retail stand-alone (Figure 29c), the roof-to-wall ratios of annual HVAC source energy fractional savings were even greater than those observed in the medium office. That is because the stand-alone retail is a single-story building with a large footprint area (2,290 m^2), and has more than twice as much roof area as wall area (roof area to net wall area ratio = 2.1) (Table 4). Hence, the difference in cool roof fractional savings to those from the cool walls was significantly influenced by the large roof area to net wall area ratio. leading to HVAC source energy fractional savings from the roof being in most cases greater than those from the walls.

In the new retail stand-alone, making all walls cool led to HVAC source energy fractional savings in all U.S. climate zones, yielding up to 11 percent in USCZ 2B (Phoenix), and nearly 5.0 percent in USCZ 2A (Houston). The older retail stand-alone in USCZ 5B (Boise) yielded the largest HVAC fractional penalties (1.0 percent). The older retail stand-alone also led to less than 1.0 percent HVAC fractional penalties in USCZs 3C (San Francisco), 4C (Salem), 6A (Burlington), 6B (Helena), 7 (Duluth), and 8 (Fairbanks).

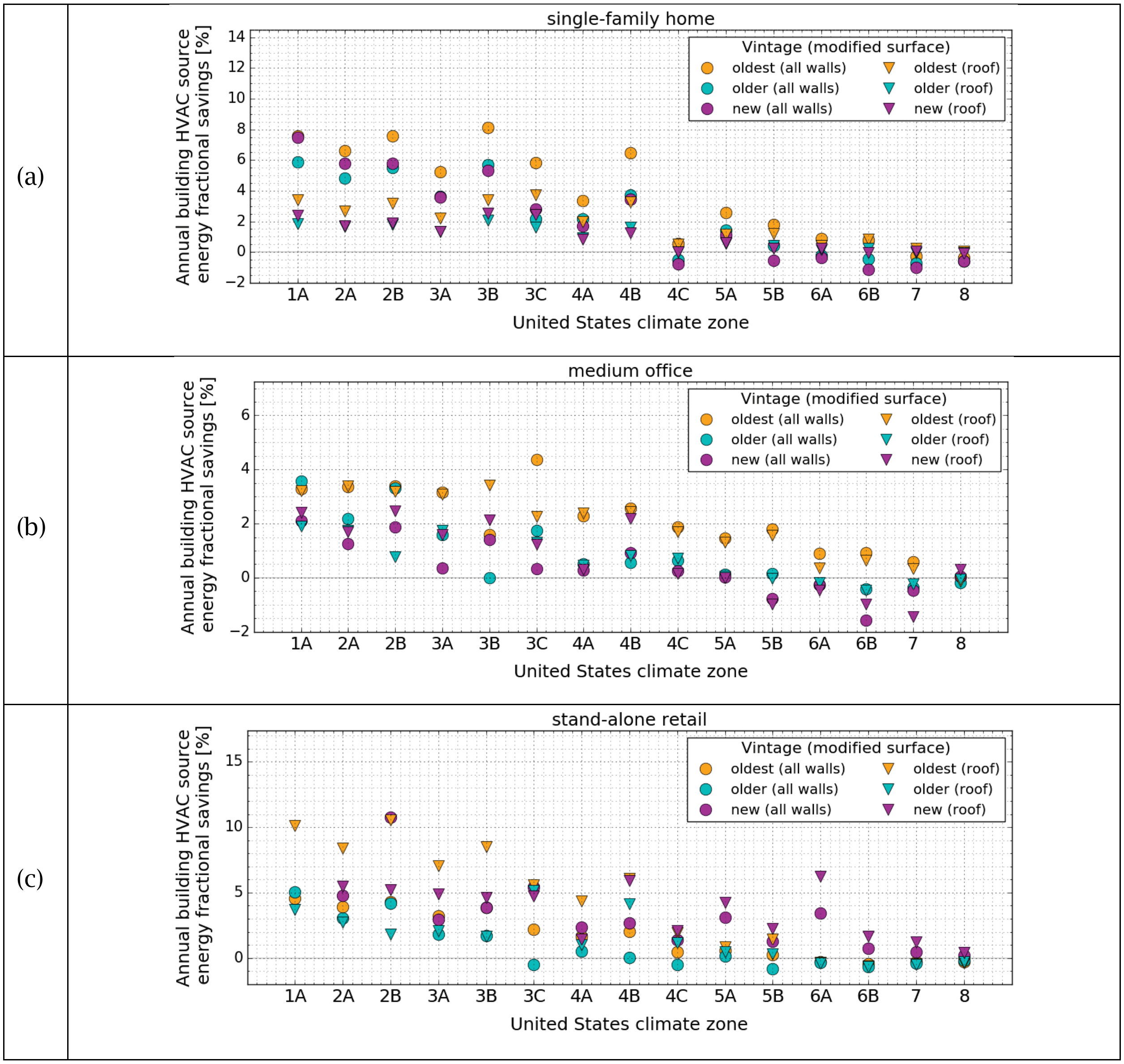


Figure 29. Annual HVAC source energy fractional savings by vintage and by U.S. climate zone for the (a) single-family home, (b) medium office, and (c) retail stand-alone. The plots compare the fractional savings from increasing the albedo of all walls by 0.35 to that from increasing the roof albedo by 0.30 (residential) or 0.40 (commercial).

3.4.3.2 Annual HVAC energy cost savings

Figure 30 shows annual HVAC energy cost savings intensity by vintage and by California climate zone for the single-family home (Figure 30a), medium office (Figure 30b), and stand-alone retail (Figure 30c). These annual HVAC energy cost savings intensities were computed using Eq. (9) and the state-dependent electricity and gas prices from Table 18. For the single-family home, we used the prices for residential buildings; for the medium office and retail stand-alone, we used the prices for commercial buildings.

The annual HVAC energy cost savings intensities show a similar trend between U.S. climate zones and between vintages that those we observed for the annual HVAC source energy savings intensities. Additionally, the proportions of cool walls energy cost savings intensities to those from cool roof were very similar to those we observed for annual HVAC energy savings intensities. These similarities happen because HVAC energy cost savings intensities and HVAC energy savings intensities are affected equally by climate (i.e., solar radiation, CDD18C, and HDD18C) and building properties (i.e., envelope insulation).

The small trend differences in savings and penalty intensities between HVAC source energy and energy cost relate to the variations in electricity and gas prices between states. As an example, making all walls cool in the new single-family home in USCZ 8 (Fairbanks) yielded an annual HVAC source energy *penalty* intensity of 10 MJ/m² (Figure 28a), but an annual HVAC energy cost *savings* intensity of \$0.10/m² (Figure 30a). The price of electricity in Fairbanks, AK, is the highest of all represented states (Table 18), which gives larger cooling energy cost savings per unit of saved cooling energy compared to the other locations. Thus, in Fairbanks, AK, while the cool walls led to annual HVAC source energy penalty (heating source energy penalty exceeds cooling source energy savings), cool walls yield annual HVAC energy cost savings (cooling energy cost savings were greater than the heating energy cost penalties).

In the single-family home (Figure 30a), cool roofs generated greater annual HVAC energy cost savings intensities than did cool walls in most locations and vintages. The new home in all vintages led to HVAC cost savings from cool walls. The savings intensity from the oldest vintage were on average, 4.8 times that those of the new vintage (Table 30). The greatest wall annual HVAC energy cost savings intensities were \$1.1/m² (oldest, USCZ 2B, Phoenix), \$0.88/m² (oldest, USCZ 1A, Miami), and \$0.85/m² (oldest, USCZ 3B, El Paso). HVAC energy cost penalties were less than \$0.1/m² and happened only in the new home in USCZs 4C (Seattle), 6B (Helena), and 7 (Duluth).

In the oldest medium office (Figure 30b), every location yielded cool walls HVAC energy cost savings intensity, which in turn were greater than those from the cool roof. These cool walls HVAC energy cost savings were greater in warm U.S. climate zones (i.e., USCZs 1A to 4B) and were smallest in the coldest climates (e.g., USCZs 7 and 8). The greatest HVAC energy cost savings when making all walls cool were \$1.8/m² (oldest, USCZ 2B, Phoenix), \$1.4/m² (oldest, USCZ 1A, Miami), and \$1.2/m² (oldest, USCZ 3A, Memphis). In USCZs 5B (Boise), 6A (Burlington), 6B (Helena), 7 (Duluth), and 8 (Fairbanks), the older and new medium offices yielded HVAC energy cost penalties of no more than \$0.20/m². The HVAC energy cost savings intensities from the oldest vintage were on average, 7.6 times that those of the new vintage (Table 30).

In the retail stand-alone (Figure 30c), the oldest vintage didn't always yield the largest annual HVAC energy cost savings or penalty intensities. As an example, in the new vintage in USCZ 2B (Phoenix), the annual HVAC energy cost savings intensity when all walls were made cool was \$3.7/m², which is about 2.5 times that of the oldest vintage. The new vintage had greater energy cost savings than the oldest vintage because the wall thermal resistance in the new vintage was half of that in the oldest vintage. The oldest retail stand-alone was simulated with metal frame walls, while the new stand-alone retail was simulated with heavy mass walls. In warm climates (e.g., USCZ 2B) the walls of the new stand-alone retail were simulated with no additional wall insulation. Thus, in some locations, the resistance of the wall assembly in the new stand-alone retail was less than that of the oldest vintage.

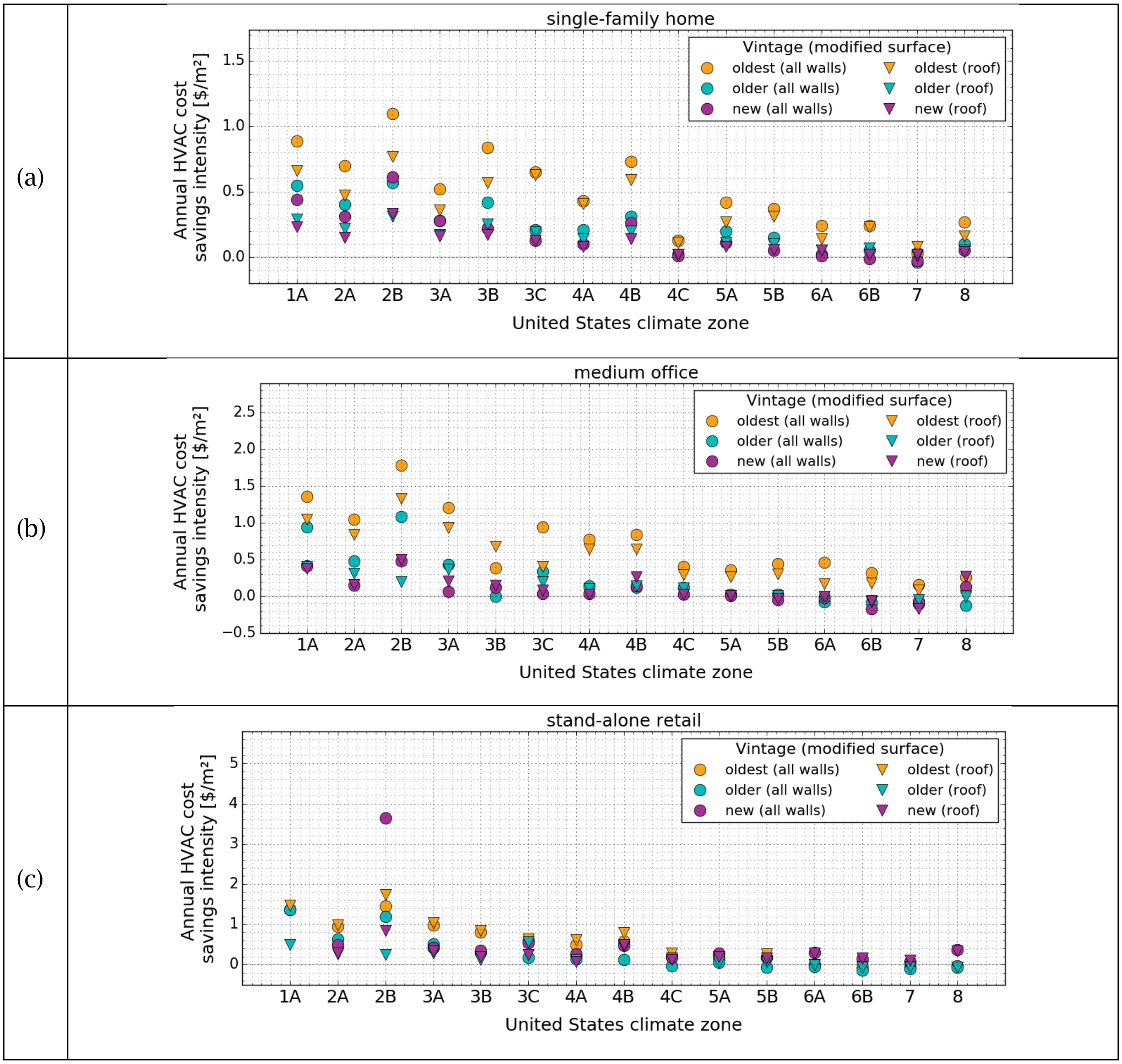


Figure 30. Annual HVAC energy cost savings intensity by vintage and by U.S. climate zone for the (a) single-family home, (b) medium office, and (c) retail stand-alone. The plots compare the savings intensity from increasing the albedo of all walls by 0.35 to that from increasing the roof albedo by 0.30 (residential) or 0.40 (commercial).

Figure 31 shows HVAC energy cost fractional savings by vintage and by U.S. climate zone for the single-family home (Figure 31a), medium office (Figure 31b), and stand-alone retail (Figure 31c). Similar to what we observed between annual HVAC source energy and energy cost savings intensities, the annual HVAC source energy and energy cost fractional savings are affected equally by climate and building properties.

For the single-family home (Figure 31a), the greatest HVAC energy cost fractional savings when all walls were made cool were 8.3 percent (oldest, USCZ 3B, El Paso), followed in descending order by 8.2 percent (oldest, USCZ 3C, San Francisco), 8.0 percent (oldest, USCZ 4B, Albuquerque), and 7.5 percent (oldest and new, USCZ 1A, Miami). In seven U.S. climate zones (1A, 2A, 2B, 3A, 3B, 3C, and 4B) making all walls cool led to HVAC energy cost savings of 4.0 percent or greater from all vintages. HVAC energy cost fractional penalties occurred only in the new vintage in USCZs 6B (Helena) and 7 (Duluth); the HVAC energy cost penalties were 0.2 percent and 0.7 percent, respectively.

In most locations and vintages of the single-family home, the annual HVAC energy cost savings intensity from the walls were equal or greater than those from the roof (Figure 30a). The HVAC energy cost fractional savings from the walls were often up to twice that of roof because the net wall area is greater than the roof area (roof-to-wall ratio 0.61, Table 4).

For the medium office (Figure 31b), USCZ 2B (Phoenix) yielded the greatest annual HVAC energy cost savings intensity for roof and walls, and for all vintages. However, the largest HVAC energy cost fractional savings were from the walls of the oldest medium office in USCZ 3C (San Francisco), yielding 4.5 percent savings. Although USCZ 3C had small HVAC energy cost savings intensities for all vintages, it yielded large HVAC energy cost fractional savings from having small base energy use compared to the other locations.

In most locations and vintages, annual HVAC energy cost savings intensity from the walls of the medium office were slightly greater than those from the roof (Figure 30b). However, the roof area in the medium office is greater than the net wall area (roof area to net wall area ratio 1.3, Table 4). Since fractional savings relate to the surface area modified, the HVAC energy cost fractional savings from the roof were often similar or greater than those from the walls (Figure 31b). The cool walls and cool roof in the oldest medium office always led to HVAC energy cost savings, and were in most cases greater than the HVAC energy cost savings from the older and new vintage. Making all walls cool in the oldest medium office led to HVAC energy cost savings of more than 3.0 percent from USCZ 1A to 3C. The largest HVAC energy cost penalties were 1.5 percent (new, USCZ 6B, Helena) and 0.70 percent (new, USCZ 5B, Boise).

The retail stand-alone is a single-story building with a large footprint area (2,290 m²), and has more than twice as much roof area as wall area (roof area to net wall area ratio = 2.1) (Table 4). This large roof area to net wall area ratio led to annual HVAC energy cost fractional savings from the roof that were greater than those from the walls (Figure 31c).

The new retail stand-alone led to HVAC energy cost fractional savings in all U.S. climate zones from cool walls and cool roof; the HVAC energy cost fractional savings from the new vintage when all walls were made cool were up to 11 percent in USCZ 2B (Phoenix), and 6.0 percent in USCZ 3C (San Francisco). The largest HVAC energy cost fractional penalties were 0.50 percent (older, USCZ 6B, Helena).

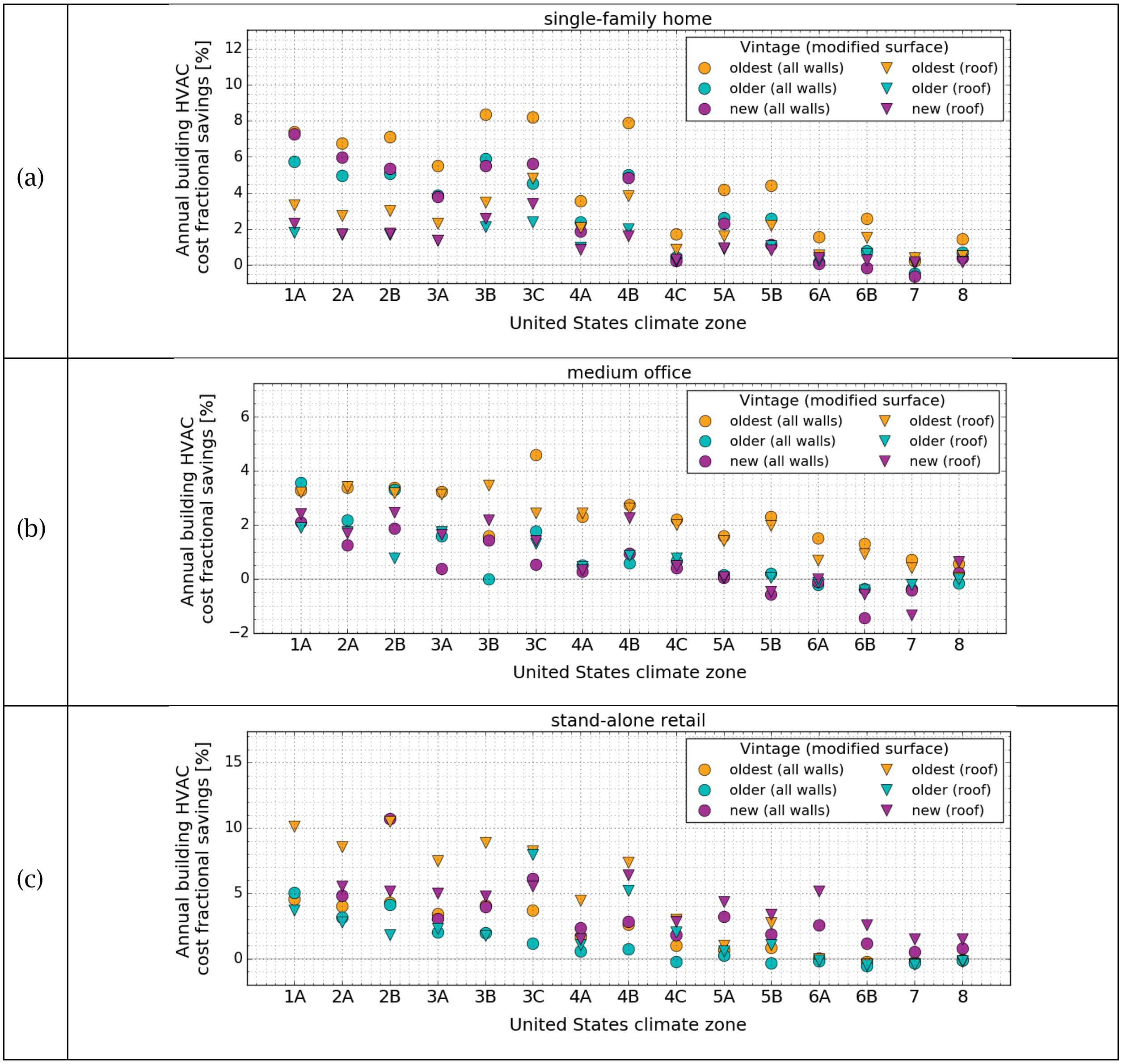


Figure 31. Annual HVAC energy cost fractional savings by vintage and by U.S. climate zone for the (a) single-family home, (b) medium office, and (c) retail stand-alone. The plots compare the fractional savings from increasing the albedo of all walls by 0.35 to that from increasing the roof albedo by 0.30 (residential) or 0.40 (commercial).

3.4.3.3 Annual CO_2e emissions reduction

Figure 32 shows annual CO_2e emissions reduction intensity by vintage and by U.S. climate zone for the single-family home (Figure 32a), medium office (Figure 32b), and stand-alone retail (Figure 32c). These emissions reduction intensities were computed using Eq. (8) and state-dependent CO_2e emissions rate of generated electricity (Table 16) and non-regional emission rates of consumed gas (Table 17). For the single-family home, we used the emissions rate for residential buildings; for the medium office and retail stand-alone, we used the emissions rate for commercial buildings.

Climate zone and vintage trends for annual CO_2e emissions reduction intensities were similar to those observed for annual HVAC source energy savings intensities. These similarities happen because CO_2e emissions reductions and HVAC energy savings are affected equally by climate (i.e., solar radiation, CDD18C, and HDD18C) and building properties (i.e., envelope insulation).

Variations in electricity emission rates between states led to the trend differences between CO_2e emissions reductions and HVAC source energy savings. For example, the cool walls and cool roof in the older and oldest single-family home in USCZ 5B (Boise) yielded annual HVAC source energy savings intensity (Figure 28a). However, in the same U.S. climate zone and vintages, the cool walls and cool roof led to CO_2e emissions increase intensity (Figure 32a). The CO_2e emissions rate from electricity in Boise, ID is among the lowest of all represented states (Table 16), which leads to small cooling CO_2e emissions reduction per unit of saved cooling energy compared to the other locations. Thus, in Boise, while the cool walls and cool roof led to annual HVAC energy savings (cooling energy savings exceed heating energy penalty), they yield annual CO_2e emissions increases (heating CO_2e emissions increase exceeds cooling CO_2e emissions reduction).

In the single-family home (Figure 32a), cool walls generated equal or greater annual CO_2e emissions reduction intensities than did cool roofs in most locations and vintages. The greatest CO_2e emissions reduction intensities when all walls were made cool were 5.3 kg/m² (oldest, USCZ 2B, Phoenix), 4.7 kg/m² (oldest, USCZs 3B and 4B, El Paso and Albuquerque), and 4.6 kg/m² (oldest, USCZ 1A, Miami). USCZs 4C (Seattle), 5B (Boise), and 6A (Burlington), have cool climates, which led to small home cooling energy savings intensities compared to the homes in warm climates. Additionally, CO_2e emissions rates from electricity were smaller in Seattle (Washington), Boise (Idaho), and Burlington (Vermont) than for cities in other states. Thus, cooling CO_2e emissions reduction from cool walls and cool roof in these three locations were small. This led to annual CO_2e emissions increase from cool walls and cool roof in all vintages.

In the medium office (Figure 32b), the cool walls CO_2e emissions reduction intensities were greatest in the oldest vintage in USCZs 1A (Miami), 2A (Houston), 2B (Phoenix), 3A (Memphis), and 4B (Albuquerque). In all U.S. climate zones that yielded CO_2e emissions reduction from the new and oldest vintages, the reductions from the oldest vintage were about 4.4 times that of the new vintage (Table 30).

In the retail stand-alone (Figure 32c), the oldest vintage didn't always lead to the largest annual CO_2e emissions reduction or increase intensities. As an example, in USCZ 2B (Phoenix), the annual CO_2e emissions reduction intensity when all walls were made cool in the new vintage was 21 kg/m², which is about 2.3 times that of the oldest vintage. The new vintage had greater CO_2e emissions reduction than the oldest vintage because the wall thermal resistance in the new vintage was half of that in the oldest vintage, leading to more annual HVAC energy savings in the new vintage. The oldest retail stand-alone was simulated with metal frame walls, while the new stand-alone retail was simulated with heavy mass walls. In warm climates (e.g., USCZ 2B) the walls of the new stand-alone retail were simulated with no additional wall insulation. Thus, in some locations, the resistance of the wall assembly in the new stand-alone retail was less than that of the oldest vintage.

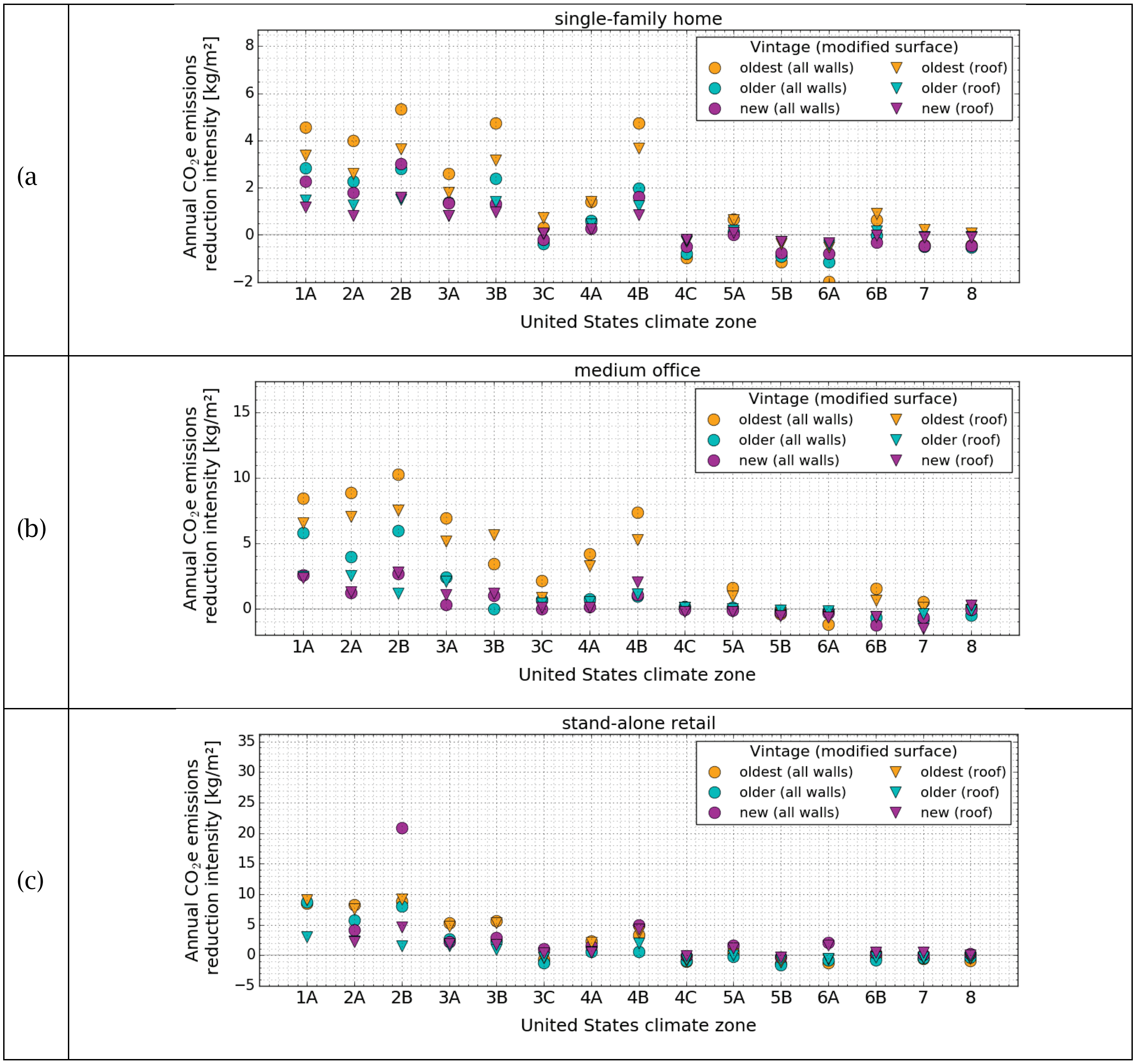


Figure 32. Annual CO_2e emissions reduction intensity by vintage and by U.S. climate zone for the (a) single-family home, (b) medium office, and (c) retail stand-alone. The plots compare the reduction intensity from increasing the albedo of all walls by 0.35 to that from increasing the roof albedo by 0.30 (residential) or 0.40 (commercial).

Figure 33 shows CO_2e emissions fractional reduction by vintage and by U.S. climate zone for the single-family home (Figure 33a), medium office (Figure 33b), and stand-alone retail (Figure 33c). Similar to what we observed between annual HVAC source energy and energy cost fractional savings, the annual CO_2e emissions fractional reduction are affected equally by climate and building properties.

When all walls were made cool in the single-family home (Figure 33a), the greatest CO_2e emission fractional reductions were 8.3 percent (oldest, USCZ 3B, El Paso), followed by 8.0 percent (oldest, USCZ 4B, Albuquerque), 7.5 percent (oldest and new, USCZ 1A, Miami), and 7.5 percent (oldest, USCZ 2B, Phoenix). In 7 U.S. climate zones (1A, 2A, 2B, 3A, 3B, 4A, and 4B) making all walls cool led to CO_2e emissions reduction of 2.0 percent or greater from all vintages. In USCZs 4C (San Francisco), 5B (Boise), and 6A (Burlington), making all walls cool led to CO_2e emissions increased from all vintages, reaching increases of up to 3.8 percent (oldest, USCZ 6A, Burlington).

Similar to the case of HVAC source energy and energy cost fractional savings, the annual CO_2e emissions reductions from increasing the albedo of all walls were often much greater than those from cool roof because a) the thermal resistance in walls is less than that of walls, and b) the net wall area is greater than the roof area (roof-to-wall ratio 0.61, Table 4).

In most locations and vintages of the single-family home, the annual CO_2e emissions reductions or penalty intensities from the roof were greater than those from the walls (Figure 32a). However, the annual CO_2e emissions fractional reductions or increases from the walls were mostly greater than those from the roof because the net wall area was greater than the roof area (roof area to net wall area ratio 0.61) (Table 4).

For the medium office (Figure 32b), we see that USCZ 2B (Phoenix) was the location with greatest cool walls annual CO_2e emissions reduction intensity for all vintages. However, the largest cool walls annual CO_2e emissions fractional reductions were in the oldest medium office in USCZ 3C (San Francisco), which led to a 6.0 percent reduction (Figure 33b). Although USCZ 3C had small CO_2e emissions savings intensity for all vintages, the small base CO_2e emissions led to large CO_2e emissions fractional reductions.

In most locations and vintages, annual CO_2e emissions reduction or increase intensities from the walls of the medium office were slightly greater than those from the roof (Figure 32b). However, since the roof area in the medium office is greater than the net wall area (roof area to net wall area ratio 1.3) (Table 4), the CO_2e emissions fractional reductions or increases from the roof were often similar or greater than those from the walls (Figure 33b).

The retail stand-alone is a single-story building with a large footprint area (2,290 m^2), and has more than twice as much roof area as wall area (roof area to net wall area ratio = 2.1) (Table 4). In most U.S. climate zones, this large roof area to net wall area ratio led to annual CO_2e emissions fractional savings or penalties from the roof that were greater than those from the walls (Figure 33c). The greatest CO_2e emissions fractional reductions when all walls were made cool were 11.9 percent (new, USCZ 2B, Phoenix). In USCZs 4C (San Francisco), 5B (Boise), and 6A (Burlington), making all walls cool led to CO_2e emissions increased from all vintages, reaching increases of up to 2.5 percent (older, USCZ 5B, Boise). In USCZs 7 and 8, raising wall albedo yielded almost no change to CO_2e emissions.

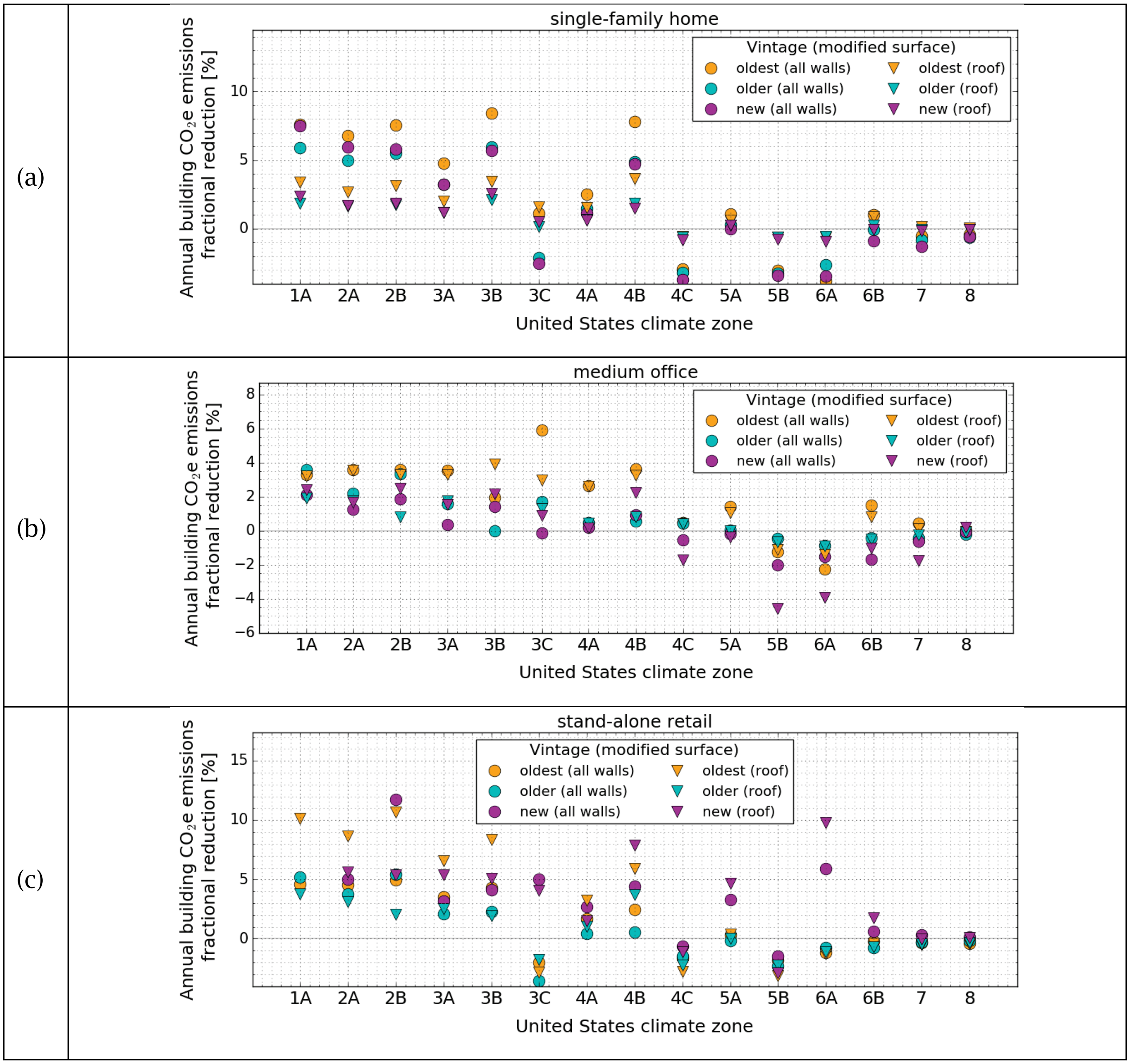


Figure 33. Annual CO_2e emissions fractional reduction by vintage and by U.S. climate zone for the (a) single-family home, (b) medium office, and (c) retail stand-alone. The plots compare the fractional reduction from increasing the albedo of all walls by 0.35 to that from increasing the roof albedo by 0.30 (residential) or 0.40 (commercial).

3.4.3.4 Annual NO_x emissions reduction

Figure 34 and Figure 35 show annual NO_x emissions reduction intensities and fractional reductions, respectively, by vintage and by U.S. climate zone for the single-family home (Figure 34a and Figure 35a), medium office (Figure 34b and Figure 35b), and stand-alone retail (Figure 34c and Figure 35c). These emissions reduction intensities were computed using Eq. (8) and (10), and the fractional reductions were computed using Eq. (8). These emission reductions were calculated using the state-dependent NO_x emissions rate of generated electricity (Table 16) and the non-regional emissions rate of consumed gas (Table 17).

The annual NO_x emissions reduction intensities and fractional reductions have the same trend between U.S. climate zones and between vintages that those we observed for the annual savings intensity and fractional savings of annual CO_2e emissions. The proportions of cool walls NO_x reductions to those from cool roof were very similar to those we observed for annual CO_2e emissions reductions. These similarities happen because NO_x and CO_2e emissions reductions are affected equally by climate (i.e., solar radiation, CDD18C, and HDD18C) and building properties (i.e. envelope thermal resistance) (see Section 3.3.3.1). All fractional savings are also affected equally by building geometry.

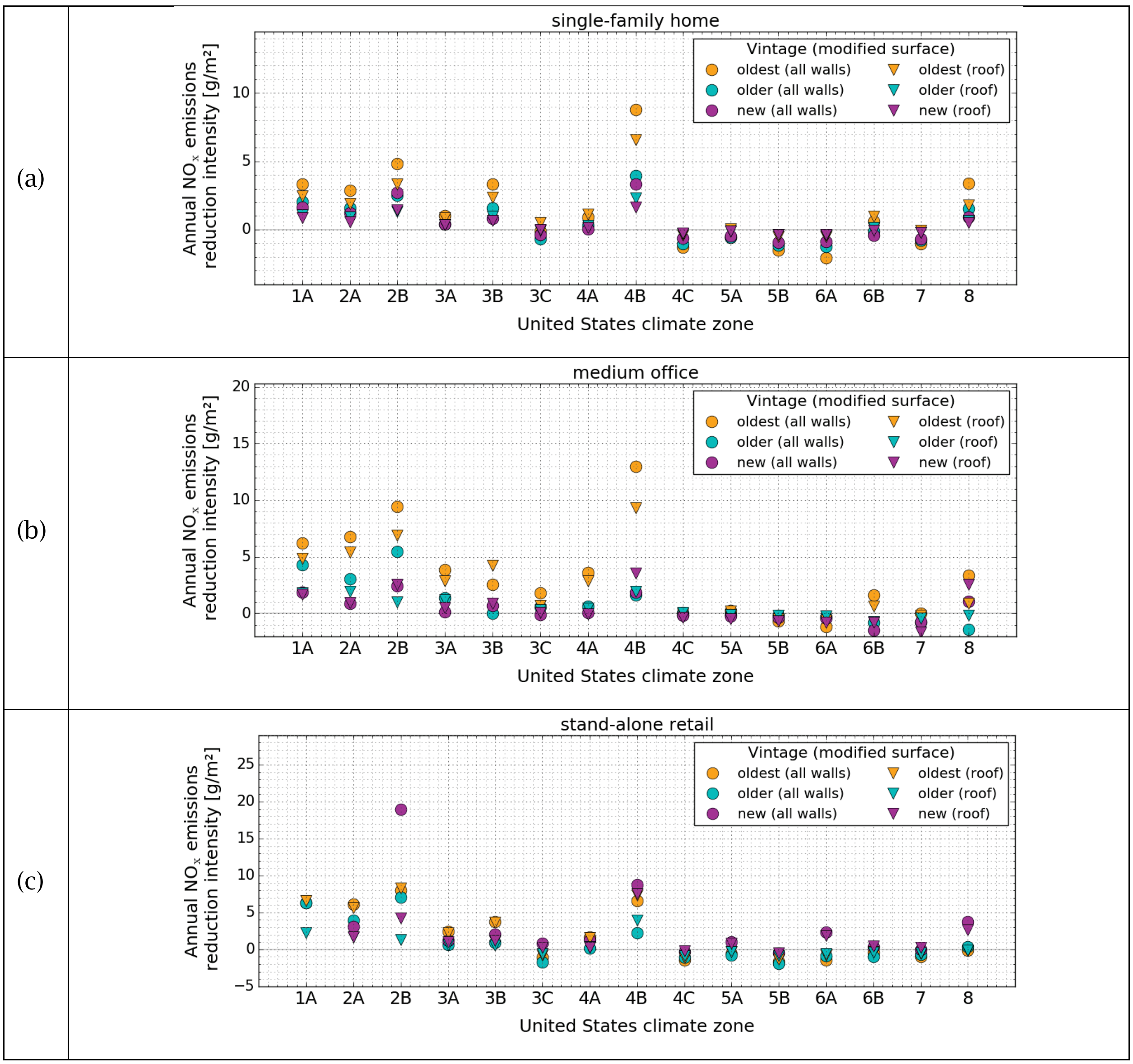
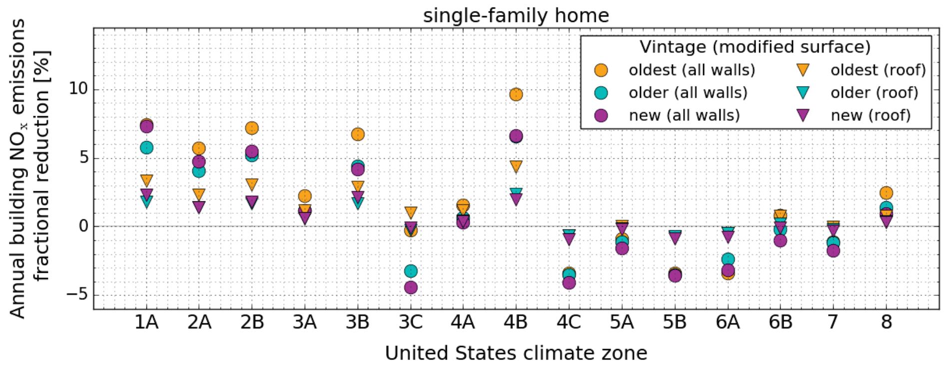
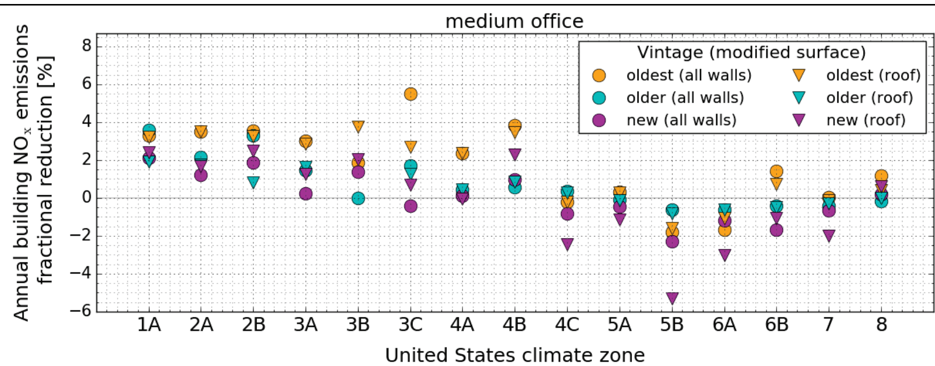


Figure 34. Annual NO_x emissions reduction intensity by vintage and by U.S. climate zone for the (a) single-family home, (b) medium office, and (c) retail stand-alone. The plots compare the reduction intensity from increasing the albedo of all walls by 0.35 to that from increasing the roof albedo by 0.30 (residential) or 0.40 (commercial).

(a)



(b)



(c)

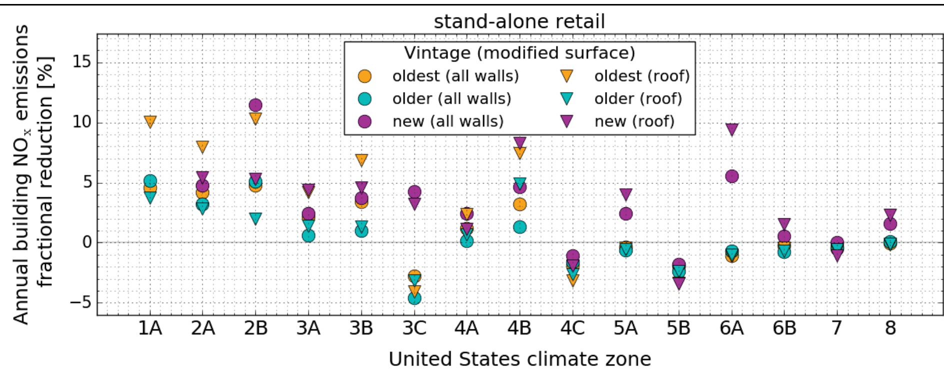


Figure 35. Annual NO_x emissions fractional reduction by vintage and by U.S. climate zone for the (a) single-family home, (b) medium office, and (c) retail stand-alone. The plots compare the fractional reduction from increasing the albedo of all walls by 0.35 to that from increasing the roof albedo by 0.30 (residential) or 0.40 (commercial).

3.4.3.5 Annual SO_2 emissions reduction

Figure 36 and Figure 37 show annual SO_2 emissions reduction intensities and fractional reductions, respectively, by vintage and by U.S. climate zone for the single-family home (Figure 36a and Figure 37a), medium office (Figure 36b and Figure 37b), and stand-alone retail (Figure 36c and Figure 37c). These emissions reduction intensities were computed using Eq. (8) and (10), and the fractional reductions were computed using Eq. (8). These emission reductions were calculated using the state-dependent SO_2 emissions rate of generated electricity (Table 16) and the non-regional emissions rate of consumed gas (Table 17).

The annual SO_2 emissions reduction intensities and fractional reductions have the same trend between U.S. climate zones and between vintages that those we observed for the annual savings intensity and fractional savings of annual CO_2e emissions. The ratios of SO_2 reductions from cool walls to those from a cool roof were very similar to those we observed for CO_2e because these reductions are affected equally by climate (i.e., solar radiation, CDD18C, and HDD18C) and building properties (i.e. envelope thermal resistance) (see Section 3.3.3.1). All fractional savings are also affected equally by building geometry.

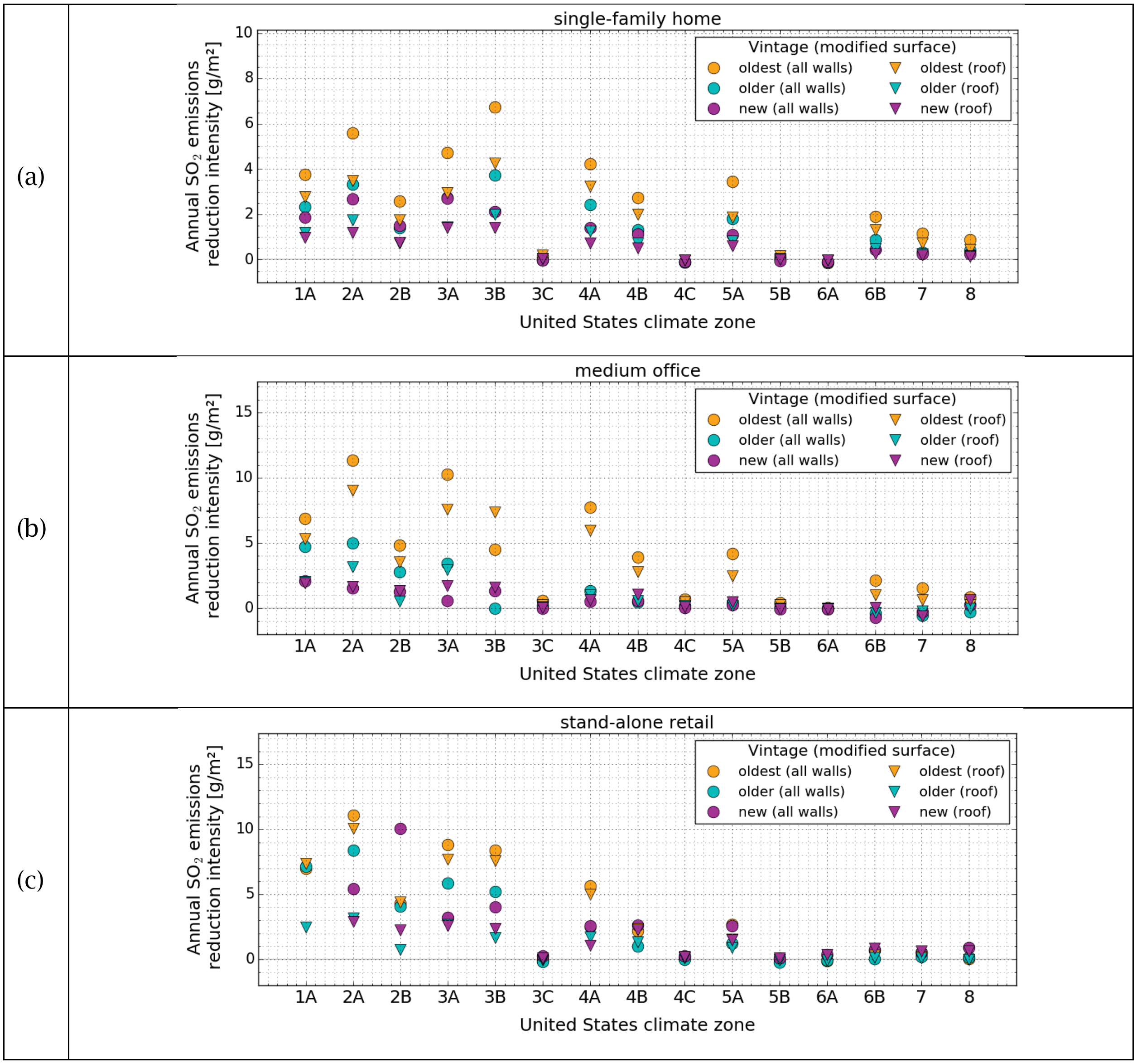


Figure 36. Annual SO_2 emissions reduction intensity by vintage and by U.S. climate zone for the (a) single-family home, (b) medium office, and (c) retail stand-alone. The plots compare the reduction intensity from increasing the albedo of all walls by 0.35 to that from increasing the roof albedo by 0.30 (residential) or 0.40 (commercial).

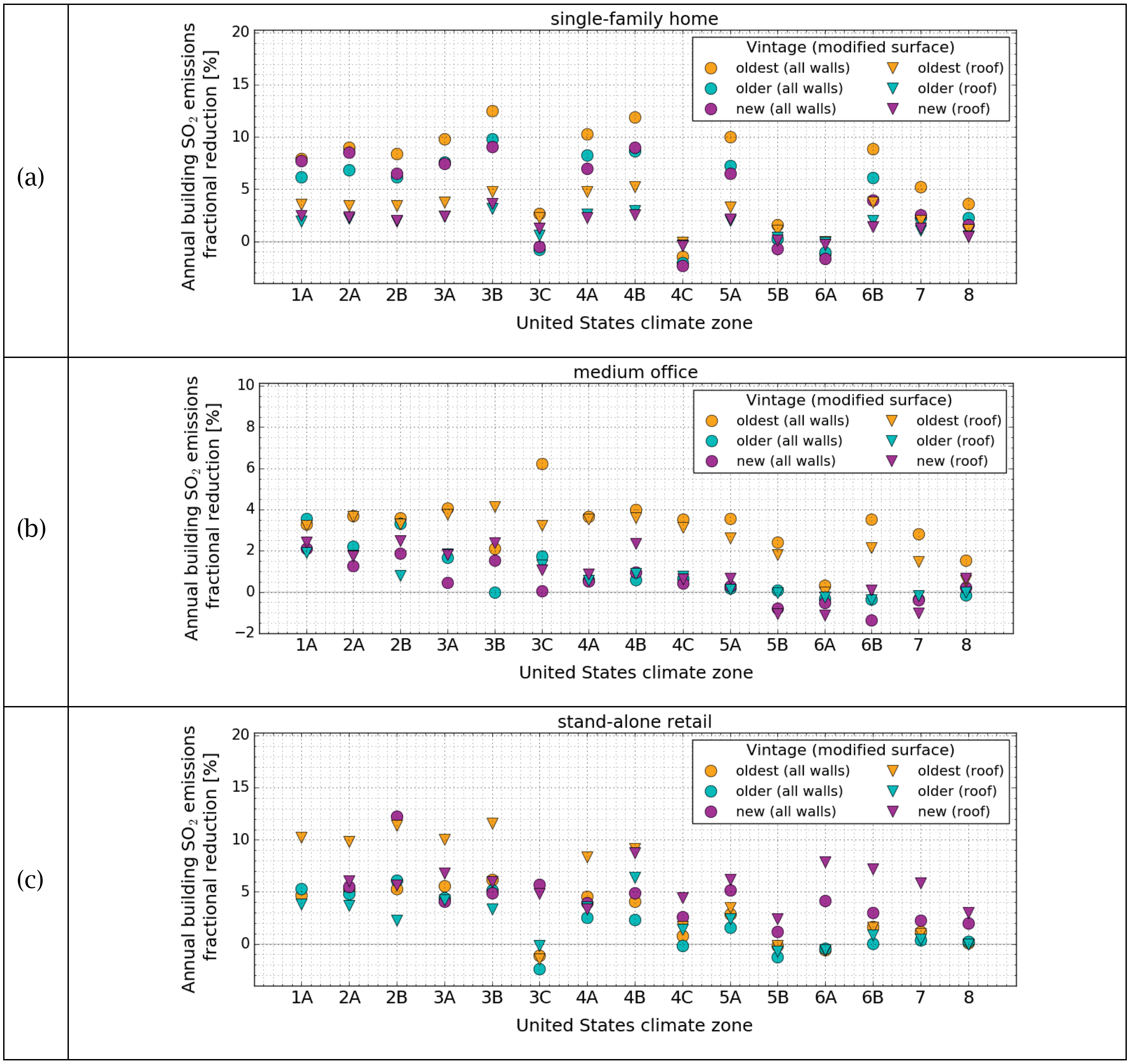


Figure 37. Annual SO_2 emissions fractional reduction by vintage and by U.S. climate zone for the (a) single-family home, (b) medium office, and (c) retail stand-alone. The plots compare the fractional reduction from increasing the albedo of all walls by 0.35 to that from increasing the roof albedo by 0.30 (residential) or 0.40 (commercial).

3.4.3.6 HVAC peak power demand reduction

Figure 38 and Figure 39 show annual-average HVAC peak power demand reduction intensity and fractional reduction, respectively, by vintage and by California climate zone for the single-family home (Figure 38a and Figure 39a), medium office (Figure 38b and Figure 39b), and stand-alone retail (Figure 38c and Figure 39c). The peak power demand reduction intensity were computed using Eqs. (7), (10), and (12).

When comparing between vintages, the reduction intensities and fractional reduction in annual-average HVAC peak power demand have a similar trend to those we observed for the annual savings intensity and fractional savings of HVAC source energy, energy cost, and emissions. However, when comparing between U.S. climate zones, the reduction intensities and fractional reduction in annual-average HVAC peak power demand show a different trend that those observed for HVAC source energy, energy cost, and emissions. These differences in trends happen because HVAC peak power demand is affected only by the summer climate (i.e. peak hours solar radiation and CDD18C), while HVAC source energy, energy cost, and emissions are affected by the annual climate (i.e. solar radiation, CDD18C, and HDD18C).

HVAC source energy, energy cost, and emissions sometimes yielded small penalty intensities and fractional penalties in cold U.S. climate zones. However, HVAC peak power demand yielded reduction intensities and fractional reduction in all U.S. climate zones. Furthermore, in the single-family home (Figure 38a), the peak power demand reduction intensities in cold U.S. climate zones were similar to those from warm U.S. climate zones. Additionally, the peak power demand fractional reduction in the single-family home (Figure 39a) increased slightly with U.S. climate zone.

(a)

(b)

(c)

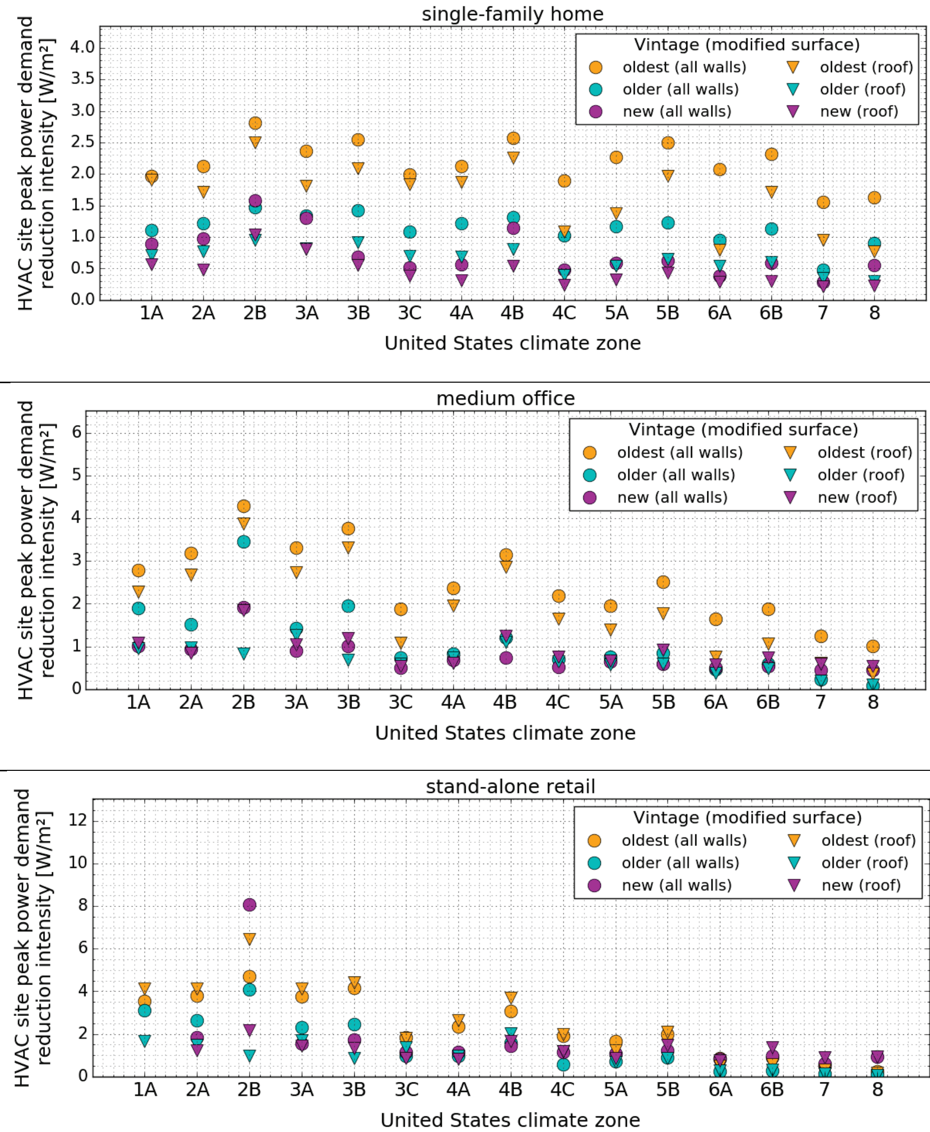


Figure 38. Annual-average HVAC peak power demand reduction intensity by vintage and by U.S. climate zone for the (a) single-family home, (b) medium office, and (c) retail stand-alone. The plots compare the reduction intensity from increasing the albedo of all walls by 0.35 to that from increasing the roof albedo by 0.30 (residential) or 0.40 (commercial).

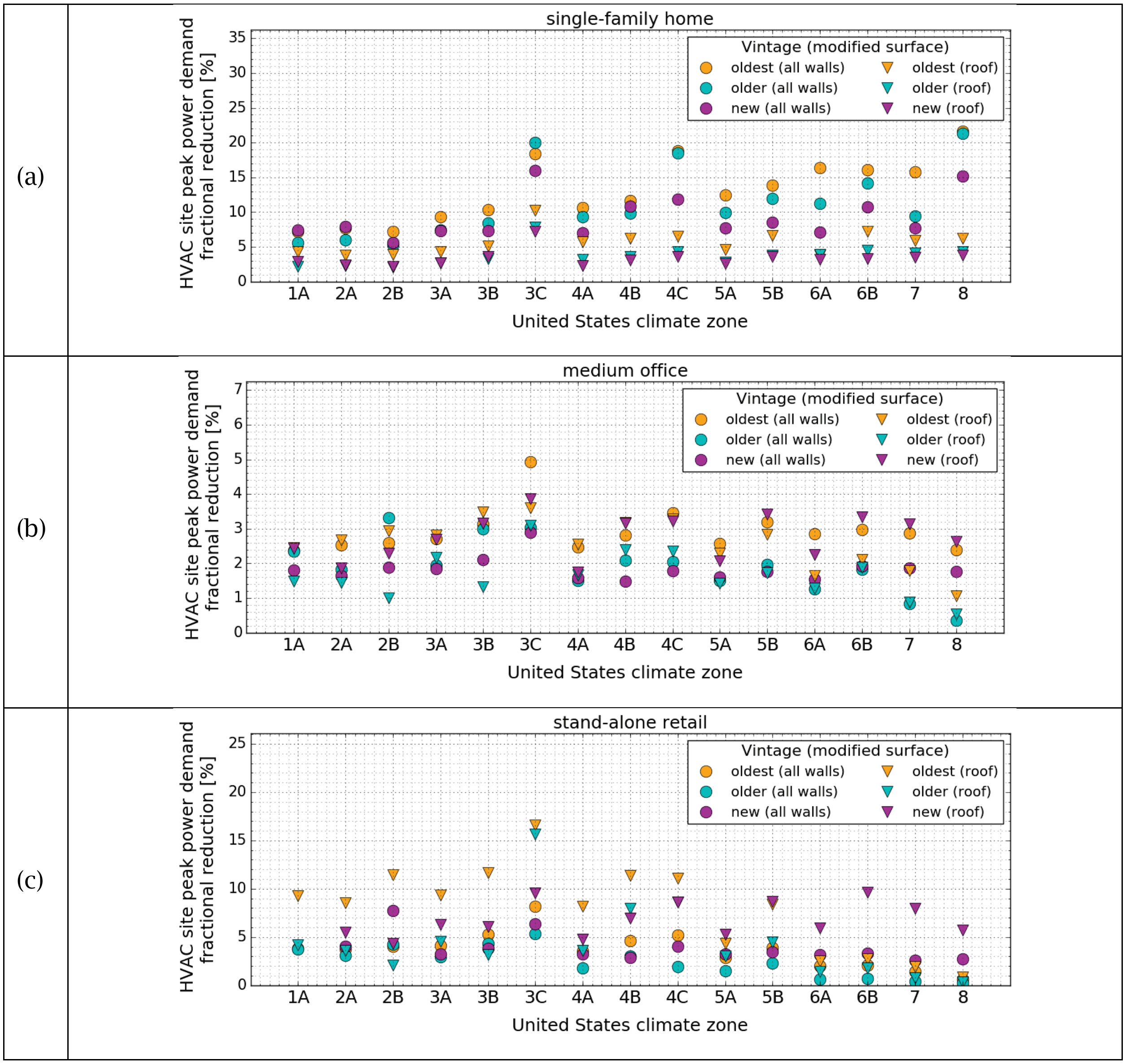


Figure 39. Annual-average HVAC peak power demand fractional reduction by vintage and by U.S. climate zone for the (a) single-family home, (b) medium office, and (c) retail stand-alone. The plots compare the fractional reduction from increasing the albedo of all walls by 0.35 to that from increasing the roof albedo by 0.30 (residential) or 0.40 (commercial).

3.4.3.7 Comparing savings between vintages

Table 30 and Table 31 give oldest-to-new vintage and older-to-new vintage ratios respectively, of annual HVAC source energy savings, emissions reductions, and HVAC energy cost savings. The savings were from increasing the albedo of all walls by 0.35 (to 0.60 from 0.25). The ratios are given by building type and are the mean of both building orientations. The calculations omit ratios that were negative to exclude the few instances where the new vintage generated small annual penalties, while the older and oldest vintages generated annual savings.

In the case of oldest-to-new vintage (Table 30), the oldest-to-new ratios vary widely by building category. In the residential building categories, the oldest-to-new ratio were mostly between 2.0 and 3.0. The medium office yielded the greatest oldest-to-new ratios. The large hotel was the only building category where the energy and energy cost savings as well as the emissions reductions in the oldest vintage were less than those in the new vintage.

In the case of older-to-new vintage (Table 31), savings from the older vintage of residential buildings were typically between 1.2 to 2.0 times that of the new vintage. The medium office yielded the greatest older-to-new ratios. For the large hotel, the savings and reductions from the older vintage were about 0.10 times that of the new vintage.

Table 30. United States average ratios of oldest vintage to new vintage savings by building type and metric for the mean values of the two building orientations.

	U.S. average annual savings ratios (oldest-to-new)				
Prototype building	HVAC source energy [MJ/MJ]	CO_2e [kg/kg]	NO_x [g/g]	SO_2 [g/g]	HVAC energy cost [$/$]
Single-family home (gas furnace)	3.0	2.3	2.9	2.7	4.8
Single-family home (heat pump)	2.5	2.5	2.5	2.5	2.5
Single-family home (electric resistance)	1.9	1.9	1.9	1.9	1.9
Apartment building (gas furnace)	3.0	2.7	2.5	2.8	5.1
Apartment building (heat pump)	2.9	2.9	2.9	2.9	2.9
Apartment building (electric resistance)	2.0	2.0	2.0	2.0	2.0
Large hotel	0.5	0.4	0.7	0.4	0.4
Large office	2.4	1.2	1.5	1.4	0.7
Medium office	8.0	4.4	3.7	9.7	7.6
Small office	4.8	5.0	4.6	4.9	4.4
Fast-food restaurant	3.2	5.2	4.8	3.9	2.4
Retail stand-alone	1.1	2.1	1.9	1.1	1.1
Strip mall retail	3.9	4.0	2.6	2.2	3.8
Sit-down restaurant	6.6	4.0	3.6	5.0	8.1

Table 31. United States average ratios of older vintage to new vintage savings by building type and metric for the mean values of the two building orientations.

Prototype building	U.S. average annual saving ratios (older-to-new)				
	HVAC source energy [MJ/MJ]	CO_2e [kg/kg]	NO_x [g/g]	SO_2 [g/g]	HVAC energy cost [$/$]
Single-family home (gas furnace)	1.3	1.3	1.5	1.6	1.8
Single-family home (heat pump)	1.6	1.6	1.6	1.6	1.6
Single-family home (electric resistance)	1.2	1.2	1.2	1.2	1.2
Apartment building (gas furnace)	1.3	1.8	1.5	1.4	2.0
Apartment building (heat pump)	1.3	1.3	1.3	1.3	1.3
Apartment building (electric resistance)	1.4	1.4	1.4	1.4	1.4
Large hotel	0.1	0.1	0.2	0.1	0.1
Large office	1.5	0.9	1.0	1.0	0.6
Medium office	4.1	2.8	2.6	2.2	3.2
Small office	1.9	3.0	3.7	2.3	1.8
Fast-food restaurant	1.8	2.1	2.5	1.9	1.7
Retail stand-alone	0.5	1.6	1.1	0.6	0.5
Strip mall retail	2.0	2.1	2.4	1.1	1.7
Sit-down restaurant	3.4	2.2	2.2	2.7	3.7

3.4.4 Sum of savings from walls modified one at a time to savings from modifying multiple walls simultaneously (United States)

This section compares the savings obtained from modifying a group of walls simultaneously (e.g., east and west) to the sum of the savings from modifying the walls one at a time. These comparisons are presented for whole-building annual values of (a) source cooling savings, (b) heating penalties, (c) fan savings, and (d) HVAC savings. These energy savings and penalties are shown for the new single-family home (Figure 40), new medium office (Figure 41), and new stand-alone retail (Figure 42). The plots include all the 15 wall combinations simulated in each U.S. climate zone; the values are the average of the two building orientations (east-west and north-south).

In the single-family home, the annual cooling source energy savings were nearly perfectly additive (Figure 40a). In the case of annual heating source energy, the penalties from adding individual walls were additive in many of the wall combinations of all U.S. climate zones (Figure 40b). The remaining wall combinations were close to additive. In the case of annual fan source energy, the savings were not additive for USCZs 6B (Helena) and 7 (Duluth) (Figure 40c). The annual HVAC source energy savings were nearly perfectly additive in the majority of the wall combinations and U.S. climate zones (Figure 40d).

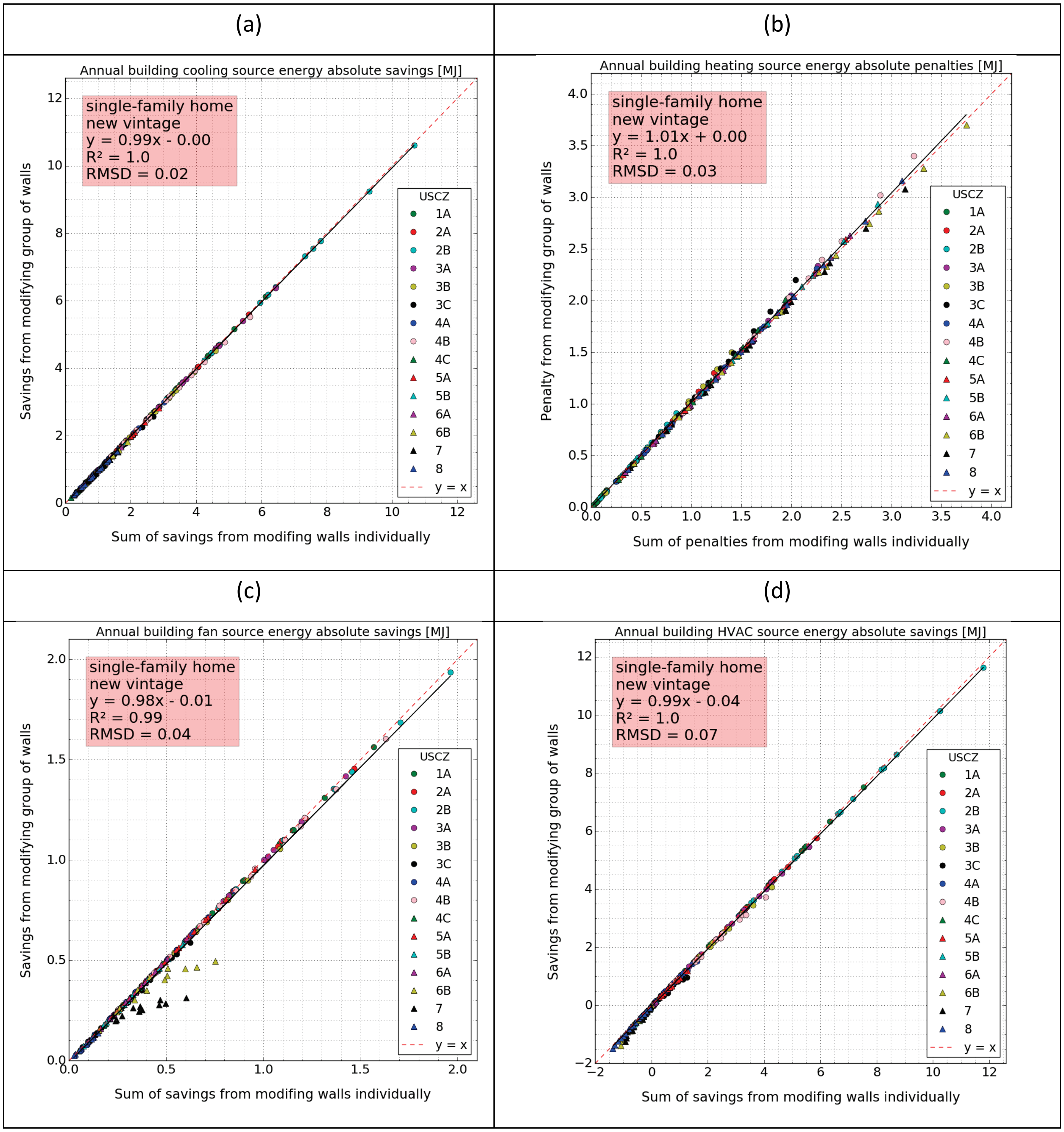


Figure 40. Comparing changes in annual whole-building source energies for the new vintage of single-family home in California climate zones from modifying group of walls simultaneously to those from adding changes from individual walls. The plots show (a) cooling savings, (b) heating penalties, fan savings, and HVAC savings.

In all U.S. climate zones, the annual cooling source energy savings of the medium office were almost perfectly additive (Figure 41a). In the case of annual heating source energy savings, the penalties from adding individual walls were not additive in USCZs 3A (Memphis) and 5B (Boise) and for one wall combination in USCZ 6B (Helena) (Figure 41b). Annual fan source energy savings were not additive for most wall combinations in USCZ 5B (Boise) (Figure 41c). The cases in which heating and fan were not additive led to HVAC source energy savings not being additive in USCZs 3A (Memphis) and 5B (Boise).

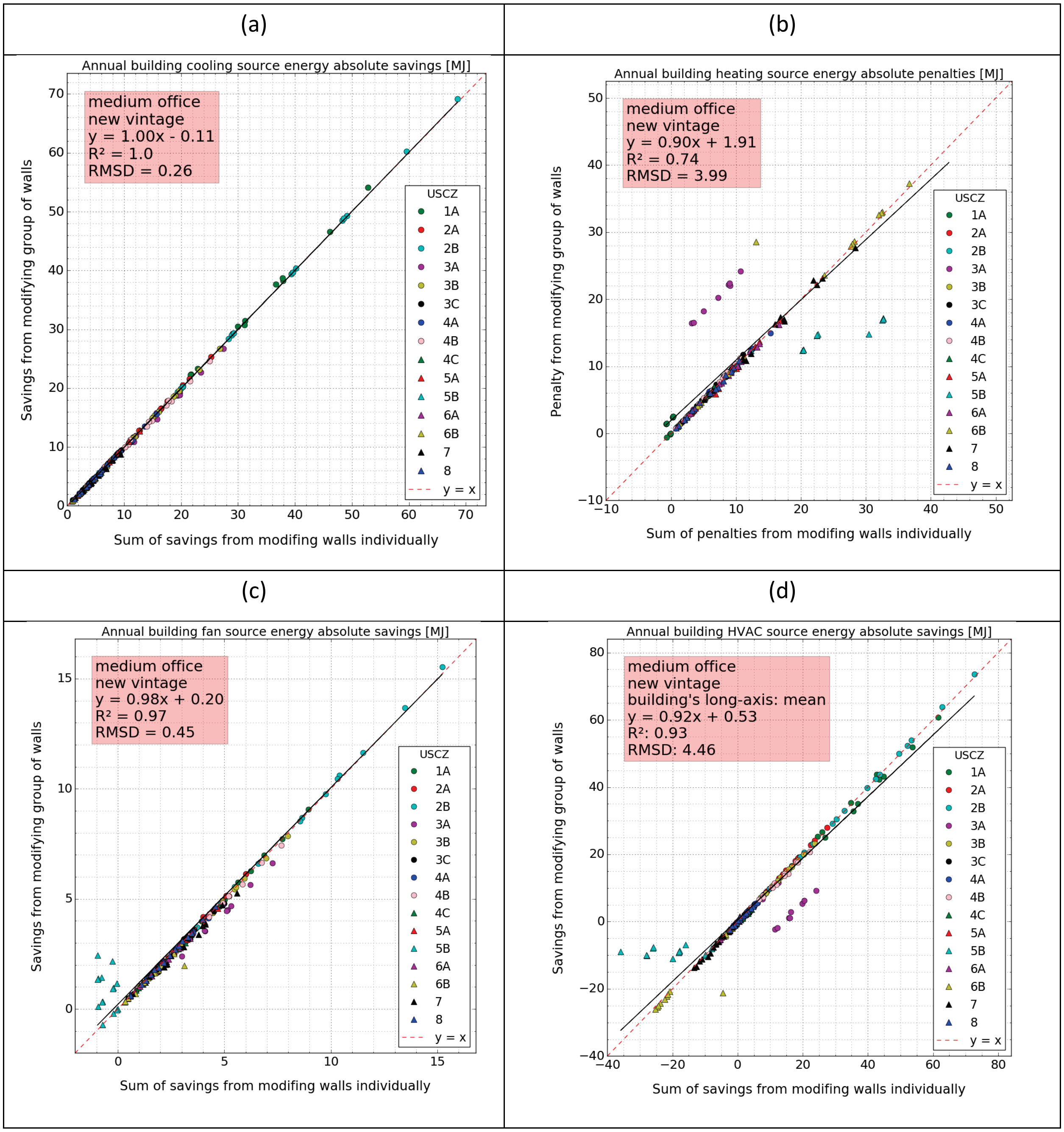


Figure 41. Comparing changes in annual whole-building source energies for the new vintage of medium office in California climate zones from modifying group of walls simultaneously to those from adding changes from individual walls. The plots show (a) cooling savings, (b) heating penalties, fan savings, and HVAC savings.

The new retail stand-alone was the only building category and vintage in which the wall combinations were mostly none additive (Table 32). Source heating and fan energy savings were far from additive in a few USCZs (Figure 42b,c). Thus, HVAC source energy savings ended up being additive only in some U.S. climate zones (Figure 42d).

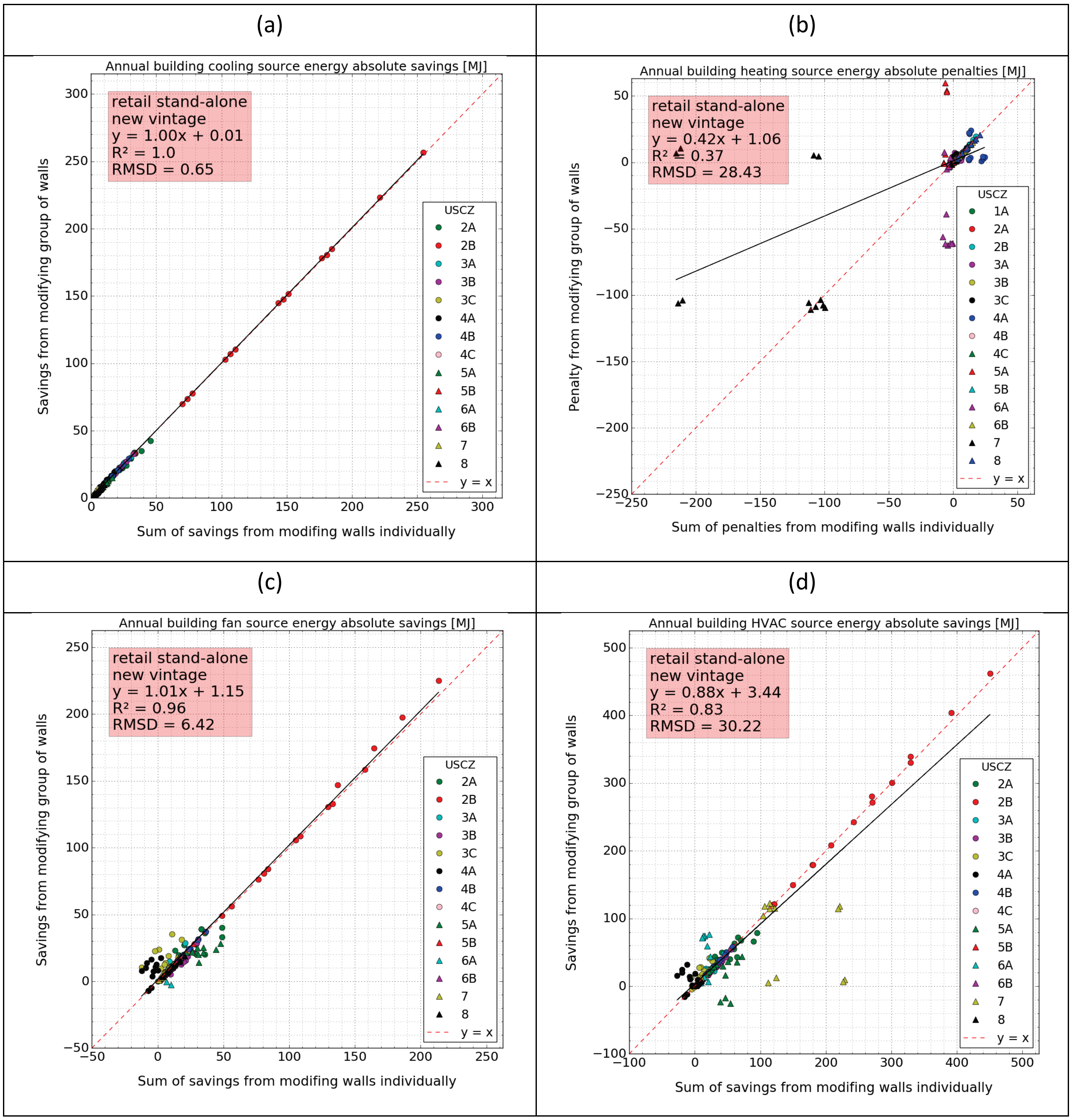


Figure 42. Comparing changes in annual whole-building source energies for the new vintage of stand-alone retail in California climate zones from modifying group of walls simultaneously to

those from adding changes from individual walls. The plots show (a) cooling savings, (b) heating penalties, fan savings, and HVAC savings.

Table 32 summarizes for the U.S. prototypes, the slope, intercept, coefficient of determination (R^2), and root mean square difference (RMSD) of linear regression comparing HVAC source energy savings from modifying multiple walls simultaneously (dependent variable) to the sum of savings from walls modified one at a time (independent variable). There was no building category in which the HVAC savings were perfectly additive for every wall combination and climate zone. However, all vintages of every residential building category show savings that were nearly perfectly additive.

Similar to what was obtained from California simulations, for almost all prototypes and climate zones in U.S., annual cooling energy savings were additive. However, for most prototypes, annual heating (electric or gas) and fan energy savings were additive only in some climate zones and for some wall orientations. Thus, when combining the savings from the different HVAC components (cooling, heating, and fan), there is no prototype in any vintage in which the HVAC system is perfectly additive in all locations and for all wall combinations.

Table 32. Slope, intercept, coefficient of determination (R^2), and root mean square difference (RMSD) of linear regression comparing HVAC source energy savings from modifying multiple walls simultaneously (dependent variable) to the sum of savings from walls modified one at a time (independent variable). These results include all U.S. climate zones and wall combinations of each prototype, and are the average values from both building orientations (E-W and N-S).

	Regression slope [MJ/MJ]			Regression intercept [MJ]			Coefficient of determination (R^2)			RMSD [MJ]		
Prototype building	**oldest**	**older**	**new**	**oldest**	**older**	**new**	**oldest**	**older**	**new**	**oldest**	**older**	**new**
Single-family home (gas furnace)	0.99	0.99	0.99	-0.06	-0.05	-0.04	1.00	1.00	1.00	0.14	0.09	0.07
Single-family home (heat pump)	0.99	0.98	0.99	-0.16	-0.02	-0.02	1.00	1.00	1.00	0.24	0.15	0.10
Single-family home (electric resistance)	1.00	1.00	1.00	-0.16	-0.07	-0.06	1.00	1.00	1.00	0.25	0.13	0.11
Apartment building (gas furnace)	1.00	1.00	1.00	-0.14	-0.07	-0.05	1.00	1.00	1.00	0.19	0.12	0.09
Apartment building (heat pump)	1.00	1.00	1.00	-0.14	-0.07	-0.04	1.00	1.00	1.00	0.23	0.11	0.08
Apartment building (electric resistance)	1.01	1.01	1.01	-0.22	-0.11	-0.08	1.00	1.00	1.00	0.38	0.22	0.16
Large hotel	1.00	0.99	1.01	0.14	0.03	-0.95	1.00	1.00	1.00	0.69	0.90	4.58
Large office	1.03	1.02	0.98	0.86	0.50	0.44	1.00	1.00	1.00	4.82	5.24	10.38
Medium office	1.00	1.00	0.92	-0.13	0.00	0.53	1.00	1.00	0.93	0.69	0.35	4.46
Small office	1.00	0.99	1.00	0.06	0.03	-0.01	1.00	1.00	1.00	0.10	0.12	0.06
Fast-food restaurant	1.00	0.97	1.00	0.02	0.05	0.02	1.00	1.00	1.00	0.25	0.28	0.08
Retail stand-alone	1.00	0.99	0.88	0.00	0.02	3.44	1.00	1.00	0.83	0.68	1.12	30.22
Strip mall retail	0.99	0.99	1.01	-0.06	0.08	0.24	1.00	1.00	0.95	0.81	1.10	3.18
Sit-down restaurant	1.00	0.99	0.99	0.03	0.08	0.01	1.00	0.99	1.00	0.50	0.96	0.21

4 Discussion

4.1 Location-dependent savings

4.1.1 California

We investigated whether annual cooling energy savings intensities and heating energy penalty intensities correlated with cooling degree days and heating degree days, respectively, as well as with absorbed sunlight. Since the insulation in the building envelope and the efficiency of the air conditioner system often vary by location, we normalized cooling degree days, heating degree days, and absorbed sunlight by the face's thermal resistance and by the air conditioner efficiency. Annual cooling energy savings and heating energy penalties increased with annual cooling degree days and annual heating degree days, respectively. However, we observed that these savings and penalties often correlated poorly with changes in absorbed summer and winter sunlight, respectively, possibly because solar irradiation is similar throughout California. Using multivariate linear regression, we investigated whether the energy savings and penalties correlated better with degree days and changes in absorbed sunlight when these two metrics were considered simultaneously. The multivariate linear regression showed that the correlation of cooling and heating energy savings to both metrics did not improve significantly, except in a few instances.

In the older and new vintage prototypes, the requirements in envelope thermal resistances varied by location. These variation in thermal resistances were an additional key factor to how cooling and heating energy savings varied by location.

The warmest California locations—those with the most cooling degree days—yielded the greatest annual cooling savings. CACZ 15 is the climate region in California that would yield the greatest cooling savings intensities from cool walls. CACZs 1 and 16 are the coldest zones in California—highest heating degree days and lowest cooling degree days—leading to the smallest annual cooling savings intensities and greatest annual heating penalty intensities of all climate zones.

Even in the coldest regions, cool walls yielded annual HVAC energy savings and peak power demand reduction in all prototypes and locations, except in the new stand-alone retail in CACZ 16. Thus, the annual cooling savings from cool walls nearly always exceeded the annual heating penalties.

CACZs 14 and 15 were the zones that benefited the most from cool walls. These are the warmest zones in California. However, CACZs 6 through 13, which had similar cooling degree days and heating degree days, also yielded large annual HVAC energy savings. Thus, the zones having similar or greater cooling degree days than heating degree days benefited the most in HVAC energy savings from cool walls. Furthermore, all CACZs greatly benefited in HVAC peak power demand reduction from cool walls.

4.1.2 United States

In the U.S., the warm climates benefitted the most from cool walls. In the case of new prototypes in the U.S., the differences in cool wall savings between locations also depended in the year of building code adopted by the states. For example, Phoenix, AZ (USCZ 2B), which has a warm climate, follows a building code that is 10+ years old. Thus, the prototypes simulated for USCZ 2B followed less stringent wall construction and HVAC efficiencies than the prototypes simulated in states that mandate newer building codes. Thus, climate zone 2B (Phoenix) benefitted the most from cool walls because it has a warm climate and the state follow 10+ year old building codes. USCZs 1A (Miami), 2A (Houston), 3A (Memphis), 3B (El Paso), 3C (San Francisco), 4A (Baltimore), and 4B (Albuquerque), were locations that also yielded cool wall savings from all vintages. The remaining U.S. climate zones are the coldest locations in the country, and experienced small cool wall energy savings and often yielded small energy penalties. However, all USCZs experienced cool wall HVAC peak power demand reduction.

4.2 Cool wall savings versus cool roof savings

Recall that in the California and U.S. case studies, the simulated increase in wall albedo (0.35) was 0.05 (16.7 percent) more than the increase in residential roof albedo (0.30), and was 0.05 (12.5 percent) less than the increase in commercial roof albedo (0.40). Thus, the differences in energy savings between cool walls and cool roofs were in part due to these differences in albedo increase.

4.2.1 California

In the older and oldest vintages of all prototypes, the east, south, and west walls yielded greater annual HVAC source energy savings intensities (per area of surface modified) than those from the roof. In these vintages, walls were built with significantly less thermal resistance than the roofs. Hence, although the roof in summer received more sunlight than any of the walls, the savings intensities from the roof were as small as those from the north wall, which was the wall that received the least sunlight in summer. In the new vintage prototypes, the wall annual HVAC savings intensities were greater than the roof savings in some of the prototypes.

The annual savings and penalty intensities were also influenced by the solar irradiation received by the individual faces. In summer, while the roof receives more daily solar irradiation than any of the four walls, the combined daily solar irradiation intercepted by the four walls was often equal or greater than the daily solar irradiation received by the roof. In winter, the solar path peaks in the southern sky at a small elevation angle; therefore, the roof receives less solar irradiation in winter than it does in summer and the south wall receives significantly more solar irradiation than it does in summer. Thus, the differences in savings and penalty intensities from the walls to those from the roof were influenced by the differences in thermal resistance and incident solar irradiation.

In prototypes with a large ratio of roof area to net wall area, whole-building annual HVAC savings from raising the albedo of all four walls were smaller than those from increasing roof albedo. The two retail prototypes and the sit-down restaurant had the largest roof area to net wall area ratios, which were at least 200 percent. In these three prototypes, the whole-building savings from the four walls were smaller than those from the roof in all three vintages. Conversely, buildings with a small roof area to net wall area ratio (e.g., the single-family home and apartment building) typically yielded whole-building wall savings that were greater than the roof savings. In the oldest vintage, the whole-building wall savings in the single-family home were up to 3.0 times that of the roof. In the new vintage, buildings with small roof area to net wall area ratio still had whole-building wall savings that were equal or greater than those from the roof.

4.2.2 United States

In all vintages, the magnitude of HVAC source energy changes from the east, south, and west walls yielded were always greater than that from the roof. In locations with warm climates (USCZ 1 to USCZ 4B), the east, south, and west walls in the single-family home yielded greater annual HVAC source energy savings intensities than those from the roof; savings intensities from the roof were similar to those from the north wall. In the U.S., the ratio of roof thermal resistance to wall thermal resistance varies widely between locations. The ratio of solar irradiation intercepted by the roof to that by each wall also varies widely between locations. Thus, the differences in HVAC savings intensities from the east, south, or west wall to those from the roof varied widely between USCZs. In locations with cold climates, the annual HVAC source energy penalty intensities from the north, east, and west wall were similar to those from the roof.

In the warm climates, increasing the albedo of all four walls led to annual HVAC source energy savings intensity that were comparable to those from increasing roof albedo. The differences in savings between the four-walls and the roof varied by building category, vintage, and location. In cold climates [USCZs 5B (Boise) to 8 (Fairbanks)], the changes (savings or penalties) in annual HVAC source energy from the north, east, or west walls were similar to those from the roof. In these cold climates, the south wall yielded annual HVAC source energy penalties greater than those from any other face.

As in California, the differences in whole-building savings from increasing the albedo of all walls to those from increasing the albedo of the roof were influenced by the roof area to net wall area ratio. In building prototypes with small roof area to net wall area ratio (e.g. single-family home), savings from increasing albedo of all walls were up to 2.5 times that from roofs.

4.3 Savings by wall orientation

All walls within a given prototype have the same thermal resistance. If each modified wall undergoes the same albedo change, differences by orientation in savings or penalty intensities are driven by the differences in absorbed solar irradiation. For example, consider a building in the northern hemisphere. In summer, the east and west walls receive the most solar irradiation followed in descending order by the south wall and north wall. Under clear skies, the south wall will receive more beam sunlight in winter than in summer because the sun is lower, the wall's minimum beam incidence angle is smaller, and the wall is exposed to more hours of direct (beam) illumination.

4.3.1 California

The north wall always had the smallest cooling savings and heating penalty intensities. During the heating season, the north wall rarely yielded heating penalties; north wall generated heating penalties only in a few cases in CACZ 16.

The south wall was typically the wall with the greatest cooling savings intensity, followed closely by the west and east walls. However, the south wall typically had the greatest heating penalty intensities.

When considering the entire year, the wall with the greatest HVAC savings intensity varied by prototype and climate zone. In the commercial prototypes, the west wall, followed by the east wall, were typically the surfaces with the greatest annual HVAC saving intensities. In the residential prototypes, the greatest savings were from the south wall. However, the savings from the three walls (east, south, and west) were very similar to each other; thus, all three walls yielded significant savings from cool walls.

4.3.2 United States

As in California, the north wall in the single-family home always had the smallest cooling savings and heating penalty intensities, leading to the smallest annual HVAC savings or penalties. During the cooling season, all walls in every U.S. climate zone yielded cooling savings. The wall orientation with the greatest cooling savings varied by location, but it was either the east, south, or west wall. However, these three wall orientations typically yielded similar cooling savings. During the heating season, all walls in every U.S. climate zone yielded heating penalties; however, the penalties were significantly greater from the south wall compared to those from the other walls.

When considering annual HVAC source energy, all walls in the single-family home yielded savings from USCZ 1A (Miami) to USCZ 4B (Albuquerque). In USCZs 6B (Helena), 7 (Duluth), and 8 (Fairbanks), every wall led to annual HVAC energy penalties or to no change in HVAC energy. The south wall led to annual HVAC energy penalties from USCZ 4C (Seattle) to USCZ 8 (Fairbanks).

4.4 Savings by vintage and building geometry

4.4.1 California

The oldest vintage always yielded the greatest cool wall savings intensities, followed by the older vintage. As mentioned before, this is because walls in these vintages were built with substantially less insulation that required in new construction. The older and oldest vintages were also simulated with HVAC efficiencies that comply with 10+ year old building codes. These older and oldest vintage results are important because in California, they represent over 75 percent of the current residential building stock and about 70 percent of the commercial building stock. Cool walls in the new vintage prototypes still yielded significant annual HVAC savings intensities, which were comparable to the savings intensities from cool roofs.

Whole-building savings scale with wall area. Thus, whole-building wall savings will increase with building height. Even prototypes with a large window-to-wall area ratio (i.e., medium and large offices) benefited from cool walls since these were tall multi-level buildings with a large net wall area.

4.4.2 United States

For most building categories in the U.S., the oldest vintage yielded greater cool wall savings or penalty intensities than the other vintages. In buildings like the retail stand-alone, which the wall type and wall construction varied by vintage, the vintage yielding the greatest annual HVAC energy changes varied by U.S. climate zone.

For the case of new vintage, some U.S. climate zones were simulated in states which mandate building codes that are 10 to 13 years old (Table 3). In these U.S. climate zones, the prototypes were simulated with HVAC efficiencies comparable to those used in the older and oldest vintages. Additionally, the prototypes in these U.S. climate zones were simulated with less envelope thermal resistances than those used in the rest of the U.S. climate zones. Thus, in these U.S. climate zones that follow 10+ year old building codes, the annual HVAC source energy savings from the new vintage were often close to those from the older vintage.

4.5 Additive property of cool wall savings

4.5.1 California and United States

While the annual cooling savings were usually additive, the annual heating penalties and fan savings were sometimes non-additive. When investigating why the gas heating and fan were often non-additive, we delved into a few analyses that considered (a) auto-sized vs fixed size HVAC system and (b) hourly energy uses from each HVAC component.

In many prototypes, the fan drew constant load irrespective of changes to cooling or heating load. Therefore, fan energy use lacked any sensitivity to changes in cooling and heating energy changes. In these cases, annual HVAC energy changes were close to additive when fan energy was not included.

The additive tests indicate that it is worth exploring further this matter, since for most prototypes and in most locations, annual HVAC energy savings were close to being fully additive. If savings from individual walls are in fact additive, this will simplify estimation of cool wall savings for any of the 15 possible wall combinations. As an example, assume we are interested in knowing the savings from modifying all walls of a building. If savings are additive, the savings from modifying all walls are obtained by adding the individual savings from each of the four walls. The same approach can be applied to obtain the savings from any other wall combination.

5 Conclusions

This report presents an exhaustive study on the effects of cool walls in individual buildings in all California and U.S. climate zones. The work investigated how cool walls may lead to changes in site energy use, source energy use, pollutant emissions, energy cost, and HVAC peak power demand. As we expected, the magnitude of savings and penalties from cool walls depend on key factors, including climate, wall construction, wall orientation, building orientation, and HVAC efficiency. The influence of each of these factors on cool wall savings were investigated by simulating: (a) 31 different climate zones across California and U.S.; (b) three different building vintages (oldest, older, and new) that followed building codes adopted in each location and vintage; (c) 15 different wall combinations; and (d) two different building orientations.

5.1 California

In California, cool walls led to annual HVAC source energy savings in all 16 climate zones. Consequently, all California climate zones also yielded savings in pollutant emissions and energy cost. All CACZs also experienced HVAC peak power demand reduction. The locations that yielded the greatest cool wall savings intensities were climate zones 14 (China Lake) and 15 (Imperial), which are locations with a long and warm cooling season, and short and mild heating season. The smallest cool wall savings intensities were from California climate zones 1 (Arcata) and 16 (Mount Shasta), which are the two coldest locations in the state.

Cool walls benefitted the oldest vintage prototypes significantly more than the older and new vintage prototypes; cool walls in the oldest single-family home led up to 25 percent (CACZ 7, San Diego) in annual HVAC source energy savings. Among all vintages, cool walls reduced whole-building annual HVAC energy use 3.0 percent to 25 percent in single-family homes, 0.5 percent to 3.7 percent in medium offices, and 0.0 percent to 9.0 percent in stand-alone retail stores. Energy use, emissions, and energy cost savings from the oldest vintage were generally three to six times greater than those from the new vintage. The cool wall savings from the oldest vintage are important since they represent over 60 percent of California’s building stock.

Past and present California building codes prescribe more insulation in roofs than in walls. Additionally, in any annual season, the combined solar energy received by the four walls is more than the solar energy received by the roof. Hence, the energy use, emissions, and energy cost savings from cool walls are comparable to those from cool roofs even in buildings with a large ratio of roof area to net wall area. In buildings with small ratio of roof area to net wall area, the savings from cool walls were often significantly greater than those from cool roof. In the single-family home, which had small ratio of roof area to net wall area, the whole-building cool walls to cool roof HVAC source energy savings ratio were 1.5 to 3.5. The medium office and stand-alone retail had large ratio of roof area to net wall area; the whole-building cool walls to cool roof HVAC source energy savings ratio were 0.40 to 1.0 in medium offices, and 0.20 to 0.85 in stand-alone retail stores. Thus, the differences in savings between cool walls and cool roofs are highly dependent on two building characteristics: (a) roof and wall insulation, and (b) ratio of roof area to net wall area.

The south wall always led to the largest heating penalties; however, it also led to large savings during the cooling season. Annually, the savings from the south wall were similar to those from the east wall and west wall. These savings from the east, south, and west walls were always greater than those from the north wall. Therefore, the east, south, and west walls are the most crucial when considering adopting cool walls in any region in California.

5.2 United States

In the U.S., climate zone 2B (Phoenix) benefitted the most from cool walls because it has a warm climate and the state follows 10+ year old building codes. USCZs 1A (Miami), 2A (Houston), 3A (Memphis), 3B (El Paso), 3C (San Francisco), 4A (Baltimore), and 4B (Albuquerque), were locations that also yielded cool wall whole-building savings and savings intensities from all vintages. The remaining U.S. climate zones are the coldest locations in the country, and experienced small cool wall savings and often yielded small penalties.

As in California, the oldest vintage yielded greater cool wall savings or penalties than the other vintages. This is important since the oldest vintage buildings represent in most U.S. locations at least 60 percent of the building stock. In warm U.S. climate zones [1A (Miami, FL) to 4B (Albuquerque, NM)], cool walls in all vintages reduced whole-building annual HVAC energy use 2.0 percent to 8.5 percent in single-family homes, 0.0 percent to 4.2 percent in medium offices, and -0.5 percent to 5 percent in stand-alone retail stores. Cool walls also led to small annual HVAC source energy savings in cold United States climate zones [4C (San Francisco, CA) to 7 (Duluth, MN)] in some building categories and vintages.

The east, south, and west walls typically had similar savings, which in turn were greater than those from the north wall. Additionally, cool wall savings were similar, and sometimes much greater, than those from the cool roof. In warm U.S. climate zones [1A (Miami, FL) to 4B (Albuquerque, NM)], the ratio of whole-building cool wall savings to cool roof savings were 1.1

to 3.0 in single-family homes, 0.20 to 1.9 in medium offices, and 0.30 to 2.1 in stand-alone retail stores

This study demonstrated that in the U.S., all buildings of any vintage from USCZ 1A (Miami) to USCZ 4B (Albuquerque) would benefit from cool walls, especially on the east, south, and west faces. Additionally, all USCZs will benefit from a reduction in HVAC peak power demand.

6 Future work

Future work should further investigate the additive nature of cool wall savings, examining those simulations in which the cool wall savings were not additive. It should also explore how shadows casted and sunlight reflected by neighboring buildings influence cool wall savings.

The current study also provides the foundation for two new Codes and Standards Enhancement (CASE) studies for California's Title 24 building energy efficiency standards. The first CASE study should evaluate the prescription of cool walls for commercial and residential buildings. The second CASE study should consider the prescription of cool roofs for residential cool roof retrofits.

Finally, the current study can serve as a roadmap to any future work interested in the effect of cool walls in regions outside of U.S.

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Task Report Appendix A: Building stock age distribution

The latest available version of the Commercial Building Energy Consumption Survey (CBECS) is 2012 (EIA 2012). We used the microdata from CBECS 2012 to calculate the age distribution of existing commercial buildings in different U.S. locations. Table A-2 through Table A-6 give the age distribution of different building types related to the commercial prototypes used in this study. All buildings were grouped into four age periods (<1980, 1980-1989, 1990-1999, and 2000-2012). The darkness of the green in the cells of the tables increases with the number of buildings in the age group (see color legend in Table A-1). The tables show that in most locations and for most building types, the majority of the buildings are from <1980, 1980-1989, and 2000-2012.

The latest version of the Residential Energy Consumption Survey (RECS) available with microdata when our study began was 2009 (EIA 2009). We used the microdata from RECS 2009 to calculate the age distribution of existing single-family home (Table A-7) and apartment buildings (Table A-8) in different U.S. states. All buildings were grouped into five age periods (<1980, 1980-1989, 1990-1999, 2000-2004, and 2005-2009). As done with the commercial buildings, the darkness of the green in the table cells increases with the number buildings in each age group.

Table A-1. Legend for color scheme in Table A-2 through Table A-8.

Color	Fraction of existing buildings [%]
	> 30
	20-30
	10-20
	< 10

Table A-2. Age distribution of offices by U.S. census division computed using CBECS 2012.

CBECS building category: office **Related EnergyPlus building categories: small office, medium office, large office**					
Census Division	**Representative cities (USCZ)**	**< 1980 [%]**	**1980-1989 [%]**	**1990-1999 [%]**	**2000-2012 [%]**
South Atlantic	Miami (1A) Baltimore (4A)	43	24	11	21
West South Central	Houston (2A) El Paso (3B)	39	26	11	24
Mountain	Phoenix (2B) Albuquerque (4B) Boise (5B) Helena (6B)	40	13	19	28
East South Central	Memphis (3A)	51	22	11	17
Pacific	San Francisco (3C) Salem (4C) Fairbanks (8)	51	23	15	11
East North Central	Chicago (5A)	59	12	18	12
New England	Burlington (6A)	60	18	9	13
West North Central	Duluth (7)	58	15	14	13

Table A-3. Age distribution of retail stores (no malls) by U.S. census division computed using CBECS 2012.

CBECS building category: retail other than mall **Related EnergyPlus building category: stand-alone retail**					
Census Division	**Representative cities (USCZ)**	**< 1980 [%]**	**1980-1989 [%]**	**1990-1999 [%]**	**2000-2012 [%]**
South Atlantic	Miami (1A) Baltimore (4A)	46	20	12	23
West South Central	Houston (2A) El Paso (3B)	47	9	21	24
Mountain	Phoenix (2B) Albuquerque (4B) Boise (5B) Helena (6B)	35	33	12	19
East South Central	Memphis (3A)	45	21	23	11
Pacific	San Francisco (3C) Salem (4C) Fairbanks (8)	68	7	12	13
East North Central	Chicago (5A)	50	22	8	20
New England	Burlington (6A)	69	7	15	10
West North Central	Duluth (7)	63	18	5	14

Table A-4. Age distribution of strip shopping malls by U.S. census division computed using CBECS 2012.

CBECS building category: strip shopping mall Related EnergyPlus building category: retail strip mall					
Census Division	**Representative cities (USCZ)**	**< 1980 [%]**	**1980-1989 [%]**	**1990-1999 [%]**	**2000-2012 [%]**
South Atlantic	Miami (1A) Baltimore (4A)	38	25	9	28
West South Central	Houston (2A) El Paso (3B)	54	8	12	26
Mountain	Phoenix (2B) Albuquerque (4B) Boise (5B) Helena (6B)	32	6	1	62
East South Central	Memphis (3A)	11	49	22	18
Pacific	San Francisco (3C) Salem (4C) Fairbanks (8)	43	13	11	34
East North Central	Chicago (5A)	45	12	29	14
New England	Burlington (6A)	65	11	15	10
West North Central	Duluth (7)	49	39	7	5

Table A-5. Age distribution of sit-down and fast-food restaurants by U.S. census division computed using CBECS 2012.

CBECS building category: Food service Related EnergyPlus building categories: sit-down restaurant, fast-food restaurant					
Census Division	**Representative cities (USCZ)**	**< 1980 [%]**	**1980-1989 [%]**	**1990-1999 [%]**	**2000-2012 [%]**
South Atlantic	Miami (1A) Baltimore (4A)	39	15	19	27
West South Central	Houston (2A) El Paso (3B)	40	16	30	14
Mountain	Phoenix (2B) Albuquerque (4B) Boise (5B) Helena (6B)	57	15	8	20
East South Central	Memphis (3A)	42	26	13	20
Pacific	San Francisco (3C) Salem (4C) Fairbanks (8)	64	10	17	9
East North Central	Chicago (5A)	54	19	17	9
New England	Burlington (6A)	66	10	17	8
West North Central	Duluth (7)	48	7	16	29

Table A-6. Age distribution of hotels by U.S. census division computed using CBECS 2012.

CBECS building category: lodging Related EnergyPlus building category: large hotel					
Census Division	**Representative cities (USCZ)**	**< 1980 [%]**	**1980-1989 [%]**	**1990-1999 [%]**	**2000-2012 [%]**
South Atlantic	Miami (1A) Baltimore (4A)	60	21	5	15
West South Central	Houston (2A) El Paso (3B)	39	23	26	12
Mountain	Phoenix (2B) Albuquerque (4B) Boise (5B) Helena (6B)	61	6	17	15
East South Central	Memphis (3A)	76	4	14	6
Pacific	San Francisco (3C) Salem (4C) Fairbanks (8)	58	21	10	11
East North Central	Chicago (5A)	36	9	19	35
New England	Burlington (6A)	32	7	12	49
West North Central	Duluth (7)	40	18	2	39

Table A-7. Age distribution of detached single-family homes by state or group of states computed using RECS 2009.

RECS building category: single-family detached Related EnergyPlus building category: single-family home						
RECS reported state or group of states	**Representative cities (USCZ)**	**< 1980 [%]**	**1980-1989 [%]**	**1990-1999 [%]**	**2000-2004 [%]**	**2005-2009 [%]**
Florida	Miami (1A)	45	17	16	14	8
Texas	Houston (2A) El Paso (3B)	50	16	15	11	8
Arizona	Phoenix (2B)	30	16	31	15	8
Tennessee	Memphis (3A)	51	10	18	11	10
California	San Francisco (3C)	67	13	12	5	4
Delaware, District of Columbia, Maryland, Virginia	Baltimore (4A)	59	16	19	4	2
Nevada, New Mexico	Albuquerque (4B)	36	21	25	7	10
Alaska, Hawaii, Oregon, Washington	Seattle (4C) Fairbanks (8)	51	14	17	10	8
Illinois	Peoria (5A)	66	10	8	13	2
Idaho, Montana, Utah, Wyoming	Boise (5B) Helena (6B)	47	25	15	3	10
Connecticut, Maine, New Hampshire, Rhode Island, Vermont	Burlington (6A)	69	13	8	8	3
Iowa, Minnesota, North Dakota, South Dakota	Duluth (7)	64	11	13	6	6

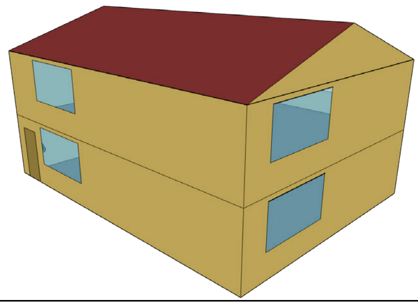
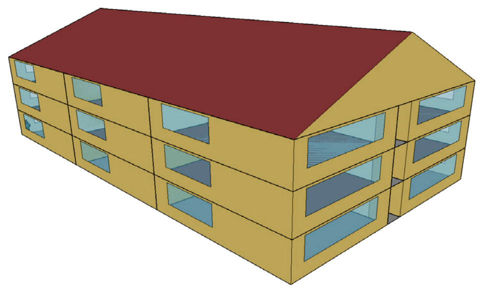
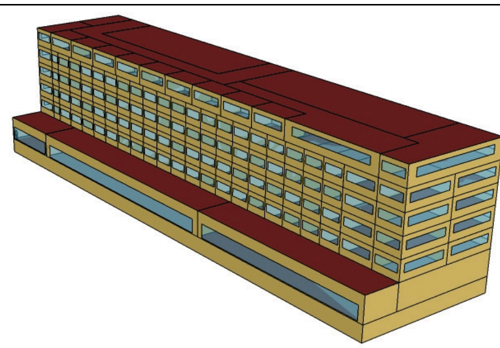
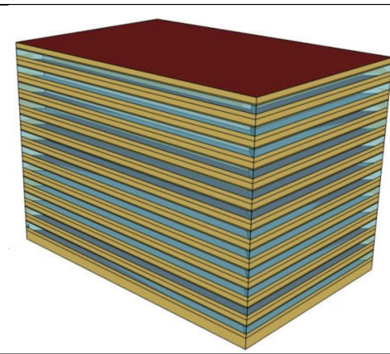
Table A-8. Age distribution of apartment buildings by state or group of states computed using RECS 2009.

RECS building category: apartment building with 5+ units Related EnergyPlus building category: apartment building						
RECS reported state or group of states	**Representative cities (USCZ)**	**< 1980 [%]**	**1980-1989 [%]**	**1990-1999 [%]**	**2000-2004 [%]**	**2005-2009 [%]**
Florida	Miami (1A)	46	25	13	8	8
Texas	Houston (2A) El Paso (3B)	56	24	9	5	7
Arizona	Phoenix (2B)	29	26	17	11	19
Tennessee	Memphis (3A)	43	18	30	4	5
California	San Francisco (3C)	65	19	10	3	3
Delaware, District of Columbia, Maryland, Virginia	Baltimore (4A)	56	7	10	18	8
Nevada, New Mexico	Albuquerque (4B)	0	14	0	29	57
Alaska, Hawaii, Oregon, Washington	Seattle (4C) Fairbanks (8)	52	22	18	7	1
Illinois	Peoria (5A)	62	5	20	3	9
Idaho, Montana, Utah, Wyoming	Boise (5B) Helena (6B)	9	73	18	0	0
Connecticut, Maine, New Hampshire, Rhode Island, Vermont	Burlington (6A)	67	29	1	3	0
Iowa, Minnesota, North Dakota, South Dakota	Duluth (7)	55	22	13	5	6

Task Report Appendix B: Building prototype characteristics

Table B-1 illustrates the 10 prototypes used in the study.

Table B-1. Sketches of building category prototypes.

Single-family home	
Apartment building	
Large hotel	
Large office	

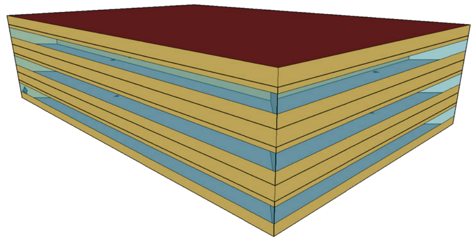
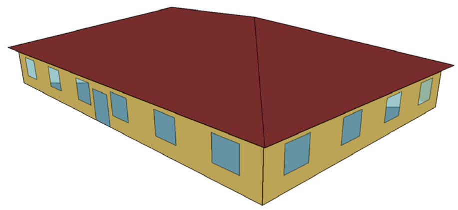
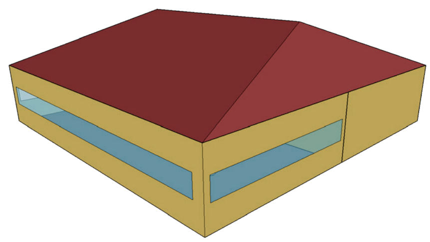
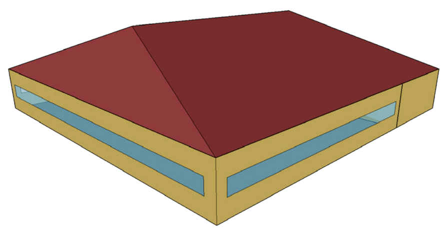
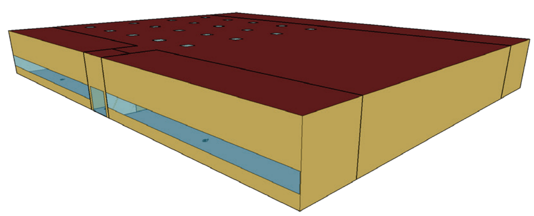
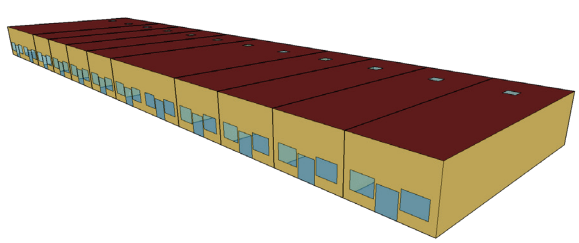
Medium office	
Small office	
Fast-food restaurant	
Sit-down restaurant	
Retail stand-alone	
Strip mall retail	

Table B-2 describes the geometry, envelope construction, and HVAC system for each vintage of the single-family home. Details of the internal loads (e.g. persons, lighting, equipment) and their hourly schedules are further described in the EnergyPlus single-family home prototypes.

Table B-2. Geometry, envelope construction, and HVAC system for each vintage of the single-family home.

Property	Oldest vintage	Older vintage	New vintage
General building characteristics			
Conditioned floor area (m²)	223	Same	Same
Roof area (m²)	118	Same	Same
Number of stories	2	Same	Same
Ratio of roof area to net wall area [a]	0.61	Same	Same
Ratio of window area to net wall area	0.15	Same	Same
Roof albedo			
Base case	0.10	Same	Same
Alternative cases	0.25, 0.40, and 0.60	Same	Same
Roof thermal emittance	0.90	Same	Same
Roof construction			
Thermal resistance (m²·K/W) [ft²·°F·h/BTU]			
Asphalt shingles	0.077 [0.440]	Same	Same
1/2” oriented strand board (OSB)	0.109 [0.620]	Same	Same
Attic			
Rise to run [slope]	4:12 [18.4°]	Same	Same
Ceiling construction (top to bottom)			
Thermal resistance (m²·K/W) [ft²·°F·h/BTU]			
Insulated wood frame (10% framing factor)	Varies by climate zone (Table C-3 &Table C-6)	Same	Same
1/2” drywall	0.079 [0.450]	Same	Same
Wall construction (outside to inside)			
Thermal resistance (m²·K/W) [ft²·°F·h/BTU]			
Stucco	0.018 [0.103]	Same	Same
Paper felt	0.011 [0.060]	Same	Same
Sheathing	0.135 [0.767]	Same	Same
5/8” OSB	0.137 [0.775]	Same	Same

Insulated wood frame (15% framing factor)		Varied by climate zone (Table C-2 &Table C-5)		Same		Same
1/2” drywall		0.079 [0.450]		Same		Same
Net wall area when long-axis of building extends east-west (m²)						
North		52.9		Same		Same
East		39.2		Same		Same
South		52.9		Same		Same
West		39.2		Same		Same
Foundation		Slab		Same		Same
Windows						
Thermal transmittance (W/m²·K)		Varies by climate zone and orientation		Same		Same
Visible transmittance		Varies by climate zone and orientation		Same		Same
Window area when long-axis of building extends east-west (m²)						
North		8.29		Same		Same
East		8.29		Same		Same
South		8.29		Same		Same
West		8.29		Same		Same
Effective air leakage area (cm²)						
Living unit		842		Same		Same
Attic		370		Same		Same
HVAC system						
Air conditioner		Direct expansion unitary system		Same		Same
California						
SEER (BTU/Wh)		10		10		14
Estimated COP [b] (Wh/Wh)		2.64		2.64		3.69
U.S.						
SEER (BTU/Wh)		10		10		10 to 13 (varies by climate zone)
Estimated COP [b] (Wh/Wh)		2.64		2.64		2.64 to 3.43 (varies by climate zone)
Gas furnace (California and U.S.)						
Annual Fuel Utilization Efficiency (AFUE) (%)		0.80		Same		Same
Electric heating (U.S.)						
COP		3.04		3.04		3.04 to 3.26 (varies by climate zone)

Distribution						
Type		Single-zone constant air volume		Same		Same
Design flow rate (m^3/s)		0.0283		Same		Same
Maximum number of occupants		3		Same		Same

[a] Net wall area excludes windows and doors.

[b] To obtain COP, divide SEER by 3.79 (ECOX 2017).

Table B-3 describes the geometry, envelope construction, and HVAC system for each vintage of the medium office. Details of the internal loads (e.g. persons, lighting, equipment) and their hourly schedules are further described in the EnergyPlus medium office prototypes.

Table B-3. Details on the geometry, envelope construction, and HVAC system for each vintage of the medium office.

Property		Oldest vintage		Older vintage		New vintage
General building characteristics						
Conditioned floor area (m^2)		4,980		Same		Same
Roof area (m^2)		1,660		Same		Same
Number of stories		3		Same		Same
Ratio of roof area to net wall area [a]		1.25		Same		Same
Ratio of window area to net wall area		0.33		Same		Same
Roof albedo						
Base case		0.20		Same		Same
Alternative cases		0.10, 0.25, 0.40, and 0.60		Same		Same
Roof thermal emittance		0.90		Same		Same
Roof construction						
Thermal resistance ($m^2 \cdot K/W$) [$ft^2 \cdot °F \cdot h/BTU$]						
Built-up roofing		0.059 [0.337]		Same		Same
Insulation above deck		Varies by climate zone (Table C-3 &Table C-6)		Same		Same
Metal surface		0.000 [0.000]		Same		Same
Wall construction (outside to inside)						
Thermal resistance ($m^2 \cdot K/W$) [$ft^2 \cdot °F \cdot h/BTU$]						
Stucco		0.035 [0.200]		Same		Same
Gypsum board		0.079 [0.451]		Same		Same
Insulated metal frame		Varies by climate zone (Table C-2 &Table C-5)		Same		Same

Gypsum board		0.079 [0.451]		Same		Same
Net wall area when long-axis of building extends east-west (m^2)						
North		398		Same		Same
East		265		Same		Same
South		398		Same		Same
West		265		Same		Same
Foundation type		Slab		Same		Same
Windows						
Thermal transmittance ($W/m^2 \cdot K$)		Varies by climate zone and orientation		Same		Same
Visible transmittance		Varies by climate zone and orientation		Same		Same
Window area when long-axis of building extends east-west (m^2)						
North		0.00		Same		Same
East		0.00		Same		Same
South		83.9		Same		Same
West		0.00		Same		Same
HVAC system						
Air conditioner						
California						
SEER (BTU/Wh)						
Estimated COP [b] (Wh/Wh)		Precision air conditioning unit		Same		Same
U.S.						
Estimated SEER [b] (BTU/Wh)		14		14		15
COP (Wh/Wh)		3.78		3.78		3.95
Gas furnace						
Annual Fuel Utilization Efficiency (AFUE) (%)		11		11		12 to 13 (varies by climate zone)
Electric heating		2.84		2.84		3.23 to 3.40 (varies by climate zone)
COP						
Distribution		0.80		Same		Same
Type						
		3.78		3.78		3.95
		Multi-zone variable air volume		Same		Same

[a] Net wall area excludes windows and doors.

[b] To obtain COP, divide SEER by 3.79 (ECOX 2017).

Table B-4 describes the geometry, envelope construction, and HVAC system for each vintage of the stand-alone retail. Details of the internal loads (e.g. persons, lighting, equipment) and their hourly schedules are further described in the EnergyPlus stand-alone retail prototypes.

Table B-4. Details on the geometry, envelope construction, and HVAC system for each vintage of the stand-alone retail.

Property		Oldest vintage		Older vintage		New vintage
General building characteristics						
Conditioned floor area (m^2)		2,290		Same		Same
Roof area (m^2)		2,290		Same		Same
Number of stories		1		Same		Same
Ratio of roof area to net wall area [a]		2.07		Same		Same
Ratio of window area to net wall area		0.07		Same		Same
Roof albedo						
Base case		0.20		Same		Same
Alternative cases		0.10, 0.25, 0.40, and 0.60		Same		Same
Roof thermal emittance		0.90		Same		Same
Roof construction						
Thermal resistance ($m^2 \cdot K/W$) [$ft^2 \cdot °F \cdot h/BTU$]						
Built-up roofing		0.059 [0.337]		Same		Same
Insulation above deck		Varies by climate zone (Table C-3 &Table C-6)		Same		Same
Metal surface		0.000 [0.000]		Same		Same
Wall construction in California (outside to inside)						
Thermal resistance ($m^2 \cdot K/W$) [$ft^2 \cdot °F \cdot h/BTU$]						
Stucco		0.035 [0.200]		Same		Same
Gypsum board		0.079 [0.451]		Same		Same
Insulated metal frame		Varies by climate zone (Table C-2 &Table C-5)		Same		Same
Gypsum board		0.079 [0.451]		Same		Same
Wall construction in U.S. (outside to inside)						
Thermal resistance ($m^2 \cdot K/W$) [$ft^2 \cdot °F \cdot h/BTU$]						
Oldest vintage						
Wood siding		0.091 [0.516]		NA [b]		NA

Insulated metal frame		Varied by climate zone (Table C-2 &Table C-5)		NA		NA
Gypsum board		0.079 [0.451]		NA		NA
Older vintage						
Stucco		NA		0.037 [0.208]		NA
Heavy-weight concrete		NA		0.155 [0.880]		NA
Wall insulation		NA		Varies by climate zone (Table C-2 &Table C-5)		NA
Gypsum board		NA		0.079 [0.451]		NA
New vintage						
Normal-weight concrete		NA		NA		0.088 [0.499]
Wall insulation		NA		NA		Varies by climate zone (Table C-2 & Table C-5)
Gypsum board		NA		NA		0.079 [0.451]
Net wall area when long-axis of building extends east-west (m^2)						
North		331		Same		Same
East		258		Same		Same
South		247		Same		Same
West		258		Same		Same
Foundation type		Slab		Same		Same
Windows						
Thermal transmittance (W/m²·K)		Varies by climate zone and orientation		Same		Same
Visible transmittance		Varies by climate zone and orientation		Same		Same
Window area when long-axis of building extends east-west (m^2)						
North		0.00		Same		Same
East		0.00		Same		Same
South		83.9		Same		Same
West		0.00		Same		Same
HVAC system						
Air conditioner						
California						
SEER (BTU/Wh)						
Estimated COP [c] (Wh/Wh)		Precision air conditioning unit		Same		Same
U.S.						
Estimated SEER [c] (BTU/Wh)		11		11		13

COP (Wh/Wh)		2.84		2.84		3.49
Gas furnace						
Annual Fuel Utilization Efficiency (AFUE) (%)		11		11		12 to 14 (varies by climate zone)
Electric heating		2.84		2.84		3.23 to 3.8 (varies by climate zone)
COP						
Distribution		0.80		Same		Same
Type						
		Single-zone constant air volume		Same		Same

[a] Net wall area excludes windows and doors.

[b] NA = not applicable.

[c] To obtain COP, divide SEER by 3.79 (ECOX 2017).

Task Report Appendix C: Estimation of wall and roof thermal resistances

Each roof and wall in EnergyPlus is modeled as a series of layers; each layer represents one type of material. In an actual building, envelope insulation is usually placed in the cavities formed by wood or metal frames. Thus, a fraction of the wall's cross section is wood (or metal) and the remainder is insulation. In this scenario, conduction through the wood (or metal) lowers the thermal resistance of the insulated frame; this effect is commonly known as thermal bridging.

In EnergyPlus, thermal bridging can be addressed by calculating the equivalent (parallel path) thermal resistance (R_e) of the insulated studded frame. This equivalent thermal resistance is then assigned to the EnergyPlus envelope layer that describes the insulated studded frame.

The following example assumes a wood frame, although it is also applicable to a metal frame. If fraction f of the wall cross section is wood (W) and the remainder is insulation (I), the equivalent thermal resistance of the insulated wood-studded frame will be

$$R_{\mathrm{e}} = \frac{R_{\mathrm{I}} \times R_{\mathrm{W}}}{f \times R_{\mathrm{I}} + (1 - f) \times R_{\mathrm{W}}} \tag{13}$$

where R_{I} and R_{W} are the thermal resistances of the insulating material and of the stud of the wood frame, respectively. f is commonly referred to as the "framing factor". Assuming frame is made of Douglas fir wood, which has a thermal resistance of R-0.99 per inch (Table 4.1.1 in 2016 Title 24 Reference Appendices) (CEC 2016d), a two-by-four wood stud has a thermal resistance (R_{W}) of R-3.5 (3.5 $\mathrm{ft^2 \cdot {}^\circ F \cdot h \cdot BTU^{-1}}$) or RSI-0.62 (0.62 $\mathrm{m^2 \cdot K \cdot W^{-1}}$).

In a wood-framed roof, a portion of the required insulation is placed between the rafters; the remaining insulation is typically placed over the insulated wood frame. In this scenario, the equivalent thermal resistance is computed as

$$R_{\mathrm{e}} = (R_{\mathrm{I}} - R_{\mathrm{I,\,cavity}}) \frac{R_{\mathrm{I,\,cavity}} \times R_{\mathrm{W}}}{f \times R_{\mathrm{I}} + (1 - f) \times R_{\mathrm{W}}} \tag{14}$$

where $R_{\mathrm{I,\,cavity}}$ is the maximum insulation that fits in the frame cavities.

C.1 California

The equivalent thermal resistances we calculated for each California prototype was computed so that the thermal resistance of the building envelope comply with California building codes. This section details the methods taken to calculate the equivalent thermal resistance by building type (commercial or residential) and by vintage. Section C.1.1 and Section C.1.2 summarize the methods we used to calculate the equivalent thermal resistances of our California residential and commercial prototypes, respectively. Section C.1.3 gives all the California equivalent thermal resistances that were calculated in this study.

C.1.1 Residential prototypes

C.1.1.1 New vintage

In 2016 Title 24 Building Energy Efficiency Standards (CEC 2016c), Table 150.1-A prescribes by California climate zone the thermal transmittance ("U-factor") requirements for different building envelope construction types (e.g., wood frame, metal frame, heavy mass) and for different envelope assemblies (e.g. roof, walls). The thermal transmittances given in Table 150.1-A describe the entire assembly, from indoor surface air film to outdoor surface air film.

We selected from Table 150.1-A the assembly thermal transmittances for wood-framed roof and wood-framed walls required in each California climate zone. For every location, the thermal resistances of the roof assembly ($R_{\text{roof, assembly}}$) and of the wall assembly ($R_{\text{wall, assembly}}$) were obtained as the reciprocals of the corresponding thermal transmittances.[4]

Let $R_{\text{roof, no\_I}}$ represent the thermal resistance of the roof excluding the insulating layer and $R_{\text{wall, no\_I}}$ represent the thermal resistance of the wall excluding the insulating layer. We calculated $R_{\text{roof, no\_I}}$ and $R_{\text{wall, no\_I}}$ for each new residential prototype. Then, we computed the equivalent thermal resistance R_{e} of the roof's insulating layer by subtracting $R_{\text{roof, no\_I}}$ from $R_{\text{roof, assembly}}$. Similarly, we calculated the equivalent thermal resistance R_{e} of the walls' insulating layer by subtracting $R_{\text{wall, no\_I}}$ from $R_{\text{wall, assembly}}$.

C.1.1.2 Older vintage

The 1988 Title 24 Building Energy Efficiency Standards (CEC 1988) prescribe for each California climate zone the minimum thermal resistance ("R-value") of insulation between wood framing members in roofs and walls. We selected the thermal resistances of ceiling and wall insulation prescribed for residential buildings in Alternative Package A (see Table 2-43Z1 through Table 2-43Z16 in 1988 Title 24 Standards).

A wood frame with two-by-four wood studs (actual dimensions 1.5" by 3.5") can typically contain up to R-13 of cavity insulation [see Table 4.3.1 in 2016 Title 24 Reference Appendices (CEC 2016d)]. Thus, for California climate zones in which the prescribed wall insulation was equal to or less than R-13, we computed the wall equivalent thermal resistance using Eq. (13), assuming two-by-four wood studs spaced 16" center-to-center (framing factor f approximately 0.15). For locations with prescribed wall insulation greater than R-13, the wall equivalent thermal resistance was computed with Eq. (13) assuming two-by-six wood studs (actual dimensions 1.5" by 5.5") with framing factor 0.15.

[4] Strictly speaking, thermal resistance is the reciprocal of thermal conductance (measured from surface to surface) rather than that of thermal transmittance (measured from air film to air film). We neglect that minor difference.

For roofs in the older residential buildings, we assumed two-by-four wood rafters following the recommendations in Section JA4.2 of 2016 Title 24 Reference Appendices (CEC 2016d). From the prescribed ceiling insulations in 1988 Title 24 Standards, only R-13 insulation fits in the frame cavity. Thus, the equivalent thermal resistances were computed using Eq. (14) with $R_{\mathrm{I,\,cavity}} = 13$.

C.1.1.3 Oldest vintage

In the 2016 Title 24 Residential Compliance Manual (CEC 2016b), Table 8-1 gives default assumptions of insulation thermal transmittance ("U-factor"), that can be found in different vintages of residential buildings. We assumed these thermal transmittances in Table 8-1 refer to that of only the insulation layer in the assembly. For pre-1978 buildings, the default insulation U-factor of a ceiling is U-0.079 [0.079 BTU/(ft^2·°F·h)] and of a wall is U-0.356. Treating thermal resistance as the reciprocal of thermal transmittances, the insulation thermal resistance of the roof is R-12.7 and of the wall is R-2.8. In our simulations of the oldest residential building categories, these thermal resistances were used as the equivalent thermal resistance assigned to the wood-framed insulating layer in EnergyPlus.

C.1.2 Commercial prototypes

C.1.2.1 New vintage

To compute the equivalent thermal resistances of the new commercial prototype in California, we followed the same process used for the new residential prototypes (Section C.1.1.1). From the prescriptive requirements in Component Package A (see Table 150.1-A in 2016 Title 24 Building Energy Efficiency Standards), we selected the assembly thermal transmittances for roof and walls that matched the construction type of our commercial prototypes. As an example, for the large hotel walls, we used the thermal transmittances for heavy mass walls.

The thermal resistance of the roof assembly ($R_{\mathrm{roof,\,assembly}}$) and of the wall assembly ($R_{\mathrm{wall,\,assembly}}$) were obtained as the inverse of the thermal transmittances. We then calculated $R_{\mathrm{roof,\,no\_I}}$ and $R_{\mathrm{wall,\,no\_I}}$ for each new commercial prototype. The equivalent thermal resistances, R_{e}, of the roof's insulating layer were computed by subtracting $R_{\mathrm{roof,\,no\_I}}$ from $R_{\mathrm{roof,\,assembly}}$; R_{e} of the walls' insulating layer was calculated by subtracting $R_{\mathrm{wall,\,no\_I}}$ from $R_{\mathrm{wall,\,assembly}}$.

C.1.2.2 Older vintage

The 1988 Title 24 Building Energy Efficiency Standards (CEC 1988) provide prescriptive standards for three types of commercial buildings: low-rise office buildings, high-rise office buildings, and retail and whole-sale stores. These standards define minimum thermal resistances ("R-values") for different building envelope assemblies (e.g., roof and walls). First, we matched each of our commercial building categories to one of the commercial building types detailed in 1988 Title 24 Standards. Later, we selected the roof and wall assembly thermal resistances prescribed in Alternative Package A. Table C-1 shows how we mapped the building types in 1988 Title 24 Standards to our building categories.

Table C-1. Building types from 1988 Title 24 Standards mapped to each of our simulated building categories.

Building category	Building type from 1988 Title 24 Standards		Building category	Building type from 1988 Title 24 Standards
Large office	high-rise office [a]		Sit-down restaurant	retail and wholesale store [d]
Medium office	low-rise office [b]		Fast-food restaurant	retail and wholesale store [d]
Small office	low-rise office [b]		Stand-alone retail	retail and wholesale store [d]
Large hotel	high-rise office [c]		Retail strip mall	retail and wholesale store [d]

[a] 1988 T24 Standards; Tables 2-53W1 to 2-53W16; Package A; wall heat capacity 4-10 BTU/R·ft².

[b] 1988 T24 Standards; Tables 2-53V1 to 2-53V16; Package A; wall heat capacity 4-10 BTU/R·ft².

[c] 1988 T24 Standards; Tables 2-53W1 to 2-53W16; Package A; wall heat capacity 15-20 BTU/R·ft².

[d] 1988 T24 Standards; Tables 2-53WA1 to 2-53WA16; Package A; wall heat capacity 4-10 BTU/R·ft².

From the prescriptive requirement tables in 1988 Title 24 Standards, we obtained for each prototype the roof assembly thermal resistance ($R_{\text{roof, no\_I}}$) and the wall assembly thermal resistance ($R_{\text{wall, no\_I}}$). We then computed the equivalent thermal resistances following the same process used for the older residential prototypes (Section C.1.1.2). The equivalent thermal resistance of the roof's insulating layer was calculated by subtracting $R_{\text{roof, no\_I}}$ from $R_{\text{roof, assembly}}$. Similarly, we computed the equivalent thermal resistance of the walls' insulating layer by subtracting $R_{\text{wall, no\_I}}$ from $R_{\text{wall, assembly}}$.

C.1.2.3 Oldest vintage

We did not find a reference that provided estimates of thermal insulation typically installed in pre-1978 commercial buildings in California. To estimate the equivalent thermal resistances for our oldest commercial prototypes, we first calculated the equivalent thermal resistance ratio of oldest to older residential prototype. This ratio was computed for each California climate zone and used to scale down the equivalent thermal resistances from the older commercial prototypes. These scaled-down equivalent thermal resistances were used in the oldest commercial prototypes.

As an example, the wall equivalent thermal resistances in the oldest residential prototypes in CACZ 1 was R-2.8, and that in the older residential prototypes was R-13.9. The ratio of wall equivalent thermal resistances of oldest to older prototype is 0.20 (R-2.8 / R-13.9). The wall equivalent thermal resistances in the older medium office in CACZ 1 is R-5.4. Thus, for the oldest medium office in CACZ 1, the estimated wall equivalent thermal resistances is R-0.6 (R-5.4 × 0.20).

C.1.3 Equivalent thermal resistances used in the California commercial and residential prototypes

Table C-2 gives the equivalent thermal resistance used in the walls of all California prototypes.

Table C-2. Equivalent thermal resistance, R_e, of the insulated wall frame by vintage and by California climate zone for all prototypes.

		Equivalent thermal resistance of the insulated wall frame, R [$ft^2 \cdot °F \cdot h \cdot BTU^{-1}$]															
Vintage	**Prototype**	**CZ 01**	**CZ 02**	**CZ 03**	**CZ 04**	**CZ 05**	**CZ 06**	**CZ 07**	**CZ 08**	**CZ 09**	**CZ 10**	**CZ 11**	**CZ 12**	**CZ 13**	**CZ 14**	**CZ 15**	**CZ 16**
oldest	Single-family home	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8
	Apartment building	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8
	Large office	0.3	1.4	1.4	1.5	1.5	1.3	1.3	1.3	1.3	1.3	1.4	1.4	1.4	0.3	0.3	0.3
	Medium office	0.6	1.9	1.9	2.1	2.1	1.9	1.9	1.9	1.9	1.9	1.6	1.6	1.6	0.5	0.5	0.6
	Small office	0.6	1.9	1.9	2.1	2.1	1.9	1.9	1.9	1.9	1.9	1.6	1.6	1.6	0.5	0.5	0.6
	Large hotel	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
	Sit-down restaurant	0.6	2.0	2.0	2.2	2.2	2.0	2.0	2.0	2.0	2.0	1.7	1.7	1.7	0.6	0.6	0.6
	Fast-food restaurant	0.4	1.7	1.7	1.9	1.9	1.7	1.7	1.7	1.7	1.7	1.4	1.4	1.4	0.3	0.3	0.4
	Retail stand-alone	0.6	1.9	1.9	2.1	2.1	1.9	1.9	1.9	1.9	1.9	1.6	1.6	1.6	0.5	0.5	0.6
	Strip mall retail	0.6	1.9	1.9	2.1	2.1	1.9	1.9	1.9	1.9	1.9	1.6	1.6	1.6	0.5	0.5	0.6
older	Single-family home	13.9	8.3	8.3	8.3	8.3	8.3	8.3	8.3	8.3	8.3	8.3	8.3	8.3	13.9	13.9	13.9
	Apartment building	13.9	8.3	8.3	8.3	8.3	8.3	8.3	8.3	8.3	8.3	8.3	8.3	8.3	13.9	13.9	13.9
	Large office	4.5	4.5	4.5	4.6	4.6	4.3	4.3	4.3	4.3	4.3	4.4	4.4	4.4	4.5	4.5	4.5
	Medium office	5.4	5.6	5.6	6.0	6.0	5.5	5.5	5.5	5.5	5.5	5.0	5.0	5.0	5.3	5.3	5.4
	Small office	5.4	5.6	5.6	6.0	6.0	5.5	5.5	5.5	5.5	5.5	5.0	5.0	5.0	5.3	5.3	5.4
	Large hotel	1.9	1.0	1.0	1.2	1.2	0.6	0.6	0.6	0.6	0.6	1.0	1.0	1.0	1.9	1.9	1.9
	Sit-down restaurant	5.4	5.6	5.6	6.0	6.0	5.5	5.5	5.5	5.5	5.5	5.0	5.0	5.0	5.3	5.3	5.4
	Fast-food restaurant	5.3	5.5	5.5	5.9	5.9	5.4	5.4	5.4	5.4	5.4	4.9	4.9	4.9	5.1	5.1	5.3
	Retail stand-alone	5.4	5.6	5.6	6.0	6.0	5.5	5.5	5.5	5.5	5.5	5.0	5.0	5.0	5.3	5.3	5.4
	Strip mall retail	5.4	5.6	5.6	6.0	6.0	5.5	5.5	5.5	5.5	5.5	5.0	5.0	5.0	5.3	5.3	5.4
new	Single-family home	16.6	16.6	16.6	16.6	16.6	12.4	12.4	16.6	16.6	16.6	16.6	16.6	16.6	16.6	16.6	16.6

	Apartment building	16.6	16.6	16.6	16.6	16.6	12.4	12.4	16.6	16.6	16.6	16.6	16.6	16.6	16.6	16.6	16.6
	Large office	12.5	14.2	10.2	14.2	14.2	12.5	12.5	14.2	14.2	14.2	14.2	14.2	14.2	14.2	14.2	14.2
	Medium office	12.5	14.2	10.2	14.2	14.2	12.5	12.5	14.2	14.2	14.2	14.2	14.2	14.2	14.2	14.2	14.2
	Small office	12.5	14.2	10.2	14.2	14.2	12.5	12.5	14.2	14.2	14.2	14.2	14.2	14.2	14.2	14.2	14.2
	Large hotel	2.0	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	3.4	2.0	2.7	3.4	3.4	4.2
	Sit-down restaurant	12.5	14.2	10.2	14.2	14.2	12.5	12.5	14.2	14.2	14.2	14.2	14.2	14.2	14.2	14.2	14.2
	Fast-food restaurant	8.4	14.8	7.0	14.8	7.7	7.0	7.0	7.7	14.8	14.8	20.1	14.8	14.8	14.8	21.7	14.8
	Retail stand-alone	12.5	14.2	10.2	14.2	14.2	12.5	12.5	14.2	14.2	14.2	14.2	14.2	14.2	14.2	14.2	14.2
	Strip mall retail	12.5	14.2	10.2	14.2	14.2	12.5	12.5	14.2	14.2	14.2	14.2	14.2	14.2	14.2	14.2	14.2

Table C-3 gives the equivalent thermal resistance used in the roof of all California prototypes.

Table C-3. Equivalent thermal resistance, R_e, of the insulated roof frame by vintage and by California climate zone for all prototypes.

Vintage	Prototype	Equivalent thermal resistance of the insulated roof frame, R [$ft^2 \cdot °F \cdot h \cdot BTU^{-1}$]															
		CZ 01	CZ 02	CZ 03	CZ 04	CZ 05	CZ 06	CZ 07	CZ 08	CZ 09	CZ 10	CZ 11	CZ 12	CZ 13	CZ 14	CZ 15	CZ 16
oldest	Single-family home	12.7	12.7	12.7	12.7	12.7	12.7	12.7	12.7	12.7	12.7	12.7	12.7	12.7	12.7	12.7	12.7
	Apartment building	12.7	12.7	12.7	12.7	12.7	12.7	12.7	12.7	12.7	12.7	12.7	12.7	12.7	12.7	12.7	12.7
	Large office	6.7	6.7	6.7	6.7	6.7	11.1	11.1	6.7	6.7	6.7	6.7	6.7	6.7	5.0	6.7	5.0
	Medium office	5.4	3.8	3.8	3.8	3.8	6.6	6.6	3.8	3.8	3.8	3.8	3.8	3.8	4.0	5.4	4.0
	Small office	2.8	1.2	1.2	1.2	1.2	4.1	4.1	1.2	1.2	1.2	1.2	1.2	1.2	1.4	2.8	1.4
	Large hotel	6.7	6.7	6.7	6.7	6.7	11.1	11.1	6.7	6.7	6.7	6.7	6.7	6.7	5.0	6.7	5.0
	Sit-down restaurant	2.1	0.6	0.6	0.6	0.6	3.4	3.4	0.6	0.6	0.6	0.6	0.6	0.6	0.8	2.1	0.8
	Fast-food restaurant	2.1	0.6	0.6	0.6	0.6	3.4	3.4	0.6	0.6	0.6	0.6	0.6	0.6	0.8	2.1	0.8
	Retail stand-alone	5.4	3.8	3.8	3.8	3.8	6.6	6.6	3.8	3.8	3.8	3.8	3.8	3.8	4.0	5.4	4.0
	Strip mall retail	5.4	3.8	3.8	3.8	3.8	6.6	6.6	3.8	3.8	3.8	3.8	3.8	3.8	4.0	5.4	4.0
older	Single-family home	27.2	27.2	27.2	27.2	27.2	16.2	16.2	27.2	27.2	27.2	27.2	27.2	27.2	35.2	27.2	35.2
	Apartment building	27.2	27.2	27.2	27.2	27.2	16.2	16.2	27.2	27.2	27.2	27.2	27.2	27.2	35.2	27.2	35.2
	Large office	13.9	13.9	13.9	13.9	13.9	13.9	13.9	13.9	13.9	13.9	13.9	13.9	13.9	13.9	13.9	13.9
	Medium office	11.4	8.4	8.4	8.4	8.4	8.4	8.4	8.4	8.4	8.4	8.4	8.4	8.4	11.4	11.4	11.4
	Small office	8.8	5.8	5.8	5.8	5.8	5.8	5.8	5.8	5.8	5.8	5.8	5.8	5.8	8.8	8.8	8.8
	Large hotel	13.9	13.9	13.9	13.9	13.9	13.9	13.9	13.9	13.9	13.9	13.9	13.9	13.9	13.9	13.9	13.9
	Sit-down restaurant	8.2	5.1	5.1	5.1	5.1	5.1	5.1	5.1	5.1	5.1	5.1	5.1	5.1	8.1	8.1	8.1
	Fast-food restaurant	8.2	5.1	5.1	5.1	5.1	5.1	5.1	5.1	5.1	5.1	5.1	5.1	5.1	8.1	8.1	8.1
	Retail stand-alone	11.4	8.4	8.4	8.4	8.4	8.4	8.4	8.4	8.4	8.4	8.4	8.4	8.4	11.4	11.4	11.4
	Strip mall retail	11.4	8.4	8.4	8.4	8.4	8.4	8.4	8.4	8.4	8.4	8.4	8.4	8.4	11.4	11.4	11.4
new	Single-family home	35.2	35.2	27.2	43.2	27.2	27.2	27.2	43.2	43.2	43.2	43.2	43.2	43.2	43.2	43.2	43.2
	Apartment building	35.2	35.2	27.2	43.2	27.2	27.2	27.2	43.2	43.2	43.2	43.2	43.2	43.2	43.2	43.2	43.2
	Large office	28.3	28.3	28.3	28.3	28.3	19.3	19.3	19.3	28.3	28.3	28.3	28.3	28.3	28.3	28.3	28.3
	Medium office	28.3	28.3	28.3	28.3	28.3	19.3	19.3	19.3	28.3	28.3	28.3	28.3	28.3	28.3	28.3	28.3
	Small office	25.7	25.7	25.7	25.7	25.7	16.7	16.7	16.7	25.7	25.7	25.7	25.7	25.7	25.7	25.7	25.7
	Large hotel	28.3	28.3	28.3	28.3	28.3	19.3	19.3	19.3	28.3	28.3	28.3	28.3	28.3	28.3	28.3	28.3
	Sit-down restaurant	25.1	25.1	25.1	25.1	25.1	16.1	16.1	16.1	25.1	25.1	25.1	25.1	25.1	25.1	25.1	25.1
	Fast-food restaurant	25.1	25.1	25.1	25.1	25.1	16.1	16.1	16.1	25.1	25.1	25.1	25.1	25.1	25.1	25.1	25.1
	Retail stand-alone	28.3	28.3	28.3	28.3	28.3	19.3	19.3	19.3	28.3	28.3	28.3	28.3	28.3	28.3	28.3	28.3
	Strip mall retail	28.3	28.3	28.3	28.3	28.3	19.3	19.3	19.3	28.3	28.3	28.3	28.3	28.3	28.3	28.3	28.3

Table C-4. Ratios of thermal resistances for roof assembly to wall assembly by vintage and by California climate zone for all prototypes. The thermal resistances consider the entire envelope construction from indoor surface air film to outdoor surface air film.

Vintage	Prototype	Thermal resistance ratio of roof assembly to wall assembly, [R/R]															
		CZ 01	CZ 02	CZ 03	CZ 04	CZ 05	CZ 06	CZ 07	CZ 08	CZ 09	CZ 10	CZ 11	CZ 12	CZ 13	CZ 14	CZ 15	CZ 16
	Single-family home	2.7															
	Apartment building	2.7															
	Large office	3.5	2.3	2.3	2.3	2.3	3.8	3.8	2.4	2.4	2.4	2.4	2.4	2.4	2.7	3.5	2.7
	Medium office	2.6	1.3	1.3	1.2	1.2	2.0	2.0	1.3	1.3	1.3	1.4	1.4	1.4	2.1	2.6	2.0
	Small office	2.6	1.3	1.3	1.2	1.2	2.0	2.0	1.3	1.3	1.3	1.4	1.4	1.4	2.1	2.6	2.0
oldest	Large hotel	5.9	5.1	5.1	4.8	4.8	9.3	9.3	6.0	6.0	6.0	5.1	5.1	5.1	4.7	5.9	4.7
	Sit-down restaurant	2.5	1.2	1.2	1.2	1.2	2.0	2.0	1.3	1.3	1.3	1.3	1.3	1.3	2.0	2.6	2.0
	Fast-food restaurant	2.6	1.3	1.3	1.2	1.2	2.1	2.1	1.3	1.3	1.3	1.4	1.4	1.4	2.1	2.7	2.1
	Retail stand-alone	2.6	1.3	1.3	1.2	1.2	2.0	2.0	1.3	1.3	1.3	1.4	1.4	1.4	2.1	2.6	2.0
	Strip mall retail	2.6	1.3	1.3	1.2	1.2	2.0	2.0	1.3	1.3	1.3	1.4	1.4	1.4	2.1	2.6	2.0
	Single-family home	1.8	2.7	2.7	2.7	2.7	1.7	1.7	2.7	2.7	2.7	2.7	2.7	2.7	2.3	1.8	2.3
	Apartment building	1.8	2.7	2.7	2.7	2.7	1.7	1.7	2.7	2.7	2.7	2.7	2.7	2.7	2.3	1.8	2.3
	Large office	2.3	2.3	2.3	2.3	2.3	2.4	2.4	2.4	2.4	2.4	2.3	2.3	2.3	2.3	2.3	2.3
	Medium office	1.7	1.3	1.3	1.2	1.2	1.3	1.3	1.3	1.3	1.3	1.4	1.4	1.4	1.7	1.7	1.7
	Small office	1.7	1.3	1.3	1.2	1.2	1.3	1.3	1.3	1.3	1.3	1.4	1.4	1.4	1.7	1.7	1.7
older	Large hotel	3.9	5.1	5.1	4.8	4.8	5.9	5.9	5.9	5.9	5.9	5.1	5.1	5.1	3.9	3.9	3.9
	Sit-down restaurant	1.7	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.3	1.3	1.3	1.7	1.7	1.7
	Fast-food restaurant	1.7	1.3	1.3	1.2	1.2	1.3	1.3	1.3	1.3	1.3	1.4	1.4	1.4	1.8	1.8	1.7
	Retail stand-alone	1.7	1.3	1.3	1.2	1.2	1.3	1.3	1.3	1.3	1.3	1.4	1.4	1.4	1.7	1.7	1.7
	Strip mall retail	1.7	1.3	1.3	1.2	1.2	1.3	1.3	1.3	1.3	1.3	1.4	1.4	1.4	1.7	1.7	1.7
	Single-family home	2.0	2.0	1.5	2.4	1.5	2.0	2.0	2.4	2.4	2.4	2.4	2.4	2.4	2.4	2.4	2.4
	Apartment building	2.0	2.0	1.5	2.4	1.5	2.0	2.0	2.4	2.4	2.4	2.4	2.4	2.4	2.4	2.4	2.4
	Large office	2.0	1.8	2.4	1.8	1.8	1.4	1.4	1.3	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8
	Medium office	2.0	1.8	2.4	1.8	1.8	1.4	1.4	1.3	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8
	Small office	2.0	1.8	2.4	1.8	1.8	1.4	1.4	1.3	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8
new	Large hotel	7.4	15.0	15.0	15.0	15.0	10.4	10.4	10.4	15.0	15.0	5.5	7.5	6.3	5.5	5.5	4.7
	Sit-down restaurant	2.0	1.8	2.4	1.8	1.8	1.4	1.4	1.3	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8
	Fast-food restaurant	2.8	1.8	3.3	1.8	3.0	2.3	2.3	2.1	1.8	1.8	1.3	1.8	1.8	1.8	1.2	1.8
	Retail stand-alone	2.0	1.8	2.4	1.8	1.8	1.4	1.4	1.3	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8
	Strip mall retail	2.0	1.8	2.4	1.8	1.8	1.4	1.4	1.3	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8

C.2 United States

We calculated the effective thermal resistance for the roof and walls for the older and oldest residential U.S. prototypes so that the thermal properties of the building envelope follow typical residential construction practices of older and oldest vintage residential buildings. In the remaining U.S. prototypes, we did not make any changes to the roof and wall thermal resistances. Section C.2.1 summarizes the methods we used to calculate the equivalent thermal resistances of the older and oldest U.S. residential prototypes. Section C.2.2 gives all the U.S. equivalent thermal resistances that were either calculated in this study or already defined in the prototypes.

C.2.1 Residential prototypes

C.2.1.1 Older vintage

Huang et al. (1999) compiled U.S. residential building characteristics from the 1984 Residential Energy Consumption Survey (RECS), the Census Bureau, and the 1987 National Association of Homebuilders Annual Survey, then tabulated typical construction practices by U.S. Census Division and for three periods of construction (pre-1940, 1950-1970, and 1980s). The study provides the thermal resistance of the insulation present in the roof and walls of single-family homes and multi-family buildings.

To calculate the equivalent thermal resistance for our U.S. older residential prototypes, we used the insulation thermal resistances provided by Huang et al. (1999) for the 1980s period. For each of our prototypes, we used the insulation values from the Census Division that contains the city simulated by the prototype.

The wall equivalent thermal resistances were calculated with Eq. (13) and assuming wood frame with two-by-four studs. The roof equivalent thermal resistances were computed with Eq. (14) and assuming wood frame with two-by-four rafters.

C.2.1.2 Oldest vintage

To calculate the equivalent thermal resistances for our U.S. oldest residential prototypes, we used the insulation thermal resistances provided by Huang et al. (1999) for the period 1950-1970. For this period, Huang's study provided building characteristics for retrofitted and non-retrofitted buildings.

We averaged the retrofitted and non-retrofitted values of insulation thermal resistances. We used the average values to calculate: (a) wall equivalent thermal resistances using Eq. (13) and assuming wood frame with two-by-four studs, and (b) roof equivalent thermal resistances using Eq. (14) and assuming wood frame with two-by-four rafters.

C.2.2 Equivalent thermal resistances used in the U.S. commercial and residential prototypes

Table C-5 gives the equivalent thermal resistance used in the walls of all U.S. prototypes.

Table C-5. Equivalent thermal resistance, R_e, of the insulated wall frame by vintage and by U.S. climate zone for all prototypes.

		Equivalent thermal resistance of the insulated wall frame, R [$ft^2 \cdot °F \cdot h \cdot BTU^{-1}$]														
Vintage	**Prototype**	**CZ 1A**	**CZ 2A**	**CZ 2B**	**CZ 3A**	**CZ 3B**	**CZ 3C**	**CZ 4A**	**CZ 4B**	**CZ 4C**	**CZ 5A**	**CZ 5B**	**CZ 6A**	**CZ 6B**	**CZ 7**	**CZ 8**
oldest	Single-family home	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5
	Apartment building	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5
	Large office	2.0	2.0	2.0	2.1	2.0	2.1	3.2	3.0	3.3	4.0	3.8	4.5	4.5	5.0	5.6
	Medium office	2.5	2.5	2.5	2.6	2.5	2.6	3.8	3.6	3.9	4.6	4.4	5.1	5.1	5.5	6.2
	Small office	2.5	2.5	2.5	2.6	2.5	2.6	3.8	3.6	3.9	4.6	4.4	5.1	5.1	5.5	6.2
	Large hotel	2.0	2.0	2.0	2.1	2.0	2.1	3.2	3.0	3.3	4.0	3.8	4.5	4.5	5.0	5.6
	Sit-down restaurant	2.5	2.5	2.5	2.6	2.5	2.6	3.8	3.6	3.9	4.6	4.4	5.1	5.1	5.5	6.2
	Fast-food restaurant	2.0	2.0	2.0	2.1	2.0	2.1	3.2	3.0	3.3	4.0	3.8	4.5	4.5	5.0	5.6
	Retail stand-alone	2.5	2.5	2.5	2.6	2.5	2.6	3.8	3.6	3.9	4.6	4.4	5.1	5.1	5.5	6.2
	Strip mall retail	2.5	2.5	2.5	2.6	2.5	2.6	3.8	3.6	3.9	4.6	4.4	5.1	5.1	5.5	6.2
older	Single-family home	8.3	8.3	9.2	8.3	8.3	8.3	8.3	9.2	8.3	9.2	9.2	9.2	9.2	13.9	8.3
	Apartment building	8.3	8.3	9.2	8.3	8.3	8.3	8.3	9.2	8.3	9.2	9.2	9.2	9.2	13.9	8.3
	Large office	2.0	0.6	0.1	1.1	1.1	1.1	5.9	2.9	7.6	7.6	4.8	11.7	10.3	14.0	18.9
	Medium office	2.5	4.8	2.4	5.9	4.4	5.9	9.4	8.2	9.1	10.4	10.4	13.6	12.1	15.4	20.4
	Small office	0.1	0.6	0.1	1.1	1.1	1.1	5.9	2.9	7.6	7.6	4.8	11.7	10.3	14.0	18.9
	Large hotel	2.0	0.6	0.1	1.1	1.1	1.1	5.9	2.9	7.6	7.6	4.8	11.7	10.3	14.0	18.9
	Sit-down restaurant	2.5	4.8	2.4	5.9	4.4	5.9	9.4	8.2	9.1	10.4	10.4	13.6	12.1	15.4	20.4
	Fast-food restaurant	1.2	4.8	2.4	5.9	4.4	5.9	9.4	8.2	9.1	10.4	10.4	13.6	12.1	15.4	20.4
	Retail stand-alone	0.1	0.6	0.1	1.1	1.1	1.1	5.9	2.9	7.6	7.6	4.8	11.7	10.3	14.0	18.9
	Strip mall retail	2.5	4.8	2.4	5.9	4.4	5.9	9.4	8.2	9.1	10.4	10.4	13.6	12.1	15.4	20.4
new	Single-family home	8.5	8.5	8.5	8.5	13.3	13.3	13.3	8.5	13.3	13.3	13.3	13.3	13.3	13.3	13.3
	Apartment building	8.5	8.5	8.5	8.5	13.3	13.3	13.3	8.5	13.3	13.3	13.3	13.3	13.3	13.3	13.3
	Large office	0.2	4.8	0.2	6.3	6.3	6.3	7.8	4.8	7.8	9.3	9.3	10.7	10.7	12.3	10.7
	Medium office	5.9	9.7	5.9	9.7	10.8	10.8	13.4	5.9	13.4	16.0	13.4	18.2	13.4	13.4	13.4
	Small office	9.1	9.1	9.1	9.1	9.1	9.1	13.4	9.1	9.1	17.4	13.4	17.4	17.4	17.4	17.4
	Large hotel	0.2	4.8	0.2	6.3	6.3	6.3	7.8	4.8	7.8	9.3	9.3	10.7	10.7	12.3	10.7
	Sit-down restaurant	5.9	9.7	5.9	9.7	10.8	10.8	13.4	5.9	13.4	16.0	13.4	18.2	13.4	13.4	13.4
	Fast-food restaurant	9.1	9.1	9.1	9.1	9.1	9.1	13.4	9.1	9.1	17.4	13.4	17.4	17.4	17.4	17.4
	Retail stand-alone	0.2	4.8	0.2	6.3	6.3	6.3	7.8	4.8	7.8	9.3	9.3	10.7	10.7	12.3	10.7
	Strip mall retail	5.9	9.7	5.9	9.7	10.8	10.8	13.4	5.9	13.4	16.0	13.4	18.2	13.4	13.4	13.4

Table C-6 gives the equivalent thermal resistance used in the roof of all U.S. prototypes.

Table C-6. Equivalent thermal resistance, R_e, of the insulated roof frame by vintage and by U.S. climate zone for all prototypes.

Vintage	Prototype	Equivalent thermal resistance of the insulated roof frame, R [ft²·°F·h·BTU⁻¹] CZ 1A	CZ 2A	CZ 2B	CZ 3A	CZ 3B	CZ 3C	CZ 4A	CZ 4B	CZ 4C	CZ 5A	CZ 5B	CZ 6A	CZ 6B	CZ 7	CZ 8
oldest	Single-family home	7.8	10.2	9.1	10.2	10.2	7.8	7.8	9.1	12.2	12.2	9.1	19.2	9.1	11.7	12.2
	Apartment building	7.8	10.2	9.1	10.2	10.2	7.8	7.8	9.1	12.2	12.2	9.1	19.2	9.1	11.7	12.2
	Large office	8.6	8.6	8.6	8.6	8.6	8.6	10.2	9.8	10.3	12.8	12.0	15.6	15.6	15.2	15.6
	Medium office	8.6	8.6	8.6	8.6	8.6	8.6	10.2	9.8	10.3	12.8	12.0	15.6	15.6	15.2	15.6
	Small office	8.6	8.6	8.6	8.6	8.6	8.6	10.2	9.8	10.3	12.8	12.0	15.6	15.6	15.2	15.6
	Large hotel	8.6	8.6	8.6	8.6	8.6	8.6	10.2	9.8	10.3	12.8	12.0	15.6	15.6	15.2	15.6
	Sit-down restaurant	8.6	8.6	8.6	8.6	8.6	8.6	10.2	9.8	10.3	12.8	12.0	15.6	15.6	15.2	15.6
	Fast-food restaurant	8.6	8.6	8.6	8.6	8.6	8.6	10.2	9.8	10.3	12.8	12.0	15.6	15.6	15.2	15.6
	Retail stand-alone	8.6	8.6	8.6	8.6	8.6	8.6	10.2	9.8	10.3	12.8	12.0	15.6	15.6	15.2	15.6
	Strip mall retail	8.6	8.6	8.6	8.6	8.6	8.6	10.2	9.8	10.3	12.8	12.0	15.6	15.6	15.2	15.6
older	Single-family home	24.2	24.2	26.2	24.2	24.2	22.2	24.2	26.2	29.2	29.2	26.2	24.2	26.2	29.2	29.2
	Apartment building	24.2	24.2	26.2	24.2	24.2	22.2	24.2	26.2	29.2	29.2	26.2	24.2	26.2	29.2	29.2
	Large office	12.1	13.7	20.3	12.5	19.4	9.9	15.8	15.5	14.2	17.8	18.5	21.1	19.3	23.6	31.1
	Medium office	12.1	13.7	20.3	12.5	19.4	9.9	15.8	15.5	14.2	17.8	18.5	21.1	19.3	23.6	31.1
	Small office	11.2	12.9	19.5	11.6	18.6	9.1	15.0	14.7	13.3	16.9	17.6	20.3	18.4	22.7	30.3
	Large hotel	12.1	13.7	20.3	12.5	19.4	9.9	15.8	15.5	14.2	17.8	18.5	21.1	19.3	23.6	31.1
	Sit-down restaurant	11.2	12.9	19.5	11.6	18.6	9.1	15.0	14.7	13.3	16.9	17.6	20.3	18.4	22.7	30.3
	Fast-food restaurant	11.2	12.9	19.5	11.6	18.6	9.1	15.0	14.7	13.3	16.9	17.6	20.3	18.4	22.7	30.3
	Retail stand-alone	12.1	13.7	20.3	12.5	19.4	9.9	15.8	15.5	14.2	17.8	18.5	21.1	19.3	23.6	31.1
	Strip mall retail	12.1	13.7	20.3	12.5	19.4	9.9	15.8	15.5	14.2	17.8	18.5	21.1	19.3	23.6	31.1
new	Single-family home	24.5	29.3	24.5	24.5	29.3	29.3	34.5	29.3	34.5	34.5	29.3	34.5	34.5	34.5	34.5
	Apartment building	26.3	32.9	26.3	26.3	32.9	32.9	41.2	32.9	41.2	41.2	32.9	41.2	41.2	41.2	41.2
	Large office	14.8	24.5	14.8	19.7	24.5	24.5	30.1	14.8	19.7	30.1	19.7	30.1	19.7	19.7	19.7
	Medium office	14.8	24.5	14.8	19.7	24.5	24.5	30.1	14.8	19.7	30.1	19.7	30.1	19.7	19.7	19.7
	Small office	27.8	35.4	27.8	35.4	35.4	35.4	46.0	27.8	35.4	46.0	35.4	46.0	35.4	35.4	35.4
	Large hotel	14.8	24.5	14.8	19.7	24.5	24.5	30.1	14.8	19.7	30.1	19.7	30.1	19.7	19.7	19.7
	Sit-down restaurant	27.8	35.4	27.8	35.4	35.4	35.4	46.0	27.8	35.4	46.0	35.4	46.0	35.4	35.4	35.4
	Fast-food restaurant	27.8	35.4	27.8	35.4	35.4	35.4	46.0	27.8	35.4	46.0	35.4	46.0	35.4	35.4	35.4
	Retail stand-alone	14.8	24.5	14.8	19.7	24.5	24.5	30.1	14.8	19.7	30.1	19.7	30.1	19.7	19.7	19.7
	Strip mall retail	14.8	24.5	14.8	19.7	24.5	24.5	30.1	14.8	19.7	30.1	19.7	30.1	19.7	19.7	19.7

Table C-7. Ratios of thermal resistances for roof assembly to wall assembly by vintage and by U.S. climate zone for all prototypes. The thermal resistances consider the entire envelope construction from indoor surface air film to outdoor surface air film.

		Thermal resistance ratio of roof assembly to wall assembly, [R/R]														
Vintage	**Prototype**	**CZ 1A**	**CZ 2A**	**CZ 2B**	**CZ 3A**	**CZ 3B**	**CZ 3C**	**CZ 4A**	**CZ 4B**	**CZ 4C**	**CZ 5A**	**CZ 5B**	**CZ 6A**	**CZ 6B**	**CZ 7**	**CZ 8**
oldest	Single-family home	1.7	2.0	1.9	2.0	2.0	1.7	1.7	1.9	2.4	2.4	1.9	3.4	1.9	2.3	2.4
	Apartment building	1.7	2.0	1.9	2.0	2.0	1.7	1.7	1.9	2.4	2.4	1.9	3.4	1.9	2.3	2.4
	Large office	2.6	2.6	2.6	2.6	2.6	2.6	2.3	2.3	2.3	2.4	2.4	2.7	2.7	2.4	2.3
	Medium office	2.3	2.3	2.3	2.2	2.3	2.2	2.0	2.0	2.0	2.2	2.1	2.4	2.4	2.2	2.1
	Small office	2.3	2.3	2.3	2.2	2.3	2.2	2.0	2.0	2.0	2.2	2.1	2.4	2.4	2.2	2.1
	Large hotel	2.6	2.6	2.6	2.6	2.6	2.6	2.3	2.3	2.3	2.4	2.4	2.7	2.7	2.4	2.3
	Sit-down restaurant	2.3	2.3	2.3	2.2	2.3	2.2	2.0	2.0	2.0	2.2	2.1	2.4	2.4	2.2	2.1
	Fast-food restaurant	2.6	2.6	2.6	2.6	2.6	2.6	2.3	2.3	2.3	2.4	2.4	2.7	2.7	2.4	2.3
	Retail stand-alone	2.3	2.3	2.3	2.2	2.3	2.2	2.0	2.0	2.0	2.2	2.1	2.4	2.4	2.2	2.1
	Strip mall retail	2.3	2.3	2.3	2.2	2.3	2.2	2.0	2.0	2.0	2.2	2.1	2.4	2.4	2.2	2.1
older	Single-family home	2.4	2.4	2.4	2.4	2.4	2.2	2.4	2.4	2.9	2.6	2.4	2.2	2.4	1.9	2.9
	Apartment building	2.4	2.4	2.4	2.4	2.4	2.2	2.4	2.4	2.9	2.6	2.4	2.2	2.4	1.9	2.9
	Large office	3.6	6.4	11.8	4.8	7.3	3.9	2.2	3.6	1.6	2.0	3.0	1.7	1.7	1.6	1.6
	Medium office	3.1	2.2	5.1	1.8	3.3	1.4	1.5	1.7	1.4	1.5	1.6	1.4	1.5	1.4	1.5
	Small office	8.3	7.2	12.8	5.5	7.9	4.6	2.5	4.0	1.8	2.2	3.3	1.8	1.8	1.7	1.7
	Large hotel	3.6	6.4	11.8	4.8	7.3	3.9	2.2	3.6	1.6	2.0	3.0	1.7	1.7	1.6	1.6
	Sit-down restaurant	3.5	2.5	5.5	2.0	3.6	1.7	1.7	1.8	1.6	1.7	1.7	1.6	1.6	1.5	1.5
	Fast-food restaurant	4.9	2.5	5.5	2.0	3.6	1.7	1.7	1.8	1.6	1.7	1.7	1.6	1.6	1.5	1.5
	Retail stand-alone	7.3	6.4	11.8	4.8	7.3	3.9	2.2	3.6	1.6	2.0	3.0	1.7	1.7	1.6	1.6
	Strip mall retail	3.1	2.2	5.1	1.8	3.3	1.4	1.5	1.7	1.4	1.5	1.6	1.4	1.5	1.4	1.5
new	Single-family home	2.4	2.8	2.4	2.4	2.0	2.0	2.3	2.8	2.3	2.3	2.0	2.3	2.3	2.3	2.3
	Apartment building	2.6	3.1	2.6	2.6	2.2	2.2	2.7	3.1	2.7	2.7	2.2	2.7	2.7	2.7	2.7
	Large office	7.3	3.8	7.3	2.5	3.1	3.1	3.2	2.4	2.1	2.8	1.8	2.5	1.6	1.5	1.6
	Medium office	2.0	2.2	2.0	1.8	2.0	2.0	2.0	2.0	1.3	1.7	1.3	1.5	1.3	1.3	1.3
	Small office	2.8	3.5	2.8	3.5	3.5	3.5	3.2	2.8	3.5	2.6	2.5	2.6	2.0	2.0	2.0
	Large hotel	7.3	3.8	7.3	2.5	3.1	3.1	3.2	2.4	2.1	2.8	1.8	2.5	1.6	1.5	1.6
	Sit-down restaurant	4.0	3.3	4.0	3.3	3.1	3.1	3.2	4.0	2.5	2.8	2.5	2.5	2.5	2.5	2.5
	Fast-food restaurant	2.8	3.5	2.8	3.5	3.5	3.5	3.2	2.8	3.5	2.6	2.5	2.6	2.0	2.0	2.0
	Retail stand-alone	7.3	3.8	7.3	2.5	3.1	3.1	3.2	2.4	2.1	2.8	1.8	2.5	1.6	1.5	1.6
	Strip mall retail	2.0	2.2	2.0	1.8	2.0	2.0	2.0	2.0	1.3	1.7	1.3	1.5	1.3	1.3	1.3

Task Report Appendix D: Solar radiation in representative cities

The monthly and seasonal daily solar radiations for each of the cities simulated in this study are summarized for California (Table D-1 through Table D-16) and U.S. (Table D-17 through Table D-33).

Table D-1. Monthly and seasonal daily solar irradiation in Arcata, California (city representing California building climate zone 1).

		Solar Radiation [kWh/m²·day]						
		Horizontal (H)	North wall (N)	East wall (E)	South wall (S)	West wall (W)	Four-wall average (NESW)	Ratio of NESW to H
Month	January	1.68	0.59	1.12	2.46	1.09	1.31	78%
	February	2.67	0.82	1.73	3.40	1.75	1.92	72%
	March	3.62	0.93	2.13	3.13	2.16	2.09	58%
	April	4.60	1.19	2.52	2.74	2.62	2.27	49%
	May	5.62	1.52	2.71	2.42	3.19	2.46	44%
	June	6.17	1.95	2.82	2.49	3.91	2.79	45%
	July	5.98	1.83	2.55	2.63	3.87	2.72	46%
	August	5.08	1.49	2.15	2.85	3.45	2.48	49%
	September	4.15	1.19	2.24	3.31	2.84	2.40	58%
	October	3.03	0.90	1.81	3.38	2.12	2.05	68%
	November	2.13	0.65	1.40	3.31	1.51	1.72	81%
	December	1.59	0.49	1.18	2.92	1.08	1.42	89%
Season	Winter (DJF)	1.98	0.63	1.34	2.92	1.31	1.55	78%
	Spring (MAM)	4.61	1.21	2.45	2.76	2.66	2.27	49%
	Summer (JJA)	5.74	1.75	2.51	2.65	3.74	2.66	46%
	Fall (SON)	3.10	0.92	1.82	3.33	2.16	2.06	66%
Ratio	Winter / Summer	35%	36%	53%	110%	35%	58%	

Table D-2. Monthly and seasonal daily solar irradiation in Santa Rosa, California (city representing California building climate zone 2).

		Solar Radiation [kWh/m²·day]						
		Horizontal (H)	North wall (N)	East wall (E)	South wall (S)	West wall (W)	Four-wall average (NESW)	Ratio of NESW to H
Month	January	1.90	0.61	1.11	2.62	1.22	1.39	73%
	February	2.47	0.73	1.61	2.94	1.60	1.72	70%
	March	3.33	0.87	1.93	2.58	1.91	1.82	55%
	April	5.96	1.29	3.03	3.36	3.65	2.83	47%
	May	7.34	1.61	3.63	2.89	3.93	3.01	41%
	June	7.65	1.91	3.86	2.48	4.08	3.08	40%
	July	7.38	1.75	3.49	2.75	4.10	3.02	41%
	August	6.59	1.40	3.23	3.37	3.80	2.95	45%
	September	5.44	1.16	2.92	4.30	3.39	2.94	54%
	October	3.58	0.89	2.11	4.04	2.28	2.33	65%
	November	2.39	0.63	1.58	3.70	1.56	1.87	78%
	December	1.55	0.54	1.08	2.52	1.09	1.31	84%
Season	Winter (DJF)	1.98	0.63	1.27	2.69	1.31	1.47	75%
	Spring (MAM)	5.54	1.26	2.86	2.94	3.16	2.55	46%
	Summer (JJA)	7.21	1.69	3.53	2.87	4.00	3.02	42%
	Fall (SON)	3.80	0.90	2.20	4.01	2.41	2.38	63%
Ratio	Winter / Summer	27%	37%	36%	94%	33%	49%	

Table D-3. Monthly and seasonal daily solar irradiation in Oakland, California (city representing California building climate zone 3).

		Solar Radiation [kWh/m²·day]						
		Horizontal (H)	**North wall (N)**	**East wall (E)**	**South wall (S)**	**West wall (W)**	**Four-wall average (NESW)**	**Ratio of NESW to H**
Month	January	2.17	0.62	1.37	3.23	1.38	1.65	76%
	February	2.65	0.75	1.45	2.91	1.68	1.70	64%
	March	3.44	0.90	1.93	2.58	1.93	1.84	53%
	April	6.21	1.29	3.21	3.41	3.59	2.88	46%
	May	6.71	1.58	3.33	2.57	3.45	2.73	41%
	June	7.64	1.89	3.47	2.48	4.11	2.99	39%
	July	6.82	1.70	2.92	2.58	3.73	2.73	40%
	August	6.17	1.38	2.82	3.13	3.49	2.71	44%
	September	5.51	1.23	3.07	4.20	3.33	2.96	54%
	October	3.56	0.92	2.07	3.89	2.30	2.29	64%
	November	2.67	0.70	1.75	3.93	1.65	2.01	75%
	December	2.01	0.63	1.37	3.37	1.38	1.69	84%
Season	Winter (DJF)	2.28	0.67	1.40	3.17	1.48	1.68	74%
	Spring (MAM)	5.45	1.26	2.82	2.85	2.99	2.48	46%
	Summer (JJA)	6.88	1.66	3.07	2.73	3.78	2.81	41%
	Fall (SON)	3.91	0.95	2.29	4.01	2.42	2.42	62%
Ratio	Winter / Summer	33%	40%	45%	116%	39%	60%	

Table D-4. Monthly and seasonal daily solar irradiation in San Jose, California (city representing California building climate zone 4).

		Solar Radiation [kWh/m²·day]						
		Horizontal (H)	North wall (N)	East wall (E)	South wall (S)	West wall (W)	Four-wall average (NESW)	Ratio of NESW to H
Month	January	2.25	0.64	1.42	3.40	1.45	1.73	77%
	February	2.96	0.81	1.97	3.57	1.90	2.06	70%
	March	3.45	0.96	2.03	2.60	2.00	1.90	55%
	April	6.07	1.33	3.36	3.42	3.46	2.89	48%
	May	7.31	1.68	3.74	2.84	3.96	3.06	42%
	June	8.10	2.01	4.22	2.55	4.17	3.24	40%
	July	7.72	1.80	3.78	2.75	4.18	3.13	41%
	August	6.94	1.42	3.59	3.48	3.92	3.10	45%
	September	5.68	1.23	3.12	4.38	3.46	3.05	54%
	October	4.07	0.98	2.41	4.54	2.55	2.62	64%
	November	2.70	0.69	1.76	4.15	1.80	2.10	78%
	December	2.17	0.61	1.45	3.84	1.60	1.88	86%
Season	Winter (DJF)	2.46	0.69	1.61	3.60	1.65	1.89	77%
	Spring (MAM)	5.61	1.32	3.05	2.95	3.14	2.61	47%
	Summer (JJA)	7.59	1.74	3.86	2.93	4.09	3.16	42%
	Fall (SON)	4.15	0.97	2.43	4.35	2.61	2.59	62%
Ratio	Winter / Summer	32%	40%	42%	123%	40%	60%	

Table D-5. Monthly and seasonal daily solar irradiation in Santa Maria, California (city representing California building climate zone 5).

		Solar Radiation [kWh/m²·day]						
		Horizontal (H)	North wall (N)	East wall (E)	South wall (S)	West wall (W)	Four-wall average (NESW)	Ratio of NESW to H
Month	January	2.88	0.57	1.81	4.46	1.82	2.16	75%
	February	3.70	0.94	2.35	4.29	2.34	2.48	67%
	March	4.54	1.15	2.79	3.67	2.78	2.60	57%
	April	6.33	1.41	3.33	3.48	3.72	2.99	47%
	May	7.18	1.51	3.36	2.35	3.70	2.73	38%
	June	7.38	1.95	3.04	2.30	4.42	2.93	40%
	July	7.40	1.84	3.04	2.50	4.43	2.95	40%
	August	6.84	1.47	3.05	3.24	3.98	2.94	43%
	September	5.68	1.20	2.63	4.13	3.64	2.90	51%
	October	4.27	0.99	2.44	4.57	2.80	2.70	63%
	November	3.20	0.76	2.20	4.82	2.05	2.46	77%
	December	2.67	0.67	1.85	4.57	1.82	2.23	83%
Season	Winter (DJF)	3.08	0.73	2.00	4.44	1.99	2.29	74%
	Spring (MAM)	6.01	1.36	3.16	3.17	3.40	2.77	46%
	Summer (JJA)	7.21	1.76	3.04	2.68	4.28	2.94	41%
	Fall (SON)	4.38	0.98	2.42	4.50	2.83	2.69	61%
Ratio	Winter / Summer	43%	41%	66%	166%	47%	78%	

Table D-6. Monthly and seasonal daily solar irradiation in Long Beach, California (city representing California building climate zone 6).

		Solar Radiation [kWh/m²·day]						
		Horizontal (H)	North wall (N)	East wall (E)	South wall (S)	West wall (W)	Four-wall average (NESW)	Ratio of NESW to H
Month	January	2.61	0.65	1.51	3.74	1.66	1.89	72%
	February	3.46	0.83	1.89	3.67	2.02	2.10	61%
	March	4.64	1.20	2.48	3.73	2.91	2.58	56%
	April	5.95	1.46	2.89	3.17	3.63	2.79	47%
	May	6.56	1.78	3.09	2.46	3.78	2.78	42%
	June	7.06	1.94	2.85	2.17	4.26	2.81	40%
	July	7.30	1.82	3.06	2.40	4.25	2.88	39%
	August	6.65	1.53	3.16	3.02	3.94	2.91	44%
	September	5.46	1.27	2.77	3.72	3.35	2.78	51%
	October	4.17	1.06	2.24	4.22	2.64	2.54	61%
	November	3.21	0.81	1.94	4.55	2.17	2.37	74%
	December	2.64	0.70	1.75	4.28	1.76	2.12	80%
Season	Winter (DJF)	2.90	0.73	1.71	3.90	1.81	2.04	70%
	Spring (MAM)	5.72	1.48	2.82	3.12	3.44	2.72	47%
	Summer (JJA)	7.00	1.76	3.02	2.53	4.15	2.87	41%
	Fall (SON)	4.28	1.05	2.32	4.17	2.72	2.56	60%
Ratio	Winter / Summer	41%	41%	57%	154%	44%	71%	

Table D-7. Monthly and seasonal daily solar irradiation in San Diego, California (city representing California building climate zone 7).

		Solar Radiation [kWh/m²·day]						
		Horizontal (H)	**North wall (N)**	**East wall (E)**	**South wall (S)**	**West wall (W)**	**Four-wall average (NESW)**	**Ratio of NESW to H**
Month	January	3.01	0.67	1.84	4.46	1.92	2.22	74%
	February	3.85	0.84	2.16	4.30	2.26	2.39	62%
	March	4.87	1.20	2.69	3.81	3.10	2.70	55%
	April	6.08	1.45	3.29	3.17	3.46	2.84	47%
	May	6.46	1.70	2.83	2.35	3.53	2.60	40%
	June	6.97	1.72	2.86	1.93	3.67	2.54	36%
	July	7.19	1.82	3.06	2.25	4.24	2.84	40%
	August	6.75	1.47	3.08	2.97	3.82	2.84	42%
	September	5.73	1.21	2.83	3.81	3.53	2.84	50%
	October	4.28	1.03	2.21	4.23	2.69	2.54	59%
	November	3.54	0.82	2.17	4.99	2.32	2.58	73%
	December	2.88	0.66	1.90	4.71	1.95	2.30	80%
Season	Winter (DJF)	3.25	0.72	1.96	4.49	2.04	2.30	71%
	Spring (MAM)	5.80	1.45	2.94	3.11	3.36	2.71	47%
	Summer (JJA)	6.97	1.67	3.00	2.38	3.91	2.74	39%
	Fall (SON)	4.52	1.02	2.40	4.35	2.85	2.65	59%
Ratio	Winter / Summer	47%	43%	65%	188%	52%	84%	

Table D-8. Monthly and seasonal daily solar irradiation in Fullerton, California (city representing California building climate zone 8).

		Solar Radiation [kWh/m²·day]						
		Horizontal (H)	North wall (N)	East wall (E)	South wall (S)	West wall (W)	Four-wall average (NESW)	Ratio of NESW to H
Month	January	3.06	0.72	1.90	4.51	1.85	2.25	73%
	February	3.21	0.93	1.92	3.37	2.06	2.07	64%
	March	4.47	1.05	2.26	3.38	2.76	2.36	53%
	April	6.53	1.40	3.54	3.34	3.63	2.98	46%
	May	6.52	1.73	3.14	2.36	3.70	2.73	42%
	June	7.19	1.87	3.14	2.20	3.90	2.78	39%
	July	7.28	1.87	3.25	2.41	4.28	2.95	41%
	August	6.72	1.54	3.52	3.06	3.66	2.95	44%
	September	5.71	1.29	3.04	4.03	3.39	2.94	51%
	October	3.75	1.01	2.08	3.72	2.30	2.27	61%
	November	3.21	0.83	2.02	4.36	2.12	2.33	73%
	December	2.81	0.74	1.76	4.53	1.93	2.24	80%
Season	Winter (DJF)	3.03	0.80	1.86	4.14	1.95	2.19	72%
	Spring (MAM)	5.84	1.39	2.98	3.03	3.36	2.69	46%
	Summer (JJA)	7.06	1.76	3.30	2.55	3.95	2.89	41%
	Fall (SON)	4.22	1.04	2.38	4.04	2.60	2.52	60%
Ratio	Winter / Summer	43%	45%	56%	162%	49%	76%	

Table D-9. Monthly and seasonal daily solar irradiation in Burbank, California (city representing California building climate zone 9).

		Solar Radiation [kWh/m²·day]						
		Horizontal (H)	**North wall (N)**	**East wall (E)**	**South wall (S)**	**West wall (W)**	**Four-wall average (NESW)**	**Ratio of NESW to H**
Month	January	2.97	0.65	1.96	4.56	1.81	2.25	76%
	February	3.19	0.81	1.82	3.33	1.88	1.96	61%
	March	4.99	0.99	2.68	3.76	2.81	2.56	51%
	April	6.42	1.26	3.28	3.06	3.59	2.80	44%
	May	6.74	1.70	3.53	2.30	3.62	2.79	41%
	June	7.79	1.90	3.70	2.17	4.06	2.96	38%
	July	7.60	1.91	4.14	2.43	3.98	3.11	41%
	August	7.23	1.51	3.92	3.26	4.05	3.19	44%
	September	5.36	1.22	3.11	3.77	3.28	2.84	53%
	October	3.90	0.96	2.47	4.02	2.24	2.42	62%
	November	3.56	0.79	2.23	5.15	2.38	2.64	74%
	December	2.66	0.67	1.79	4.41	1.84	2.18	82%
Season	Winter (DJF)	2.94	0.71	1.86	4.10	1.84	2.13	72%
	Spring (MAM)	6.05	1.31	3.17	3.04	3.34	2.71	45%
	Summer (JJA)	7.54	1.77	3.92	2.62	4.03	3.09	41%
	Fall (SON)	4.27	0.99	2.60	4.31	2.63	2.63	62%
Ratio	Winter / Summer	39%	40%	47%	157%	46%	69%	

Table D-10. Monthly and seasonal daily solar irradiation in Riverside, California (city representing California building climate zone 10).

		Solar Radiation [kWh/m²·day]						
		Horizontal (H)	**North wall (N)**	**East wall (E)**	**South wall (S)**	**West wall (W)**	**Four-wall average (NESW)**	**Ratio of NESW to H**
Month	January	3.09	0.75	1.87	4.62	2.06	2.33	75%
	February	3.51	0.92	2.14	3.93	2.21	2.30	66%
	March	4.87	1.07	2.42	3.69	2.96	2.54	52%
	April	6.17	1.39	3.46	3.15	3.38	2.84	46%
	May	6.91	1.77	3.36	2.45	3.89	2.87	41%
	June	7.92	2.02	3.76	2.26	4.24	3.07	39%
	July	7.61	1.98	4.14	2.46	4.04	3.16	41%
	August	7.12	1.59	3.96	3.24	3.93	3.18	45%
	September	4.93	1.22	2.90	3.42	2.95	2.62	53%
	October	3.83	0.99	2.28	3.84	2.27	2.34	61%
	November	3.55	0.82	2.20	5.06	2.34	2.60	73%
	December	2.94	0.73	2.02	4.95	1.98	2.42	82%
Season	Winter (DJF)	3.18	0.80	2.01	4.50	2.09	2.35	74%
	Spring (MAM)	5.98	1.41	3.08	3.10	3.41	2.75	46%
	Summer (JJA)	7.55	1.86	3.95	2.65	4.07	3.14	42%
	Fall (SON)	4.10	1.01	2.46	4.11	2.52	2.52	62%
Ratio	Winter / Summer	42%	43%	51%	169%	51%	75%	

Table D-11. Monthly and seasonal daily solar irradiation in Beale, California (city located in California building climate zone 11, 105 miles south of Red Bluff, CA, which is the city representing CACZ 11).

		Solar Radiation [kWh/m²·day]						
		Horizontal (H)	**North wall (N)**	**East wall (E)**	**South wall (S)**	**West wall (W)**	**Four-wall average (NESW)**	**Ratio of NESW to H**
Month	January	1.87	0.59	1.19	2.78	1.22	1.44	77%
	February	2.53	0.82	1.52	2.87	1.70	1.73	68%
	March	3.93	1.05	2.43	3.32	2.31	2.28	58%
	April	5.16	1.27	2.87	3.02	3.04	2.55	49%
	May	7.42	1.68	4.20	2.96	3.87	3.18	43%
	June	7.15	1.94	3.83	2.51	3.82	3.03	42%
	July	7.53	1.87	4.22	2.81	4.11	3.25	43%
	August	7.11	1.40	4.05	3.68	3.90	3.26	46%
	September	5.72	1.19	3.60	4.66	3.38	3.21	56%
	October	3.36	0.90	2.20	3.66	2.01	2.19	65%
	November	2.12	0.66	1.33	2.96	1.28	1.56	74%
	December	2.08	0.63	1.39	3.71	1.52	1.81	87%
Season	Winter (DJF)	2.16	0.68	1.37	3.12	1.48	1.66	77%
	Spring (MAM)	5.50	1.34	3.16	3.10	3.07	2.67	48%
	Summer (JJA)	7.26	1.73	4.03	3.00	3.94	3.18	44%
	Fall (SON)	3.73	0.91	2.38	3.76	2.22	2.32	62%
Ratio	Winter / Summer	30%	39%	34%	104%	38%	52%	

Table D-12. Monthly and seasonal daily solar irradiation in Sacramento, California (city representing California building climate zone 12).

		Solar Radiation [kWh/m²·day]						
		Horizontal (H)	**North wall (N)**	**East wall (E)**	**South wall (S)**	**West wall (W)**	**Four-wall average (NESW)**	**Ratio of NESW to H**
Month	January	1.74	0.55	0.97	2.50	1.24	1.31	76%
	February	2.64	0.81	1.70	3.12	1.64	1.82	69%
	March	4.73	1.06	2.88	4.07	2.62	2.66	56%
	April	6.40	1.38	3.82	3.71	3.73	3.16	49%
	May	7.35	1.69	4.18	2.93	3.85	3.16	43%
	June	8.09	2.07	4.49	2.62	4.28	3.37	42%
	July	7.87	1.92	4.40	2.85	4.28	3.37	43%
	August	7.05	1.40	4.17	3.58	3.87	3.25	46%
	September	5.42	1.19	3.42	4.40	3.26	3.07	57%
	October	3.65	0.90	2.37	4.16	2.34	2.44	67%
	November	2.51	0.72	1.64	3.69	1.58	1.91	76%
	December	1.88	0.62	1.16	3.06	1.35	1.55	82%
Season	Winter (DJF)	2.09	0.66	1.28	2.89	1.41	1.56	75%
	Spring (MAM)	6.16	1.38	3.63	3.57	3.40	2.99	49%
	Summer (JJA)	7.67	1.80	4.35	3.02	4.14	3.33	43%
	Fall (SON)	3.86	0.94	2.47	4.09	2.39	2.47	64%
Ratio	Winter / Summer	27%	37%	29%	96%	34%	47%	

Table D-13. Monthly and seasonal daily solar irradiation in Sacramento, California (city representing California building climate zone 12).

		Solar Radiation [kWh/m²·day]						
		Horizontal (H)	**North wall (N)**	**East wall (E)**	**South wall (S)**	**West wall (W)**	**Four-wall average (NESW)**	**Ratio of NESW to H**
Month	January	1.86	0.67	1.16	2.28	1.11	1.31	70%
	February	3.19	0.95	2.10	3.74	2.06	2.21	69%
	March	4.72	1.23	2.76	3.95	2.90	2.71	57%
	April	6.53	1.48	3.75	3.82	3.77	3.21	49%
	May	7.35	1.84	4.12	2.83	3.90	3.17	43%
	June	8.18	2.14	4.52	2.49	4.40	3.39	41%
	July	7.84	1.99	4.33	2.67	4.38	3.34	43%
	August	7.31	1.56	4.15	3.58	4.28	3.39	46%
	September	5.73	1.20	3.51	4.33	3.43	3.12	54%
	October	4.36	1.03	2.80	4.82	2.60	2.81	65%
	November	2.73	0.77	1.60	3.80	1.87	2.01	74%
	December	1.92	0.61	1.19	2.95	1.25	1.50	78%
Season	Winter (DJF)	2.32	0.74	1.48	2.99	1.48	1.67	72%
	Spring (MAM)	6.20	1.52	3.55	3.53	3.52	3.03	49%
	Summer (JJA)	7.78	1.89	4.33	2.91	4.35	3.37	43%
	Fall (SON)	4.28	1.00	2.64	4.32	2.63	2.65	62%
Ratio	Winter / Summer	30%	39%	34%	103%	34%	50%	

Table D-14. Monthly and seasonal daily solar irradiation in China Lake, California (city representing California building climate zone 14).

		Solar Radiation [kWh/m²·day]						
		Horizontal (H)	North wall (N)	East wall (E)	South wall (S)	West wall (W)	Four-wall average (NESW)	Ratio of NESW to H
Month	January	3.19	0.74	2.33	5.41	2.13	2.65	83%
	February	4.02	0.94	2.77	5.13	2.69	2.89	72%
	March	5.60	1.08	3.48	4.72	3.49	3.20	57%
	April	6.98	1.50	4.32	3.73	3.84	3.34	48%
	May	8.08	1.97	4.57	2.85	4.55	3.49	43%
	June	8.55	2.16	4.81	2.36	4.57	3.47	41%
	July	7.91	1.91	4.61	2.49	4.16	3.29	42%
	August	7.41	1.50	4.46	3.31	4.35	3.41	46%
	September	6.15	1.14	3.87	4.59	3.82	3.35	55%
	October	4.79	0.95	3.20	5.42	3.09	3.17	66%
	November	3.45	0.73	2.33	5.55	2.55	2.79	81%
	December	2.81	0.65	2.02	5.26	2.12	2.51	89%
Season	Winter (DJF)	3.34	0.78	2.38	5.27	2.32	2.68	80%
	Spring (MAM)	6.88	1.52	4.12	3.77	3.96	3.34	49%
	Summer (JJA)	7.96	1.86	4.63	2.72	4.36	3.39	43%
	Fall (SON)	4.80	0.94	3.14	5.19	3.15	3.10	65%
Ratio	Winter / Summer	42%	42%	51%	194%	53%	79%	

Table D-15. Monthly and seasonal daily solar irradiation in Palm Springs, California (city located in California building climate zone 15, 100 miles north of Imperial, California, which is the city representing CACZ 15).

		Solar Radiation [kWh/m²·day]						Ratio of NESW to H
		Horizontal (H)	North wall (N)	East wall (E)	South wall (S)	West wall (W)	Four-wall average (NESW)	
Month	January	3.24	0.75	2.23	5.09	2.12	2.55	79%
	February	3.92	0.98	2.49	4.55	2.59	2.65	68%
	March	5.20	1.05	3.20	4.15	3.11	2.88	55%
	April	6.82	1.48	4.08	3.46	3.74	3.19	47%
	May	7.85	2.03	4.48	2.71	4.42	3.41	43%
	June	8.09	2.35	4.44	2.26	4.66	3.43	42%
	July	7.66	2.10	4.30	2.38	4.42	3.30	43%
	August	7.06	1.53	4.17	3.14	4.01	3.21	45%
	September	5.89	1.20	3.73	4.23	3.54	3.17	54%
	October	4.59	0.97	3.00	4.86	2.71	2.89	63%
	November	3.66	0.78	2.36	5.49	2.57	2.80	76%
	December	3.23	0.73	2.17	5.71	2.39	2.75	85%
Season	Winter (DJF)	3.46	0.82	2.30	5.12	2.37	2.65	77%
	Spring (MAM)	6.62	1.52	3.92	3.44	3.76	3.16	48%
	Summer (JJA)	7.60	1.99	4.30	2.59	4.36	3.31	44%
	Fall (SON)	4.71	0.98	3.03	4.86	2.94	2.95	63%
Ratio	Winter / Summer	46%	41%	53%	197%	54%	80%	

Table D-16. Monthly and seasonal daily solar irradiation in Montague Siskiyou County airport, which is 30 miles north of Mount Shasta, California (city representing California building climate zone 16).

		Solar Radiation [kWh/m²·day]						Ratio of NESW to H
		Horizontal (H)	North wall (N)	East wall (E)	South wall (S)	West wall (W)	Four-wall average (NESW)	
Month	January	1.94	0.56	1.33	3.45	1.49	1.71	88%
	February	2.97	0.69	1.88	4.20	2.15	2.23	75%
	March	4.41	0.93	2.73	4.27	2.86	2.70	61%
	April	5.60	1.25	3.41	3.47	3.27	2.85	51%
	May	6.87	1.65	4.02	2.92	3.61	3.05	44%
	June	7.59	2.01	4.23	2.69	4.11	3.26	43%
	July	7.82	1.81	4.44	2.98	4.28	3.38	43%
	August	7.19	1.32	4.34	3.92	4.04	3.41	47%
	September	5.69	1.00	3.62	4.91	3.69	3.30	58%
	October	3.51	0.80	2.41	4.44	2.26	2.48	71%
	November	1.95	0.56	1.26	3.11	1.35	1.57	80%
	December	1.89	0.54	1.33	3.86	1.49	1.81	95%
Season	Winter (DJF)	2.27	0.60	1.51	3.84	1.71	1.91	84%
	Spring (MAM)	5.63	1.28	3.39	3.55	3.25	2.87	51%
	Summer (JJA)	7.53	1.71	4.34	3.20	4.14	3.35	44%
	Fall (SON)	3.72	0.79	2.43	4.15	2.43	2.45	66%
Ratio	Winter / Summer	30%	35%	35%	120%	41%	57%	

Table D-17. Monthly and seasonal daily solar irradiation in Miami, Florida (city representing ASHRAE climate zone 1A).

		Solar Radiation [kWh/m²·day]						
		Horizontal (H)	**North wall (N)**	**East wall (E)**	**South wall (S)**	**West wall (W)**	**Four-wall average (NESW)**	**Ratio of NESW to H**
Month	January	3.49	0.83	2.15	4.05	1.93	2.24	64%
	February	4.25	1.09	2.54	3.87	2.47	2.49	59%
	March	5.16	1.30	3.03	3.31	3.03	2.67	52%
	April	5.93	1.28	3.08	2.34	3.11	2.45	41%
	May	5.81	1.78	3.13	1.83	3.05	2.45	42%
	June	5.54	1.93	3.07	1.59	2.59	2.30	41%
	July	6.01	1.92	3.18	1.77	2.89	2.44	41%
	August	5.49	1.40	2.68	1.94	2.67	2.17	40%
	September	4.88	1.41	2.80	2.78	2.47	2.36	48%
	October	4.32	1.03	2.43	3.42	2.33	2.30	53%
	November	3.54	1.03	2.13	3.72	2.06	2.23	63%
	December	3.22	0.83	1.67	3.83	1.97	2.08	65%
Season	Winter (DJF)	3.65	0.92	2.12	3.92	2.12	2.27	62%
	Spring (MAM)	5.63	1.46	3.08	2.49	3.06	2.52	45%
	Summer (JJA)	5.68	1.75	2.98	1.77	2.72	2.30	41%
	Fall (SON)	4.25	1.15	2.45	3.30	2.29	2.30	54%
Ratio	Winter / Summer	64%	52%	71%	221%	78%	98%	

Table D-18. Monthly and seasonal daily solar irradiation in Houston, Texas (city representing ASHRAE climate zone 2A).

		Solar Radiation [kWh/m²·day]						Ratio of NESW to H
		Horizontal (H)	North wall (N)	East wall (E)	South wall (S)	West wall (W)	Four-wall average (NESW)	
Month	January	2.83	0.82	1.66	3.42	1.81	1.93	68%
	February	3.29	0.97	1.81	3.15	2.06	2.00	61%
	March	4.27	1.16	2.33	3.03	2.55	2.27	53%
	April	4.92	1.43	2.56	2.41	2.70	2.27	46%
	May	5.44	1.70	2.90	1.94	2.91	2.36	43%
	June	5.95	1.90	3.27	1.71	2.94	2.46	41%
	July	6.18	1.82	3.27	1.88	3.04	2.50	41%
	August	5.47	1.39	2.99	2.19	2.75	2.33	43%
	September	5.05	1.30	2.93	3.18	2.87	2.57	51%
	October	4.22	1.06	2.46	3.90	2.53	2.49	59%
	November	3.17	0.88	1.90	3.75	1.94	2.12	67%
	December	2.60	0.78	1.52	3.40	1.70	1.85	71%
Season	Winter (DJF)	2.91	0.86	1.67	3.32	1.86	1.93	66%
	Spring (MAM)	4.88	1.43	2.60	2.46	2.72	2.30	47%
	Summer (JJA)	5.87	1.70	3.18	1.93	2.91	2.43	41%
	Fall (SON)	4.15	1.08	2.43	3.61	2.45	2.39	58%
Ratio	Winter / Summer	50%	50%	52%	172%	64%	79%	

Table D-19. Monthly and seasonal daily solar irradiation in Phoenix, Arizona (city representing ASHRAE climate zone 2B).

		Solar Radiation [kWh/m²·day]						Ratio of NESW to H
		Horizontal (H)	North wall (N)	East wall (E)	South wall (S)	West wall (W)	Four-wall average (NESW)	
Month	January	3.29	0.78	2.07	5.08	2.39	2.58	78%
	February	4.18	0.97	2.72	4.84	2.57	2.77	66%
	March	5.34	1.12	3.19	4.18	3.27	2.94	55%
	April	7.12	1.49	4.22	3.64	3.91	3.31	47%
	May	7.85	1.98	4.36	2.64	4.28	3.31	42%
	June	8.31	2.29	4.50	2.29	4.41	3.37	41%
	July	7.60	1.96	3.95	2.42	3.92	3.06	40%
	August	7.12	1.60	3.95	3.18	4.02	3.19	45%
	September	6.31	1.28	3.71	4.38	3.73	3.28	52%
	October	4.78	1.03	3.14	5.07	2.86	3.03	63%
	November	3.75	0.83	2.57	5.55	2.48	2.86	76%
	December	3.07	0.72	2.06	5.25	2.19	2.56	83%
Season	Winter (DJF)	3.52	0.82	2.28	5.06	2.38	2.64	75%
	Spring (MAM)	6.77	1.53	3.92	3.48	3.82	3.19	47%
	Summer (JJA)	7.68	1.95	4.13	2.63	4.12	3.21	42%
	Fall (SON)	4.95	1.05	3.14	5.00	3.02	3.05	62%
Ratio	Winter / Summer	46%	42%	55%	192%	58%	82%	

Table D-20. Monthly and seasonal daily solar irradiation in Memphis, Tennessee (city representing ASHRAE climate zone 3A).

		Solar Radiation [kWh/m²·day]						Ratio of NESW to H
		Horizontal (H)	North wall (N)	East wall (E)	South wall (S)	West wall (W)	Four-wall average (NESW)	
Month	January	2.29	0.59	1.41	3.35	1.52	1.72	75%
	February	2.82	0.77	1.76	3.09	1.65	1.82	64%
	March	4.25	1.06	2.40	3.32	2.68	2.36	56%
	April	5.34	1.28	2.99	2.85	3.04	2.54	48%
	May	5.99	1.80	3.40	2.38	3.21	2.70	45%
	June	6.65	1.96	3.48	2.25	3.49	2.79	42%
	July	6.64	1.83	3.53	2.32	3.40	2.77	42%
	August	6.19	1.56	3.39	3.03	3.56	2.88	47%
	September	4.85	1.26	2.85	3.45	2.83	2.60	54%
	October	3.86	1.02	2.29	3.98	2.46	2.44	63%
	November	2.66	0.77	1.66	3.53	1.73	1.92	72%
	December	2.21	0.64	1.51	3.48	1.51	1.79	81%
Season	Winter (DJF)	2.44	0.67	1.56	3.31	1.56	1.77	73%
	Spring (MAM)	5.19	1.38	2.93	2.85	2.97	2.53	49%
	Summer (JJA)	6.49	1.78	3.47	2.53	3.48	2.82	43%
	Fall (SON)	3.79	1.02	2.27	3.65	2.34	2.32	61%
Ratio	Winter / Summer	38%	37%	45%	131%	45%	63%	

Table D-21. Monthly and seasonal daily solar irradiation in El Paso, Texas (city representing ASHRAE climate zone 3B).

		Solar Radiation [kWh/m²·day]						
		Horizontal (H)	North wall (N)	East wall (E)	South wall (S)	West wall (W)	Four-wall average (NESW)	Ratio of NESW to H
Month	January	3.44	0.81	2.16	5.06	2.28	2.58	75%
	February	4.33	1.02	2.87	5.01	2.62	2.88	66%
	March	5.80	1.27	3.48	4.36	3.39	3.12	54%
	April	7.07	1.53	4.10	3.41	3.87	3.23	46%
	May	7.67	1.99	4.27	2.53	4.23	3.26	42%
	June	8.04	2.17	4.29	2.11	4.11	3.17	39%
	July	7.00	1.87	3.79	2.09	3.59	2.84	40%
	August	6.54	1.44	3.58	2.73	3.44	2.80	43%
	September	6.12	1.26	3.63	4.06	3.60	3.14	51%
	October	4.72	1.04	2.80	4.83	3.10	2.94	62%
	November	3.86	0.84	2.54	5.42	2.66	2.86	74%
	December	3.25	0.80	2.20	5.18	2.20	2.60	80%
Season	Winter (DJF)	3.67	0.88	2.41	5.08	2.37	2.68	73%
	Spring (MAM)	6.85	1.60	3.95	3.43	3.83	3.20	47%
	Summer (JJA)	7.19	1.83	3.89	2.31	3.72	2.94	41%
	Fall (SON)	4.90	1.05	2.99	4.77	3.12	2.98	61%
Ratio	Winter / Summer	51%	48%	62%	220%	64%	91%	

Table D-22. Monthly and seasonal daily solar irradiation in San Francisco, California (city representing ASHRAE climate zone 3C).

		Solar Radiation [kWh/m²·day]						
		Horizontal (H)	**North wall (N)**	**East wall (E)**	**South wall (S)**	**West wall (W)**	**Four-wall average (NESW)**	**Ratio of NESW to H**
Month	January	2.14	0.64	1.35	3.10	1.35	1.61	75%
	February	3.18	0.87	1.91	3.89	2.10	2.19	69%
	March	4.41	0.98	2.37	3.69	2.55	2.40	54%
	April	5.68	1.32	3.01	3.08	3.21	2.65	47%
	May	6.42	1.49	3.16	2.50	3.31	2.61	41%
	June	7.15	1.75	3.47	2.28	3.71	2.80	39%
	July	7.12	1.84	3.42	2.69	4.12	3.02	42%
	August	6.38	1.51	3.31	3.29	3.76	2.97	47%
	September	5.47	1.15	2.77	4.19	3.36	2.87	52%
	October	3.76	0.99	2.28	4.07	2.43	2.44	65%
	November	2.53	0.72	1.68	3.60	1.56	1.89	75%
	December	2.13	0.63	1.47	3.75	1.50	1.84	86%
Season	Winter (DJF)	2.48	0.71	1.58	3.58	1.65	1.88	76%
	Spring (MAM)	5.50	1.26	2.85	3.09	3.02	2.56	46%
	Summer (JJA)	6.88	1.70	3.40	2.75	3.86	2.93	43%
	Fall (SON)	3.92	0.95	2.24	3.95	2.45	2.40	61%
Ratio	Winter / Summer	36%	42%	46%	130%	43%	64%	

Table D-23. Monthly and seasonal daily solar irradiation in Baltimore, Maryland (city representing ASHRAE climate zone 4A).

		Solar Radiation [kWh/m²·day]						
		Horizontal (H)	North wall (N)	East wall (E)	South wall (S)	West wall (W)	Four-wall average (NESW)	Ratio of NESW to H
Month	January	2.02	0.59	1.43	3.35	1.37	1.69	84%
	February	2.75	0.78	1.95	3.45	1.71	1.97	72%
	March	3.90	1.04	2.42	3.55	2.31	2.33	60%
	April	5.10	1.37	2.95	3.14	2.89	2.59	51%
	May	5.64	1.67	3.14	2.55	3.11	2.62	46%
	June	6.46	1.94	3.69	2.49	3.36	2.87	44%
	July	5.97	1.82	3.32	2.49	3.33	2.74	46%
	August	5.26	1.35	2.89	2.65	2.74	2.41	46%
	September	4.29	1.19	2.64	3.21	2.51	2.39	56%
	October	3.44	0.92	2.10	3.94	2.11	2.27	66%
	November	2.21	0.65	1.49	3.39	1.57	1.77	80%
	December	1.82	0.56	1.17	3.11	1.31	1.54	84%
Season	Winter (DJF)	2.20	0.64	1.52	3.30	1.46	1.73	79%
	Spring (MAM)	4.88	1.36	2.83	3.08	2.77	2.51	52%
	Summer (JJA)	5.90	1.70	3.30	2.54	3.14	2.67	45%
	Fall (SON)	3.31	0.92	2.08	3.51	2.06	2.14	65%
Ratio	Winter / Summer	37%	38%	46%	130%	47%	65%	

Table D-24. Monthly and seasonal daily solar irradiation in Albuquerque, New Mexico (city representing ASHRAE climate zone 4B).

		Solar Radiation [kWh/m²·day]						
		Horizontal (H)	**North wall (N)**	**East wall (E)**	**South wall (S)**	**West wall (W)**	**Four-wall average (NESW)**	**Ratio of NESW to H**
Month	January	3.16	0.74	2.13	5.06	2.18	2.53	80%
	February	4.15	0.92	2.52	5.16	2.73	2.83	68%
	March	5.08	1.16	3.24	4.23	2.98	2.90	57%
	April	6.80	1.43	4.19	3.55	3.67	3.21	47%
	May	7.18	1.63	3.98	2.50	3.49	2.90	40%
	June	7.59	2.12	4.47	2.20	3.82	3.15	42%
	July	7.37	1.85	4.15	2.46	3.51	2.99	41%
	August	6.96	1.63	4.11	3.26	3.59	3.15	45%
	September	5.78	1.23	3.44	4.19	3.25	3.03	52%
	October	4.55	0.88	3.01	5.04	2.94	2.97	65%
	November	3.41	0.75	2.36	5.23	2.36	2.67	78%
	December	2.93	0.63	2.01	5.41	2.12	2.54	87%
Season	Winter (DJF)	3.41	0.76	2.22	5.21	2.35	2.63	77%
	Spring (MAM)	6.35	1.41	3.80	3.43	3.38	3.00	47%
	Summer (JJA)	7.31	1.87	4.24	2.64	3.64	3.10	42%
	Fall (SON)	4.58	0.95	2.94	4.82	2.85	2.89	63%
Ratio	Winter / Summer	47%	41%	52%	197%	64%	85%	

Table D-25. Monthly and seasonal daily solar irradiation in Salem, Oregon (city representing ASHRAE climate zone 4C, used for commercial prototypes).

		Solar Radiation [kWh/m²·day]						
		Horizontal (H)	North wall (N)	East wall (E)	South wall (S)	West wall (W)	Four-wall average (NESW)	Ratio of NESW to H
Month	January	1.33	0.49	0.89	2.07	0.92	1.09	82%
	February	1.99	0.69	1.21	2.38	1.39	1.42	71%
	March	3.11	0.86	1.87	2.84	1.89	1.86	60%
	April	4.34	1.36	2.44	2.94	2.74	2.37	55%
	May	5.46	1.76	2.91	2.89	3.35	2.73	50%
	June	6.26	2.00	3.36	2.81	3.75	2.98	48%
	July	6.78	1.96	3.88	3.20	4.13	3.29	49%
	August	5.57	1.25	3.17	3.35	3.41	2.79	50%
	September	4.55	1.14	2.79	4.14	3.04	2.78	61%
	October	2.56	0.70	1.53	3.10	1.72	1.77	69%
	November	1.35	0.52	0.84	1.79	0.89	1.01	75%
	December	1.01	0.38	0.73	1.79	0.73	0.91	90%
Season	Winter (DJF)	1.45	0.52	0.94	2.08	1.02	1.14	79%
	Spring (MAM)	4.30	1.33	2.41	2.89	2.66	2.32	54%
	Summer (JJA)	6.20	1.74	3.47	3.12	3.77	3.02	49%
	Fall (SON)	2.82	0.79	1.72	3.01	1.88	1.85	66%
Ratio	Winter / Summer	23%	30%	27%	67%	27%	38%	

Table D-26. Monthly and seasonal daily solar irradiation in Seattle, Washington (city representing ASHRAE climate zone 4C, used for residential prototypes).

		Solar Radiation [kWh/m²·day]						
		Horizontal (H)	North wall (N)	East wall (E)	South wall (S)	West wall (W)	Four-wall average (NESW)	Ratio of NESW to H
Month	January	1.02	0.40	0.66	1.61	0.70	0.84	83%
	February	1.80	0.62	1.19	2.51	1.22	1.39	77%
	March	2.83	0.86	1.69	2.72	1.63	1.72	61%
	April	4.35	1.31	2.64	3.16	2.53	2.41	55%
	May	5.49	1.71	2.84	3.09	3.23	2.72	50%
	June	5.93	1.68	3.24	2.78	2.98	2.67	45%
	July	6.19	1.77	3.17	3.23	3.81	3.00	48%
	August	5.05	1.28	2.95	3.16	3.04	2.61	52%
	September	3.68	0.98	2.23	3.34	2.54	2.27	62%
	October	2.27	0.68	1.50	2.83	1.50	1.63	72%
	November	1.16	0.45	0.77	1.66	0.77	0.91	79%
	December	0.89	0.36	0.68	1.72	0.69	0.86	96%
Season	Winter (DJF)	1.24	0.46	0.84	1.95	0.87	1.03	83%
	Spring (MAM)	4.22	1.29	2.39	2.99	2.46	2.29	54%
	Summer (JJA)	5.72	1.58	3.12	3.06	3.28	2.76	48%
	Fall (SON)	2.37	0.70	1.50	2.61	1.60	1.61	68%
Ratio	Winter / Summer	22%	29%	27%	64%	27%	37%	

Table D-27. Monthly and seasonal daily solar irradiation in Chicago, Illinois (city representing ASHRAE climate zone 5A, used for commercial prototypes).

		Solar Radiation [kWh/m²·day]						
		Horizontal (H)	**North wall (N)**	**East wall (E)**	**South wall (S)**	**West wall (W)**	**Four-wall average (NESW)**	**Ratio of NESW to H**
Month	January	1.76	0.58	1.17	2.88	1.24	1.47	83%
	February	2.50	0.80	1.59	3.20	1.65	1.81	72%
	March	3.45	1.05	2.15	3.16	2.04	2.10	61%
	April	4.39	1.18	2.51	2.72	2.50	2.23	51%
	May	5.98	1.75	3.39	2.88	3.31	2.83	47%
	June	6.29	1.98	3.65	2.64	3.43	2.93	47%
	July	6.17	1.88	3.40	2.83	3.46	2.89	47%
	August	5.14	1.52	3.05	2.96	2.98	2.63	51%
	September	4.17	1.16	2.67	3.40	2.49	2.43	58%
	October	2.92	0.87	1.99	3.47	1.84	2.04	70%
	November	1.80	0.63	1.17	2.53	1.12	1.36	75%
	December	1.49	0.49	1.09	2.67	1.02	1.32	88%
Season	Winter (DJF)	1.92	0.62	1.29	2.92	1.30	1.53	80%
	Spring (MAM)	4.61	1.32	2.68	2.92	2.62	2.39	52%
	Summer (JJA)	5.87	1.79	3.37	2.81	3.29	2.82	48%
	Fall (SON)	2.96	0.89	1.94	3.13	1.82	1.94	66%
Ratio	Winter / Summer	33%	35%	38%	104%	40%	54%	

Table D-28. Monthly and seasonal daily solar irradiation in Peoria, Illinois (city representing ASHRAE climate zone 5A, used for residential prototypes).

		Solar Radiation [kWh/m²·day]						
		Horizontal (H)	North wall (N)	East wall (E)	South wall (S)	West wall (W)	Four-wall average (NESW)	Ratio of NESW to H
Month	January	1.85	0.41	1.15	2.84	1.02	1.36	74%
	February	2.93	0.55	1.66	3.56	1.59	1.84	63%
	March	3.78	0.72	2.09	2.99	1.76	1.89	50%
	April	4.59	0.82	2.19	2.40	2.38	1.95	43%
	May	5.87	1.13	2.89	2.18	2.46	2.16	37%
	June	6.62	1.38	3.11	1.97	3.01	2.37	36%
	July	6.29	1.23	2.95	2.11	2.87	2.29	36%
	August	5.60	0.95	2.47	2.61	2.73	2.19	39%
	September	4.48	0.73	2.43	3.12	2.21	2.12	47%
	October	3.21	0.56	1.87	3.54	1.69	1.91	60%
	November	2.04	0.45	1.16	2.70	1.19	1.37	67%
	December	1.65	0.37	1.00	2.66	0.96	1.25	76%
Season	Winter (DJF)	2.14	0.44	1.27	3.02	1.19	1.48	69%
	Spring (MAM)	4.75	0.89	2.39	2.53	2.20	2.00	42%
	Summer (JJA)	6.17	1.19	2.84	2.23	2.87	2.28	37%
	Fall (SON)	3.24	0.58	1.82	3.12	1.70	1.80	56%
Ratio	Winter / Summer	35%	37%	45%	135%	42%	65%	

Table D-29. Monthly and seasonal daily solar irradiation in Boise, Idaho (city representing ASHRAE climate zone 5B).

		Solar Radiation [kWh/m²·day]						
		Horizontal (H)	North wall (N)	East wall (E)	South wall (S)	West wall (W)	Four-wall average (NESW)	Ratio of NESW to H
Month	January	1.69	0.59	1.16	2.69	1.18	1.40	83%
	February	2.50	0.76	1.62	3.42	1.79	1.90	76%
	March	3.66	0.91	2.42	3.48	2.22	2.26	62%
	April	5.46	1.43	3.49	3.71	3.12	2.94	54%
	May	6.31	1.67	3.57	3.04	3.50	2.94	47%
	June	7.56	2.09	4.37	2.92	4.17	3.39	45%
	July	7.62	1.81	4.29	3.20	4.11	3.35	44%
	August	6.60	1.46	4.00	3.91	4.11	3.37	51%
	September	5.00	1.05	3.32	4.58	3.24	3.05	61%
	October	3.40	0.79	2.51	4.39	2.17	2.47	72%
	November	1.83	0.55	1.25	3.08	1.29	1.54	84%
	December	1.40	0.44	1.00	2.78	1.00	1.30	93%
Season	Winter (DJF)	1.86	0.59	1.26	2.96	1.32	1.53	82%
	Spring (MAM)	5.14	1.34	3.16	3.41	2.95	2.71	53%
	Summer (JJA)	7.26	1.78	4.22	3.34	4.13	3.37	46%
	Fall (SON)	3.41	0.80	2.36	4.02	2.24	2.35	69%
Ratio	Winter / Summer	26%	33%	30%	89%	32%	46%	

Table D-30. Monthly and seasonal daily solar irradiation in Burlington, Vermont (city representing ASHRAE climate zone 6A).

		Solar Radiation [kWh/m²·day]						Ratio of NESW to H
		Horizontal (H)	North wall (N)	East wall (E)	South wall (S)	West wall (W)	Four-wall average (NESW)	
Month	January	1.71	0.63	1.14	2.56	1.19	1.38	81%
	February	2.45	0.78	1.65	3.13	1.50	1.77	72%
	March	3.37	0.94	2.11	3.08	2.21	2.08	62%
	April	4.81	1.34	3.08	3.27	2.93	2.65	55%
	May	5.37	1.55	3.05	2.68	3.01	2.57	48%
	June	6.04	2.02	3.51	2.71	3.50	2.94	49%
	July	5.89	1.84	3.30	2.85	3.34	2.83	48%
	August	5.26	1.52	3.13	3.26	3.20	2.78	53%
	September	3.80	1.18	2.28	3.17	2.25	2.22	58%
	October	2.59	0.83	1.69	3.04	1.69	1.81	70%
	November	1.58	0.54	1.05	2.35	1.11	1.26	80%
	December	1.11	0.39	0.77	2.03	0.77	0.99	89%
Season	Winter (DJF)	1.75	0.60	1.18	2.57	1.15	1.38	79%
	Spring (MAM)	4.52	1.28	2.74	3.01	2.72	2.44	54%
	Summer (JJA)	5.73	1.79	3.31	2.94	3.35	2.85	50%
	Fall (SON)	2.66	0.85	1.67	2.86	1.68	1.77	67%
Ratio	Winter / Summer	31%	34%	36%	88%	34%	48%	

Table D-31. Monthly and seasonal daily solar irradiation in Helena, Montana (city representing ASHRAE climate zone 6B).

		Solar Radiation [kWh/m²·day]						
		Horizontal (H)	North wall (N)	East wall (E)	South wall (S)	West wall (W)	Four-wall average (NESW)	Ratio of NESW to H
Month	January	1.48	0.47	1.16	3.14	1.14	1.48	100%
	February	2.38	1.00	1.96	3.92	2.26	2.29	96%
	March	3.58	0.99	2.27	3.78	2.49	2.38	67%
	April	4.97	1.37	3.20	3.67	3.05	2.82	57%
	May	5.87	1.85	3.76	3.08	3.48	3.04	52%
	June	6.72	1.98	4.08	2.96	3.68	3.17	47%
	July	7.14	1.95	4.34	3.49	4.09	3.47	49%
	August	5.75	1.49	3.79	3.72	3.41	3.10	54%
	September	4.30	1.08	2.94	4.08	2.83	2.73	64%
	October	2.66	0.74	1.87	3.70	1.91	2.06	77%
	November	1.69	0.53	1.21	3.21	1.33	1.57	93%
	December	1.30	0.41	0.96	2.98	1.04	1.35	103%
Season	Winter (DJF)	1.72	0.63	1.36	3.35	1.48	1.70	99%
	Spring (MAM)	4.81	1.40	3.07	3.51	3.01	2.75	57%
	Summer (JJA)	6.54	1.81	4.07	3.39	3.73	3.25	50%
	Fall (SON)	2.88	0.78	2.01	3.67	2.02	2.12	73%
Ratio	Winter / Summer	26%	35%	33%	99%	40%	52%	

Table D-32. Monthly and seasonal daily solar irradiation in Duluth, Minnesota (city representing ASHRAE climate zone 7).

		Solar Radiation [kWh/m²·day]						
		Horizontal (H)	North wall (N)	East wall (E)	South wall (S)	West wall (W)	Four-wall average (NESW)	Ratio of NESW to H
Month	January	1.64	0.54	1.21	3.14	1.18	1.52	92%
	February	2.49	0.78	1.67	3.71	1.78	1.98	80%
	March	3.63	1.02	2.42	3.76	2.35	2.39	66%
	April	4.95	1.25	3.16	3.42	3.02	2.71	55%
	May	5.86	1.79	3.32	3.20	3.73	3.01	51%
	June	6.08	1.92	3.46	2.75	3.45	2.89	48%
	July	5.80	1.61	3.22	2.77	3.34	2.74	47%
	August	4.99	1.27	2.66	3.15	3.02	2.52	51%
	September	3.71	1.06	2.24	3.26	2.49	2.26	61%
	October	2.20	0.65	1.40	2.67	1.47	1.55	71%
	November	1.53	0.54	1.09	2.58	1.14	1.34	88%
	December	1.19	0.41	0.95	2.55	0.90	1.20	101%
Season	Winter (DJF)	1.78	0.57	1.28	3.13	1.28	1.57	88%
	Spring (MAM)	4.82	1.35	2.97	3.46	3.03	2.70	56%
	Summer (JJA)	5.63	1.60	3.11	2.89	3.27	2.72	48%
	Fall (SON)	2.48	0.75	1.57	2.84	1.70	1.72	69%
Ratio	Winter / Summer	32%	36%	41%	108%	39%	58%	

Table D-33. Monthly and seasonal daily solar irradiation in Fairbanks, Alaska (city representing ASHRAE climate zone 8).

		Solar Radiation [kWh/m²·day]						Ratio of NESW to H
		Horizontal (H)	North wall (N)	East wall (E)	South wall (S)	West wall (W)	Four-wall average (NESW)	
Month	January	0.14	0.06	0.21	0.65	0.10	0.26	178%
	February	0.74	0.27	0.95	2.16	0.52	0.97	132%
	March	2.25	0.70	2.48	3.80	1.46	2.11	94%
	April	4.27	1.79	3.70	5.29	3.76	3.63	85%
	May	5.25	2.00	4.55	4.17	3.15	3.47	66%
	June	5.62	2.54	4.24	3.86	3.47	3.53	63%
	July	5.05	2.14	4.03	3.69	2.93	3.20	63%
	August	3.88	1.39	3.25	3.70	2.42	2.69	69%
	September	2.18	0.75	2.07	2.90	1.47	1.80	82%
	October	0.97	0.36	1.16	2.07	0.61	1.05	108%
	November	0.26	0.16	0.32	1.15	0.31	0.48	189%
	December	0.04	0.02	0.04	0.17	0.02	0.06	157%
Season	Winter (DJF)	0.31	0.12	0.40	1.00	0.21	0.43	140%
	Spring (MAM)	3.92	1.50	3.57	4.42	2.79	3.07	78%
	Summer (JJA)	4.85	2.02	3.84	3.75	2.94	3.14	65%
	Fall (SON)	1.14	0.42	1.18	2.04	0.80	1.11	98%
Ratio	Winter / Summer	6%	6%	10%	27%	7%	14%	

Task Report Appendix E: Cool surface savings database fields

Table E-1 lists the building properties and saving metrics recorded in the savings database.

Table E-1. List of simulation properties and saving metrics recorded in the savings database.

Category		Property	Units [a]
Building and simulation properties		Year of building code	NA [b]
		Vintage	NA
		State	NA
		Representative location	NA
		Climate zone	NA
		Building category	NA
		Building orientation	NA
		Modified surfaces	NA
		Total modified surface area	m^2
		Base wall albedo	NA
		Modified wall albedo	NA
		Base roof albedo	NA
		Modified roof albedo	NA
Annual building base	Site energy use	Cooling electricity	MWh
		Heating electricity	MWh
		Heating gas	therm
		Fan electricity	MWh
	Site peak power demand	HVAC electricity	W
Annual building absolute savings, fractional savings, and savings intensity	Site energy [c]	Cooling electricity	kWh
		Heating electricity	kWh
		Heating gas	therm
		Fan electricity	kWh
	Site peak power demand reduction [c]	HVAC electricity	W
	Source energy [c]	Cooling	MJ
		Heating	MJ
		Fan	MJ
		HVAC	MJ
	Emissions reduction [c]	CO_2	kg
		CO_2e	kg
		NO_x	g
		SO_2	g
	Energy cost [c]	Cooling	$

		Heating	$
		Fan	$
		HVAC	$

[a] Fractional values are dimensionless; intensities are per square meter of modified surface.

[b] NA = not applicable.

[c] The savings database reports positive penalties as negative savings.