Energy Research and Development Division

FINAL PROJECT REPORT

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

Appendix P: Cool Wall Application Guidelines (Task 6.1 Report)

California Energy Commission

Gavin Newsom, Governor

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Appendix P: Cool wall application guidelines (Task 6.1 report)

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Abstract

This document introduces the concept of solar-reflective “cool” walls, and provides guidelines for their building- and climate-appropriate use to conserve energy and reduce emissions of greenhouse gases and criteria pollutants across California and the United States. First, it explores the nature of cool walls by answering basic questions, such as what is a cool wall, why choose a cool wall, and where do cool walls save energy. Second, it provides a simple guide to cool wall effects by detailing the energy cost savings (or penalties) that arise from increasing wall reflectance in three common building categories—single-family home, medium office, and retail stand-alone. This includes identification of building vintage, calculating energy cost savings, and gauging cost effectiveness, with worked examples. Third, it provides a detailed guide to these effects by describing the operation and application of the Cool Surface Savings Explorer, a database tool that can report the cool wall and cool roof energy, energy cost, peak power demand, and emission savings simulated for many building categories. Fourth, it discusses how to adjust cool walls savings and penalties to account for shading and reflection by neighboring buildings by applying a “solar availability factor”.

1 Introduction

This document introduces the concept of solar-reflective “cool” walls, and provides guidelines for their building- and climate-appropriate use to conserve energy and reduce emissions of greenhouse gases and criteria pollutants across California and the United States. First, it explores the nature of cool walls through a series of questions & answers. Second, it provides a simple guide to cool wall effects by detailing the energy cost savings (or penalties) that arise from increasing wall reflectance in three common building categories—single-family home, medium office, and retail stand-alone. Third, it provides a detailed guide to these effects by describing the operation and application of the Cool Surface Savings Explorer, a database tool that can report the cool wall and cool roof energy, energy cost, peak power demand, and emission savings simulated for many building categories. Fourth, it discusses how to adjust cool walls savings and penalties to account for shading and reflection by neighboring buildings.

Note that the term "wall" means "exterior wall" throughout this document.

2 Cool wall questions and answers

2.1 What is a cool wall?

A "cool" wall is a wall surface that stays cool in the sun by reflecting sunlight, and by efficiently emitting thermal infrared radiation. Reflective walls and roofs have long been used to cool buildings in hot, sunny climates. For example, Figure 1 shows building walls in Santorini, Greece that have been white-washed (coated with a solution of powdered lime) for high reflectance.

A cool wall exhibits high solar reflectance (fraction of incident sunlight that is reflected; also known as "albedo") and high thermal emittance (ratio of radiative power emitted by a surface near 300 K [27 °C, or 80 °F] to that emitted by a black body at the same temperature). High solar reflectance is most important to staying cool in the sun.

Figure 1. Buildings with white-washed walls in Santorini, Greece.

Heat flow through walls can be reduced with insulation, and the warming and cooling of walls can be dampened with massive construction (e.g., thick concrete). Walls can also be cooled by shading. However, we use the term “cool wall” to refer exclusively to an exterior wall surface that employs high solar reflectance to reduce solar heat gain (absorption of sunlight), and high thermal emittance to efficiently reject through emission of thermal infrared radiation some of the solar energy that is absorbed.

2.2 Why choose a cool wall?

Raising wall albedo lowers its surface temperature in the sun, reducing daytime heat flow into the building’s occupied space. In the cooling season, this can save energy in an air-conditioned building, or make an uncooled building more comfortable. In the heating season, increasing wall albedo can also increase heating energy use, or make an unheated building less comfortable.

Depending on building construction, operation, and location, raising wall albedo can either reduce or increase annual energy use, energy cost, and emissions of greenhouse gases, such as carbon dioxide, and criteria pollutants, such as nitrogen oxides (NO_x) and sulfur dioxide (SO_2). It can also decrease peak power demand. Sections 3 and 4 of this document explore these savings (or penalties).

Raising wall albedo also slightly increases the amount reflected to neighboring buildings. This effect is addressed in Section 5.

Making walls more reflective increases the fraction of sunlight incident on urban surfaces that escapes the city, reducing citywide solar heat gain, lowering urban air temperature, and mitigating the urban heat island effect[1]. The urban cooling benefit is explored in the Task 3.2 report: Urban climate impacts of cool walls.

The research team is working to develop incentives for the building- and climate-appropriate use of cool walls. The goal is to recognize cool walls in building standards, such as California's Title 24 and ASHRAE 90.1; green building codes, such as CalGreen, ASHRAE 189.1, and LEED; EPA EnergyStar; and/or utility energy-efficiency rebate programs. These efforts are detailed in the Task 6.3 report: *Advancements in infrastructure development: building standards and incentive programs*.

2.3 Where do cool walls save energy?

Cool walls reduce annual HVAC (heating, ventilation, and air conditioning) energy cost in all California building climate zones (Figure 2) and in U.S. climate zones 1 – 4 (Figure 3). Please see Section 3 for details.

2.4 Is a cool wall like a cool roof?

Yes—a cool wall is the analog of a cool roof. However, the timing and amount of sunlight incident on a wall (vertical) varies by direction, and differs from that on a roof (closer to horizontal); see Table 1 (California) and Table 2 (United States). Walls also tend to be less insulated than roofs, with roughly 50% less resistance to heat flow. The combination of lower insolation (<u>in</u>cident <u>sol</u>ar radi<u>ation</u>) and lower thermal resistance tends to make the annual energy cost savings intensity (energy cost savings per unit area of surface modified) upon raising the albedo of all four walls (north, south east, and west) comparable to that from raising roof albedo. This is explored further in Section 3.

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[1] The urban heat island effect is the elevation of urban air temperature over that in surrounding rural areas. It is driven in part by the prevalence of dark, dry surfaces in cities.

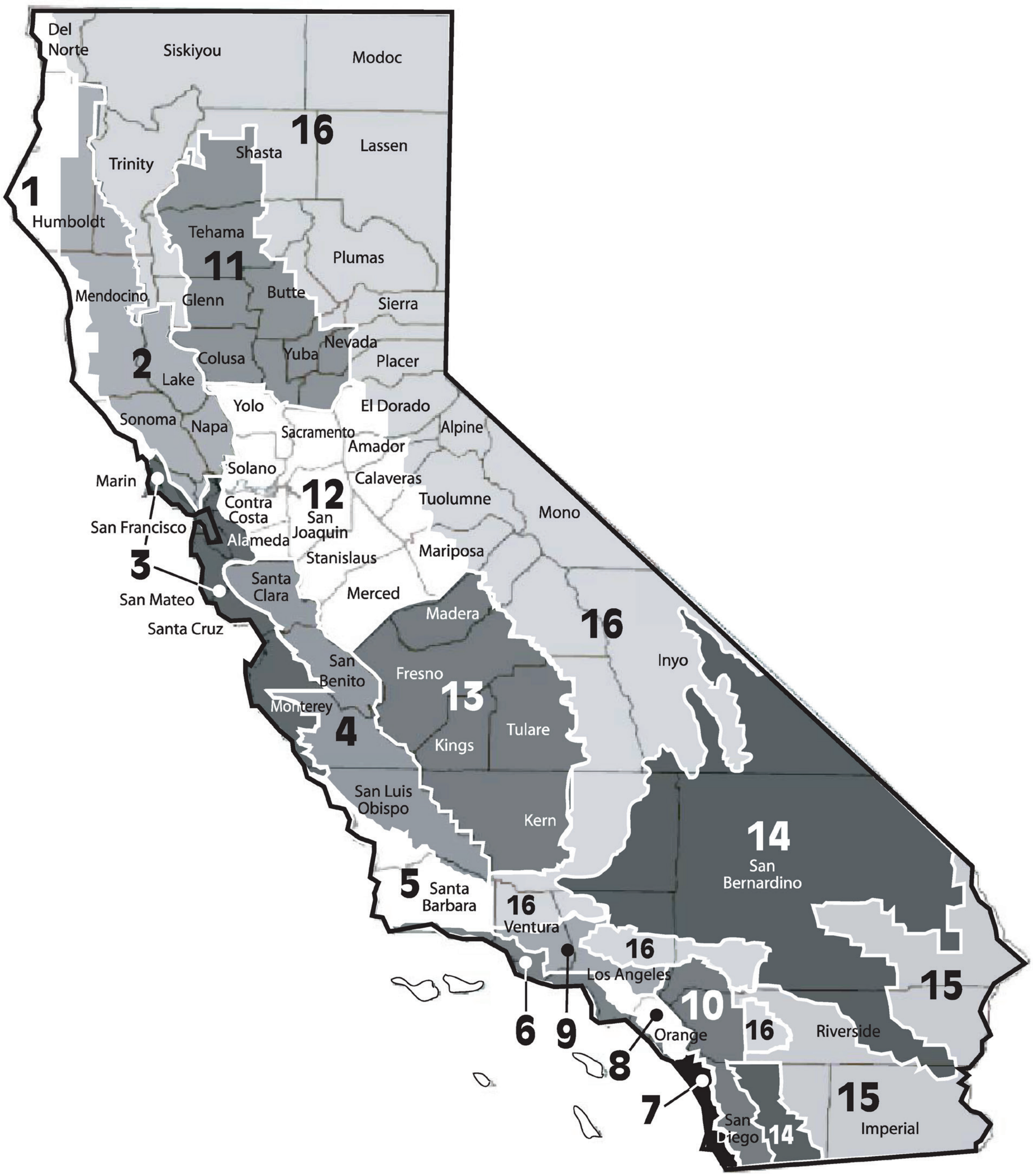

Figure 2. Map of California building climate zones (BCZs), showing zones (1 – 16) and counties.

CZ: City, State
1A: Miami, FL
2A: Houston, TX
2B: Phoenix, AZ
3A: Memphis, TN
3B: El Paso, TX
BU: Burbank, CA
FR: Fresno, CA
3C: San Francisco, CA
4A: Baltimore, MD
4B: Albuquerque, NM
4C: Seattle, WA
5A: Chicago, IL
5B: Boise, ID
6A: Burlington, VT
6B: Helena, MT
7: Duluth, MN
8: Fairbanks, AK

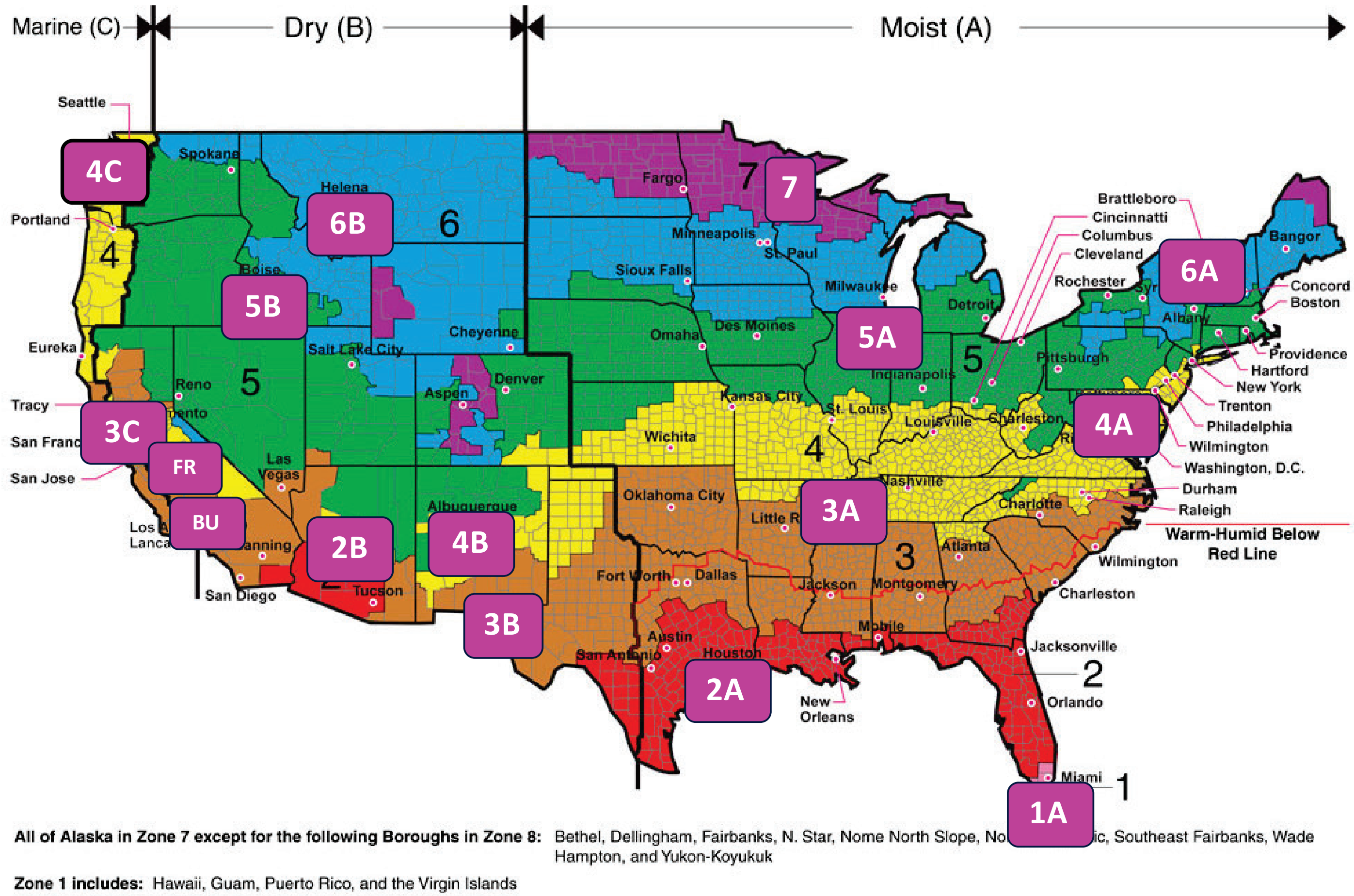

Figure 3. Map of U.S cities representing ASHRAE climate zones 1 – 8, plus two California cities (Burbank and Fresno). Adapted from Briggs et al. (2003a,b).

Table 1. 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 the cities representing each California building climate zone (Figure 2).

City or town in California	CACZ	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.

Table 2. 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 (Figure 3).

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).

2.5 Do cool walls help mitigate the urban heat island effect?

Yes. Simulations predict that increasing wall albedo throughout Los Angeles County by 0.4 would lower daily average outside air temperature in the "urban canyon" between buildings by about 0.2 ˚C (0.4 ˚F) in July. This is comparable to (about 84% of) the air temperature reduction provided by the same countywide increase in roof albedo. For details, please see the Task 3.2 report: *Urban climate impacts of cool walls.*

2.6 How do cool walls affect pedestrian comfort?

Simulations predict that in Los Angeles, the mean radiant temperature (MRT)[2] experienced when walking beside a cool wall (albedo 0.60) is about 1 °C (1.8 °F) higher than that experienced when walking beside a conventional wall (albedo 0.25). The pedestrian's average increase in daytime standard equivalent temperature (SET*)[3] is about 0.4 °C (0.7 °F). Please see the Task 3.1 report: *Pedestrian mean radiant temperature and thermal comfort* for details.

2.7 Are there specifications for cool walls?

Cool walls are an emerging measure in modern building energy efficiency standards. Cool wall specifications vary substantially across the few standards in which they appear. To wit:

- ASHRAE 90.1-2016: Energy Standard for Buildings Except Low-Rise Residential Buildings (ASHRAE 2016) permits east and west walls to be unshaded in ASHRAE climate zone 0 (hot & tropical) if they have a solar reflectance index (SRI) not less than 29, which would typically correspond to an albedo of at least 0.28.[4]

- 2011 and later editions of ASHRAE 189.1: Standard for the Design of High-Performance Green Buildings (ASHRAE 2011) have for east walls in climate zones 0 – 4 and west walls in climate zones 0 – 6 cool wall provisions similar to those in ASHRAE 90.1-2016.

- Several recent Chinese building energy efficiency standards assign extra thermal resistance to reflective walls, reducing the need for physical wall insulation. Some offer this trade-off only for very high wall albedos (at least 0.80), while others provide a thermal resistance benefit that scales with wall albedo (Ge and Levinson 2016).

As a starting point for discussion, we offer the following observations about wall reflectance and wall albedo. First, in North America, walls come in a wide color palette, from dark to light.

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[2] Mean radiant temperature (MRT) is defined as the uniform surface temperature of an imaginary enclosure in which the human body will exchange the same amount of radiant heat energy as in the actual non-uniform enclosure.

[3] SET* is defined as the air and radiant temperature of a standard isothermal environment that would cause the same thermal stress to the human body as the test environment.

[4] SRI is an artificial temperature index that compares the surface temperature of a test roof to that of black roof (solar reflectance 0.05, thermal emittance 0.90, SRI 0) and that of a bright-white roof (solar reflectance 0.80, thermal emittance 0.90, SRI 100) (ASTM 2011). It is designed for a wall-insulated horizontal surface, and should not be applied to walls. However, under the medium wind speed conditions commonly used to compute SRI, a well-insulated horizontal surface with solar reflectance 0.28 and thermal emittance 0.90 would have an SRI of 29.

For example, Figure 5 shows a recently completed apartment complex in Berkeley, CA with both white walls and dark brown walls. That said, black walls and bright-white walls seem uncommon to the authors. Second, despite entertaining reports of their abilities to toast passersby (Schiler and Valmont 2005), shiny bare-metal walls, such as that shown in Figure 6, are also unusual.

Third, Table 3 combines wall product albedo measurements made at Berkeley Lab (Figure 4) with our engineering judgement to crudely relate albedo to color. It suggests that after rounding albedos to the nearest 0.05, conventionally pigmented dark and dark-to-medium colors will have albedos 0.10 to 0.40; intermediate-performance, "cool" versions of these colors that use spectrally selective pigments[5] will have albedos 0.30 to 0.60; a conventionally pigmented off white or dull white surface will have albedo 0.60; and a conventionally pigmented bright white surface will have albedo 0.80.

[5] More about the design of spectrally selective, "cool colored" surfaces can be found in Levinson et al. (2007).

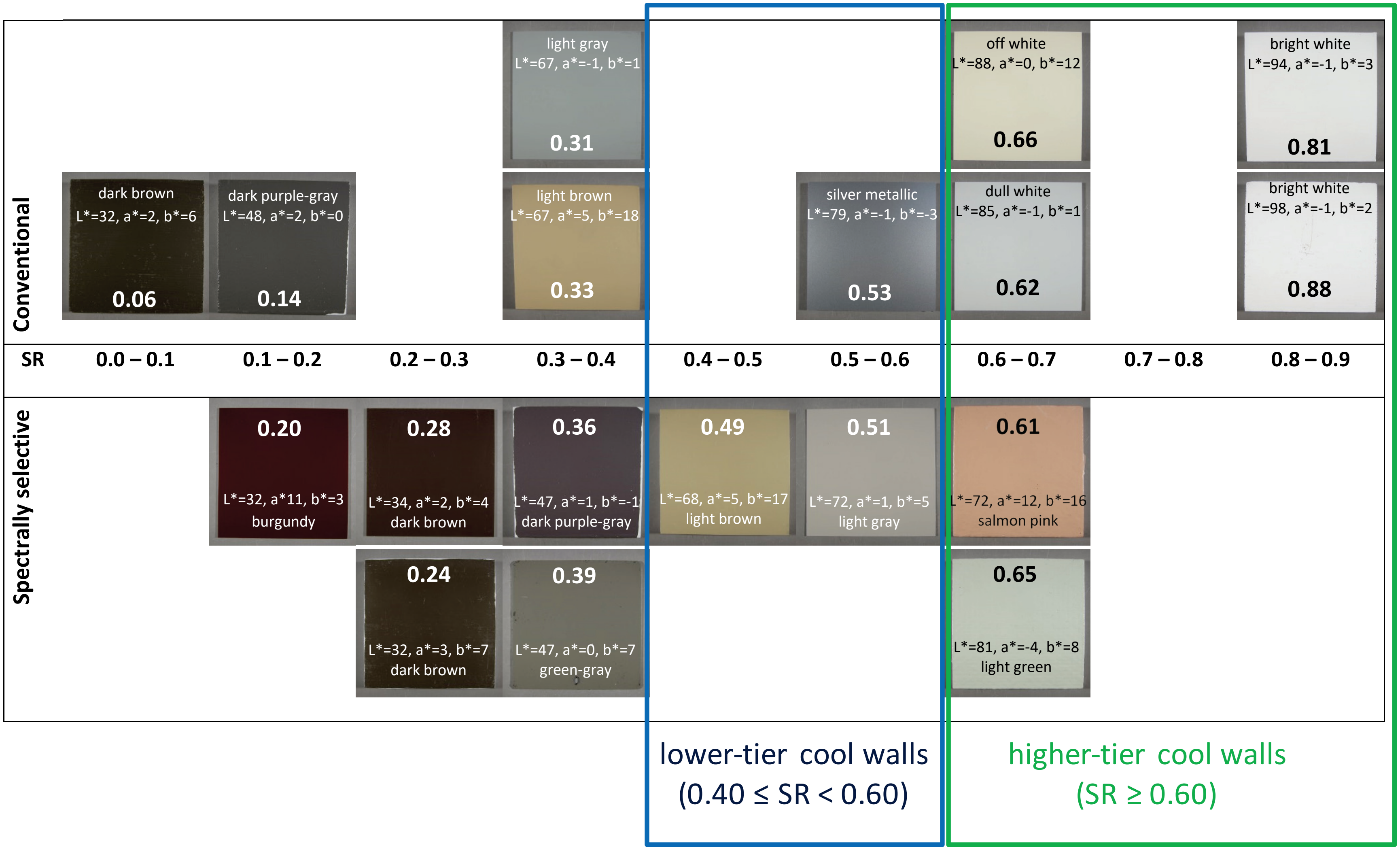


Figure 4. Initial images and radiative properties of some wall products characterized by LBNL, including AM1.5GV (air mass 1.5 global vertical) solar reflectance (SR) and CIELAB color coordinates (L*, a*, b*) computed with D65 illuminant and 10° observer. Specimens in upper group are colored with conventional pigments, while those in the lower group are colored with spectrally selective pigments ("cool colors").

Table 3. Approximate relationship between color and albedo of wall products, assuming that half of sunlight arrives in the near-infrared spectrum. Values serve only to provide general guidance and should not be quoted to more than one decimal place.

Color	Albedo with conventional pigmentation[a]	Albedo with intermediate-performance “cool color” pigmentation[b]	Albedo with high-performance “cool color” pigmentation[c]
Black	0.05	0.28	0.40
Dark	0.10 to 0.20	0.30 to 0.35	0.43 to 0.48
Dark-to-medium	0.20 to 0.40	0.35 to 0.45	0.48 to 0.58
Medium-to-light	0.40 to 0.50	0.45 to 0.50	0.58 to 0.63
Light (off white or dull white)	0.60	NA [d]	0.68
Bright white	0.80	NA	NA

[a] Assumes broadband reflectance N in the near-infrared spectrum (0.7 – 2.5 μm) is equal to broadband reflectance V in the visible spectrum (0.4 – 0.7 μm).

[b] Assumes N = 0.50.

[c] Assumes N = 0.80 for bright-white and N = 0.75 for all other colors.

[d] Not applicable (NA) because the near-infrared reflectance in the conventional formulation exceeds that in the cool-color formulation.

From these observations, we could generate typical wall albedos as follows:

- A black wall is assigned an albedo of 0.05.
- A conventionally colored wall (dark or dark-to-medium color; conventional pigmentation) is assigned an albedo of 0.25 (midway between 0.10 and 0.40).
- A cool colored wall (dark or dark-to-medium color; intermediate-performance cool-color pigmentation) is assigned an albedo of 0.40 (a bit past midway between 0.30 and 0.45).
- A light-colored wall (off white or dull white) is assigned an albedo of 0.60.
- A bright-white wall is assigned an albedo of 0.80.

Assuming that few walls will be black, bright white, or bare metal, we propose the following conventional and cool wall specifications for modeling cool wall effects.

- A warm wall (baseline scenario) is assigned albedo 0.25 (conventionally colored) and thermal emittance 0.90.

- A lower-tier cool wall (lower-performance cool wall scenario) is assigned albedo 0.40 (cool colored) and thermal emittance 0.90.

- A higher-tier cool wall (higher-performance cool wall scenario) is assigned albedo 0.60 (light colored) and thermal emittance 0.90.

We further propose that in building energy efficiency standards, green building programs, and utility incentive programs, a product with an aged thermal emittance of at least 0.75 (meaning not bare metal) could qualify as a lower-tier cool wall with aged albedo $0.40 \le \rho < 0.60$, and as a higher-tier cool wall with aged albedo $\rho \ge 0.60$.

Figure 5. White walls and dark brown walls on apartment buildings in Berkeley, CA.

Figure 6. White wall (left) and bare stainless-steel wall (right) on the Berkeley Art Museum and Pacific Film Archive in Berkeley, CA.

2.8 How can I find a cool wall product?

Appearance is a reasonable first indicator of albedo, in the sense that when conventionally pigmented, dark surfaces tend to have lower albedo and light surfaces tend to have higher albedo. Light-colored exterior wall paints are widely available.

However, about half of the radiation in sunlight arrives as invisible near-infrared (NIR) light. Near-infrared reflectance can deviate strongly from visible reflectance. For example, a natural red clay roofing tile typically reflects about 20% of visible sunlight, 60% of NIR sunlight, and about 40% of all sunlight. Therefore, a cool wall product rating system analogous to the cool roof product rating system provided by the Cool Roof Rating Council (CRRC) is needed.

2.9 How might a cool wall rating system compare to the

existing cool roof rating system?

The process for rating wall products could closely mirror that for roofing products, with four minor differences. First, wall products would be oriented vertically, rather than at a 5° or 45° tilt, during the natural exposure period. Second, the three-year natural exposure period used for roofing products may or may not be ideal for wall products; ongoing natural exposure testing at the CRRC's three test sites will help determine the optimal duration. (See the Task 4.2 report: *Natural exposure of wall products*, for details.)

Third, wall-product solar reflectance should be measured using a solar spectral irradiance representative of that incident on a vertical wall. The Task 4.1 report: *Metrics and methods to assess cool wall performance* identifies a suitable irradiance, and a solar reflectance based on this irradiance can be measured with the Devices & Services Solar Spectrum Reflectometer, version 6, following a minor upload to its firmware. Fourth, the laboratory aging practice at the heart of the CRRC's Rapid Ratings program has yet to be adapted to wall products. Thus, Rapid Ratings would not be immediately available.

2.10 Will cool walls lose reflectance over time?

Early results indicate that walls soil less than roofs. The research team has been naturally exposing wall materials at three sites in California (Berkeley, Fresno, and Los Angeles) since March 2016, and at three sites across the U.S. (Phoenix, AZ; Cleveland, OH; and Miami, FL) since August 2016 (Figure 7). After 24 months of California exposure and 12 months of U.S. exposure, the albedos of a majority of the tested materials fell by about 0.00 - 0.05 (Figure 8). A prior study found that field-applied *roof* coatings on near-horizontal substrates experienced first-year albedo losses of up to about 0.25.

California exposure will continue through April 2018 (2 years), while U.S. exposure will continue through August 2021 (5 years). More detail is available in the Task 4.2 report: *Natural exposure of wall products.*

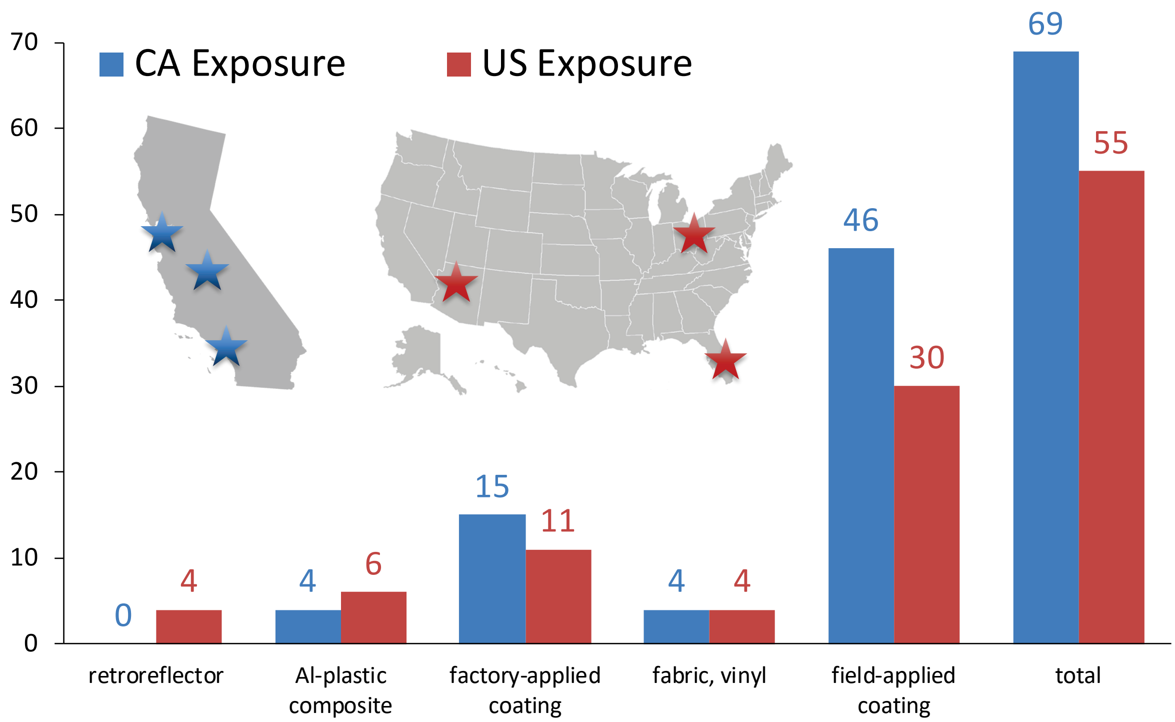


Figure 7. Distribution by type of wall materials being exposed across California (CA) and the United States (US).

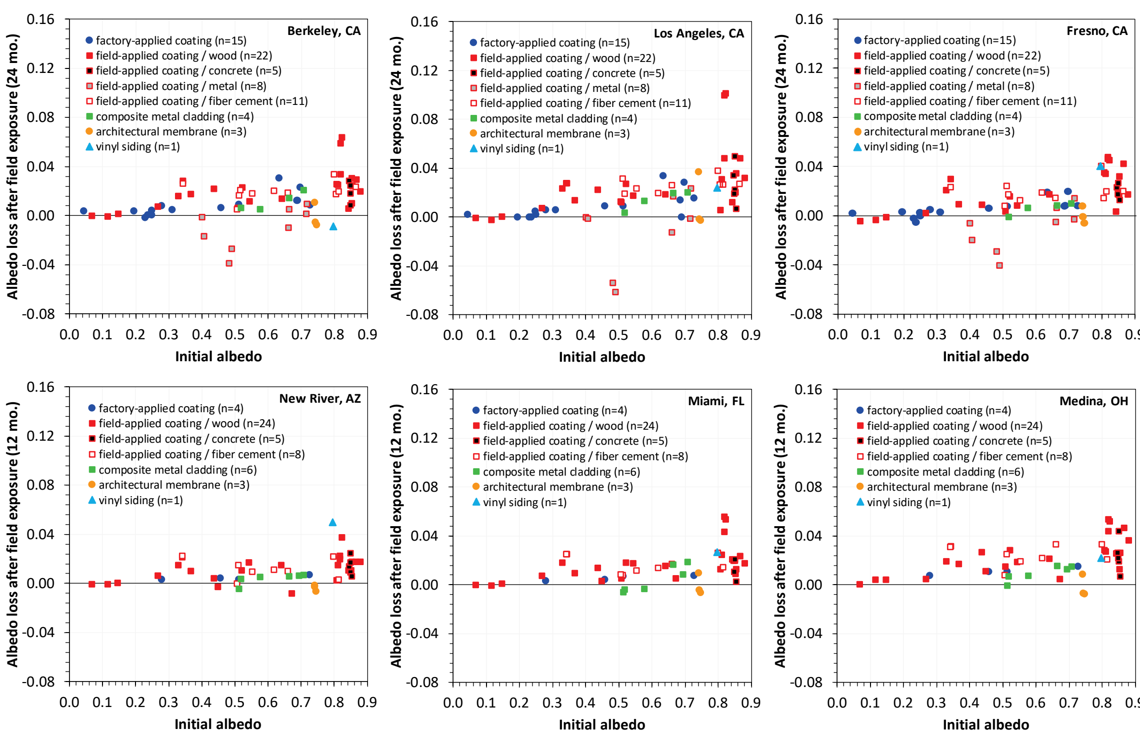


Figure 8. Decreases in albedos of tested materials exposed for 24 months across California (top row) and for 12 months across the U.S. (bottom row).

2.11 Do cool walls products cost more than conventional wall products?

Since color does not appear to affect the price of conventionally pigmented paints, it should be possible to choose a higher-tier, light-colored cool paint instead of a warm paint at no extra cost. We do not yet have data on the cost premium for substituting a lower-tier, spectrally selective (cool) dark paint for a warm paint. However, we estimate the premium as follows.

The median wet-film pigment volume concentration (PVC) in commercial artist paints surveyed by Levinson et al. (2005) was 7% (range 3 to 22%). The median density of their pigments was 3.3 g/mL (range 1.4 to 5.2 g/mL). Using these median values, 1 L of wet paint would contain $1000\text{ mL} \times 7\% \times 3.3\text{ g/mL} = 231$ g of pigment, and a U.S. gallon (3.79 L) of wet paint would contain 0.875 kg of pigment.

The median price of spectrally selective (cool) red, green, brown, and black inorganic pigments used by Levinson et al. (2016) to color roofing granules was US$18.6 per kg (range $7.3 to $30.4 per kg), while the cost of a nonselective (conventional) inorganic pigment was $1 per kg. Relative to the conventional pigment, the cost premium for the median-price cool pigment would be $17.6 per kg. At 0.875 kg of pigment per gallon, the cost premium per gallon of paint using the median-price cool pigment would be $15.4. The premium for a gallon of paint based on the lowest values of PVC (3%), pigment density (1.4), and pigment cost premium ($6.3/kg) would be $2.2, while that based on the highest values of PVC (22%), pigment density (5.2 g/mL), and pigment cost premium would be $60.2. Thus, substituting spectrally selective pigments for conventional pigments in paint would yield a median cost premium per gallon of about $15, with a range of about $2 to $60.

3 Simple guide to cool-wall effects on an isolated building

Raising wall albedo can reduce the need for space cooling and increase the need for space heating over the course of the year. One way to assess the net annual benefit (or penalty) of raising wall albedo is to simulate a building's annual heating, ventilation (a.k.a. fan), and air conditioning (HVAC) site energy uses with a conventional wall (base case), and then again with a cool wall (test case).

3.1 Identifying vintage

This section focuses on energy costs savings for three vintages (new, older, oldest) of three common categories of buildings: single-family home, medium, office and retail stand-alone (Figure 9). In the California simulations, new buildings comply with the 2016 edition of California's Title 24 building energy efficiency standards; older buildings meet 1998 Title 24; and oldest buildings follow pre-1978 construction practices. In the U.S. simulations, new buildings comply with the International Energy Conservation Code (IECC) (residential) or ASHRAE 90.1 (commercial) building energy efficiency standards in effect in each state as of 2016; older and oldest residential buildings follow 1980s and pre-1980 construction practices, respectively; older commercial buildings comply with ASHRAE 90.1-1989; and oldest commercial buildings follow pre-1980 construction practices. Prototypes and simulations are detailed in the Task 2.1 report: *Simulated HVAC energy savings in an isolated building.*

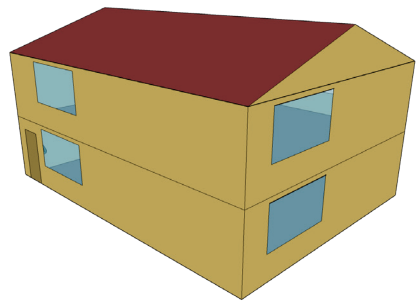
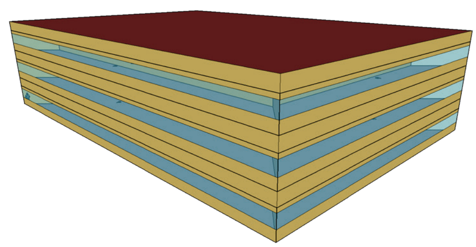
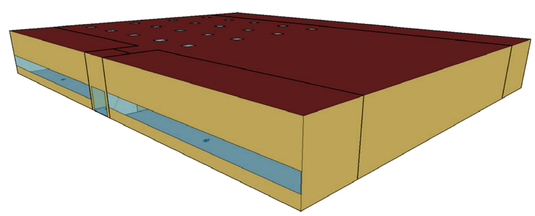
Single-family home (2 floors; footprint 110 m²)	
Medium office (3 floors; footprint 1,660 m²)	
Retail stand-alone (1 floor; footprint 2,290 m²)	

Figure 9. Sketches of the single-family home, medium office, and retail stand-alone building prototypes.

The cities representing the California and U.S. climate zones are listed in Table 4 and Table 5, respectively. A list of California building climate zones by ZIP code is available in reference CEC (2018).

Table 4. 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 5. 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.

3.2 Calculating energy cost savings

Whole-building absolute energy saving are obtained by subtracting test-case energy use from base-case energy use. The cooling energy savings will be positive (or zero, if cooling is never needed); heating energy savings will be negative (or zero, if heating is never needed); and fan energy savings can have any sign. Negative heating savings can also be expressed as a positive heating penalty.

The heating gas savings (if gas heat is used) can be multiplied by the local price of natural gas to calculate heating gas energy cost savings, while each electricity savings (for electric cooling, ventilation, and/or electric heating) can be multiplied by the local price of electricity to compute the corresponding electricity cost savings.

Normalizing whole-building annual energy cost savings ($) to the wall area modified (m^2) yields annual energy cost savings intensity ($/$m^2$). This value can be used to estimate whole-building annual energy cost savings for an arbitrary modified wall area, or to assess the cost effectiveness of a cool wall product. Figure 10 shows annual HVAC energy cost savings intensities attained by raising the albedo of all walls, or raising the albedo of the roof, in new, older, and oldest vintages of single-family home, medium, office and retail stand-alone buildings across California. Figure 11 shows the same results across the United States.

Dividing the whole-building annual energy cost savings ($) by the whole-building base-case annual energy cost ($) yields the whole-building annual energy cost savings fraction (dimensionless). The whole-building annual HVAC energy cost savings fraction gauges the extent to which raising wall albedo reduces HVAC energy expenditure. Figure 12 and Figure 13 show whole-building annual energy cost savings fractions across California and the United States, respectively.

(a)

(b)

(c)

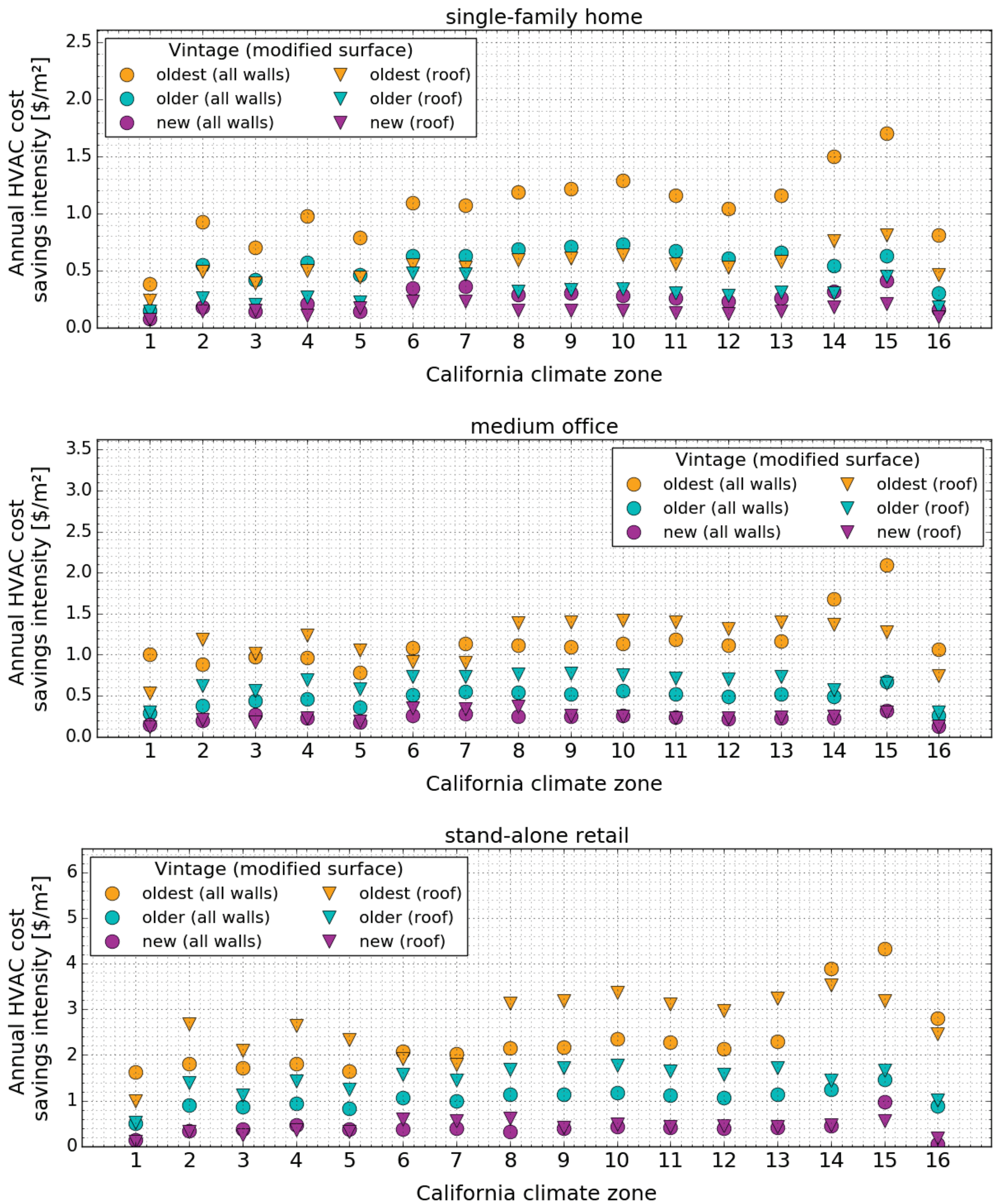


Figure 10. Annual HVAC energy cost savings intensity by vintage and by *California climate zone* for the (a) single-family home, (b) medium office, and (c) retail stand-alone. The plots compare the savings intensity from increasing the albedo of all walls by 0.35 to the savings intensity from increasing the roof albedo by 0.30 (residential) or 0.40 (commercial).

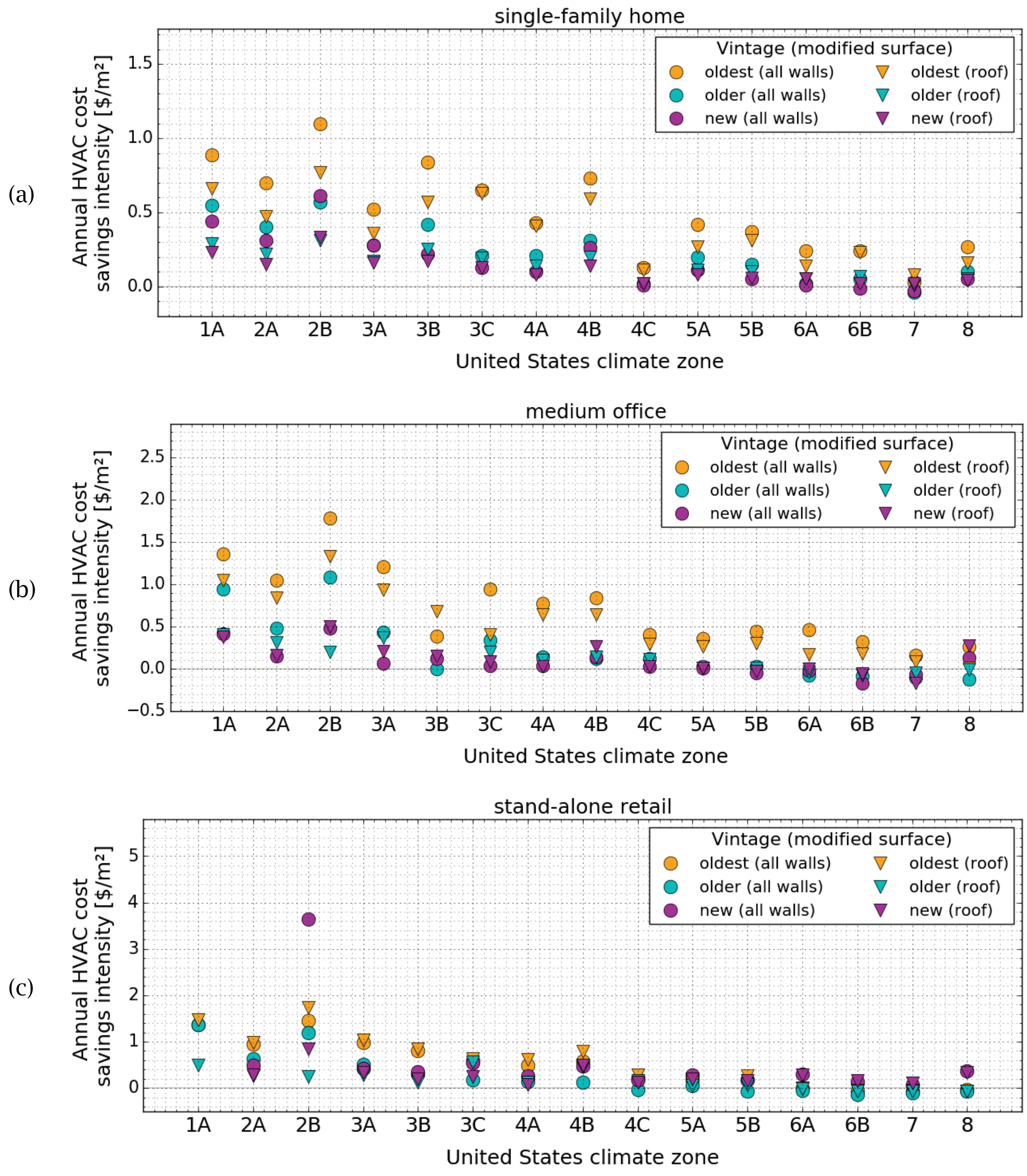


Figure 11. Annual HVAC energy cost savings intensity by vintage and by U.S. climate zone for the (a) single-family home, (b) medium office, and (c) retail stand-alone. The plots compare the savings intensity from increasing the albedo of all walls by 0.35 to the savings intensity from increasing the roof albedo by 0.30 (residential) or 0.40 (commercial). Panel (c) omits savings for new retail stand-alone in USCZ 1A (Miami) because modifying the albedo of its back wall yielded unrealistically large changes in annual fan energy use.

(a)

(b)

(c)

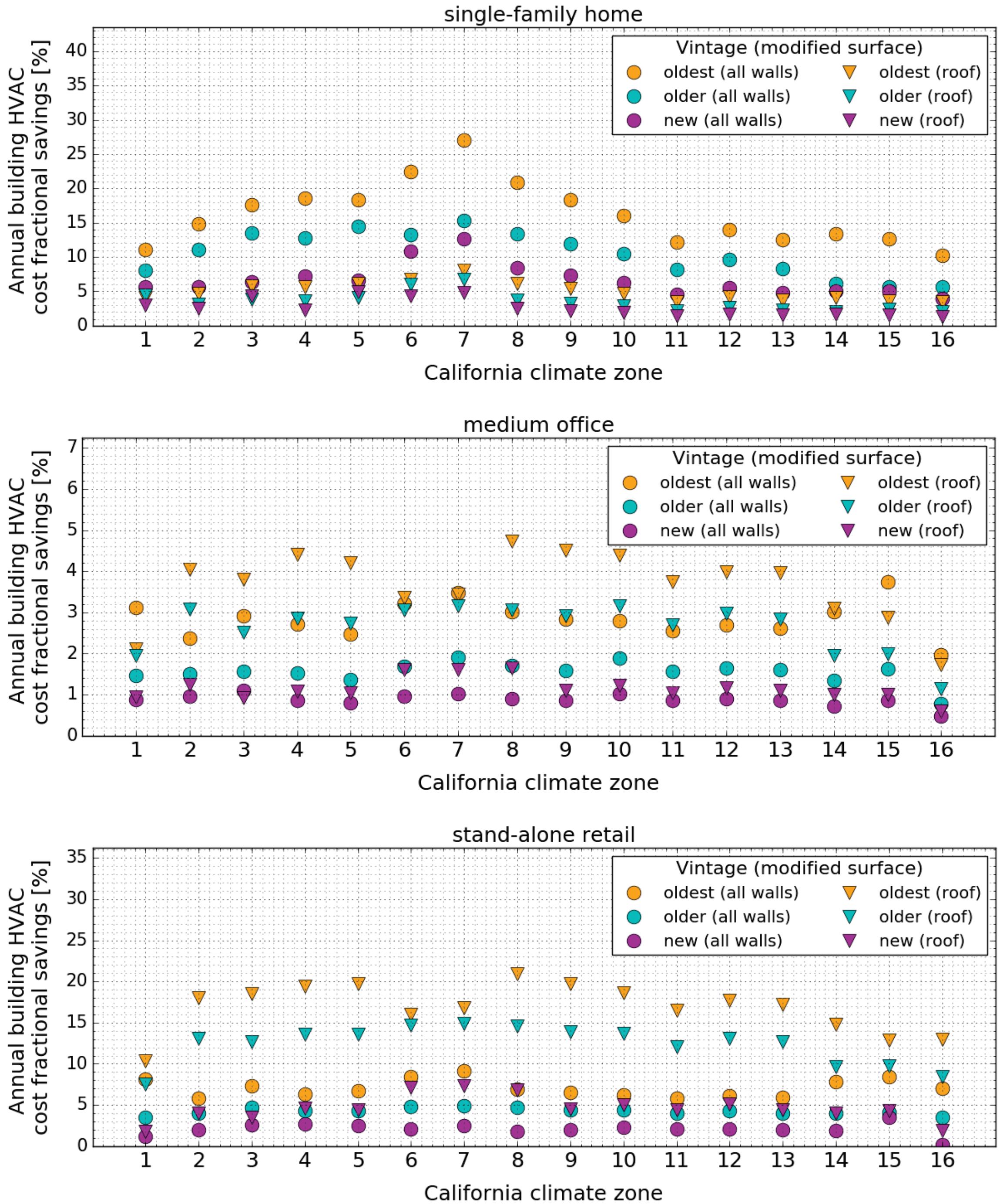


Figure 12. Annual HVAC energy cost fractional savings by vintage and by California climate zone for the (a) single-family home, (b) medium office, and (c) retail stand-alone. The plots compare the savings intensity from increasing the albedo of all walls by 0.35 to the savings intensity from increasing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

(a)

(b)

(c)

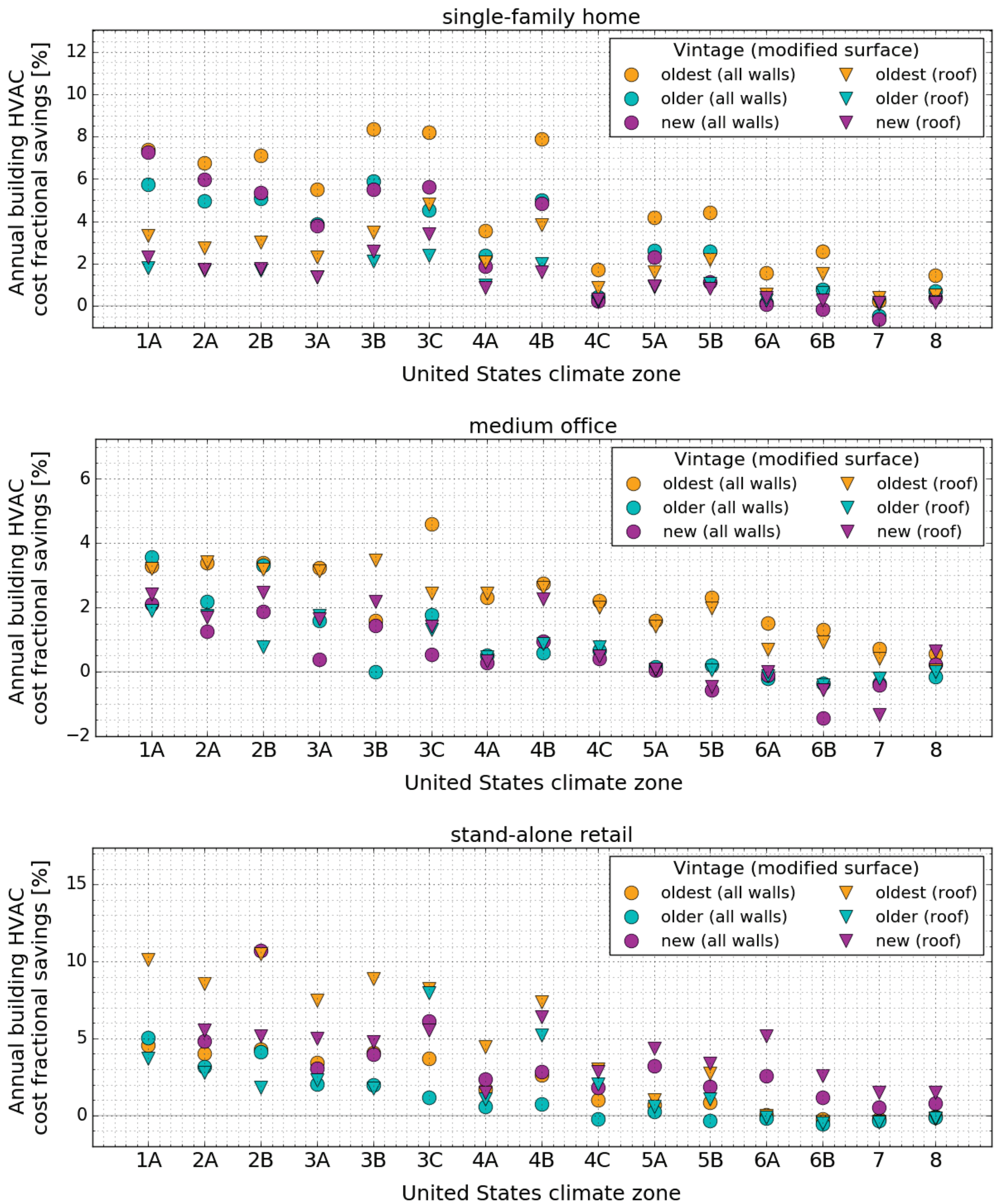


Figure 13. Annual HVAC energy cost fractional savings by vintage and by U.S. climate zone for the (a) single-family home, (b) medium office, and (c) retail stand-alone. The plots compare the savings intensity from increasing the albedo of all walls by 0.35 to the savings intensity from increasing the roof albedo by 0.30 (residential) or 0.40 (commercial). Panel (c) omits savings for new retail stand-alone in USCZ 1A (Miami) because modifying the albedo of its back wall yielded unrealistically large changes in annual fan energy use.

3.3 Gauging cost effectiveness

Annual HVAC (cooling + heating + fan) energy cost savings intensity can be used to evaluate the cost effectiveness of selecting a cool wall product instead of a conventional wall product. Two common gauges of cost effectiveness are

- simple payback time, or ratio of product cost premium per unit area to annual energy cost savings intensity; and
- life-cycle cost savings intensity, or present value (PV) of annual energy cost savings intensity over the product's service life minus initial product cost premium per unit area.

If the product cost premium is zero, the simple payback time will be zero, and the life-cycle cost savings intensity will be more helpful. Both gauges apply if the cool product costs more than the conventional product.

Given a real (inflation-adjusted) annual rate of return r, the PV of N years of constant annual energy cost savings intensity c is $b \times c$, where PV multiplier

$$b \equiv \sum_{i=1}^{N} (1 + r)^{-i} = [1 - (1 + r)^{-N}]. \quad (1)$$

(Levinson and Akbari 2010). The PV multiplier b increases with service life N, and decreases with real rate of return r (Table 6).

Table 6. Present value multiplier *b* (ratio of present value of lifetime energy cost savings) computed from Eq. (1) for various combinations of product service life *N* (years) and real (inflation-adjusted) annual rate of return *r*.

N (years)	r=1%	r=3%	r=5%	r=7%
5	4.9	4.6	4.3	4.1
10	9.5	8.5	7.7	7.0
15	13.9	11.9	10.4	9.1
20	18.0	14.9	12.5	10.6
25	22.0	17.4	14.1	11.7
30	25.8	19.6	15.4	12.4

3.4 Applying the savings tables

Table 7 details annual HVAC energy cost savings intensity ($/m²) in each California climate zone (Figure 2) by building category, vintage, and surface modified, while Table 8 does the same for annual whole-building HVAC energy cost savings fraction (%). Annual HVAC energy cost savings intensity and annual whole-building HVAC energy cost savings fraction in U.S. climates (Figure 3) are detailed in Table 9 and Table 10, respectively.[6]

These tables present cool wall savings from increasing wall albedo by 0.35 (to 0.60 from 0.25) in both residential and commercial buildings, and cool roof savings 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. Results average the savings obtained when the long-axis of the building runs east-west with those calculated when the axis runs north-west.[7]

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[6] San Francisco represents U.S. climate zone 3C, but also lies within California climate zone 3. Since the state's Title 24 standards supersede the ASHRAE and IECC standards, we recommend using the California climate zone 3 for this city.

[7] Readers interested in results based on a single orientation of the building's long axis (east-west or north-south) should use instead the Cool Surface Savings Explorer (Section 4).

Table 7. Annual HVAC energy cost savings intensity ($/m²) by California climate zone (CACZ 01 – 16), building vintage (new, older, oldest), and surface(s) modified (R = roof; N = north wall; E = east wall; S = south wall; W = west wall; N E S W = all four walls), tabulated for (a) single-family home, (b) medium office, and (c) retail standalone buildings. Results are mean of values for N-S and E-W orientations of the building's long axis.

(a) Single-family home annual HVAC energy cost savings intensity ($/m²).

	new						older						oldest					
	R	**N**	**E**	**S**	**W**	**N E S W**	**R**	**N**	**E**	**S**	**W**	**N E S W**	**R**	**N**	**E**	**S**	**W**	**N E S W**
CACZ_01	0.12	0.05	0.14	0.10	0.07	0.08	0.25	0.09	0.24	0.22	0.13	0.16	0.41	0.20	0.44	0.69	0.49	0.39
CACZ_02	0.24	0.11	0.28	0.22	0.18	0.19	0.45	0.31	0.68	0.72	0.58	0.56	0.85	0.53	1.03	1.29	1.16	0.95
CACZ_03	0.27	0.07	0.22	0.18	0.11	0.14	0.35	0.22	0.56	0.61	0.41	0.43	0.67	0.36	0.82	1.09	0.80	0.71
CACZ_04	0.19	0.11	0.30	0.27	0.20	0.22	0.46	0.29	0.73	0.81	0.58	0.58	0.87	0.49	1.13	1.45	1.11	1.00
CACZ_05	0.29	0.07	0.23	0.19	0.10	0.14	0.39	0.22	0.60	0.71	0.43	0.47	0.76	0.38	0.89	1.29	0.88	0.80
CACZ_06	0.40	0.20	0.42	0.47	0.37	0.36	0.84	0.36	0.74	0.85	0.67	0.64	0.96	0.62	1.20	1.51	1.26	1.12
CACZ_07	0.40	0.19	0.43	0.49	0.39	0.37	0.81	0.34	0.74	0.87	0.67	0.64	0.92	0.57	1.19	1.52	1.24	1.09
CACZ_08	0.26	0.18	0.36	0.37	0.31	0.30	0.56	0.40	0.80	0.92	0.76	0.71	1.03	0.69	1.30	1.61	1.39	1.21
CACZ_09	0.26	0.18	0.37	0.37	0.31	0.30	0.57	0.41	0.82	0.93	0.78	0.73	1.05	0.70	1.33	1.63	1.45	1.24
CACZ_10	0.26	0.15	0.39	0.36	0.28	0.29	0.58	0.37	0.89	0.99	0.76	0.74	1.11	0.66	1.47	1.79	1.48	1.32
CACZ_11	0.23	0.15	0.35	0.30	0.27	0.26	0.53	0.36	0.79	0.86	0.75	0.68	0.99	0.63	1.28	1.53	1.45	1.19
CACZ_12	0.21	0.14	0.34	0.26	0.23	0.24	0.50	0.35	0.79	0.75	0.65	0.62	0.92	0.59	1.24	1.33	1.26	1.07
CACZ_13	0.24	0.15	0.37	0.30	0.27	0.27	0.54	0.36	0.84	0.82	0.72	0.68	1.01	0.63	1.38	1.45	1.37	1.18
CACZ_14	0.30	0.19	0.46	0.37	0.33	0.33	0.53	0.31	0.73	0.64	0.55	0.55	1.31	0.84	1.78	1.89	1.78	1.53
CACZ_15	0.36	0.22	0.52	0.50	0.44	0.42	0.78	0.34	0.79	0.79	0.69	0.65	1.42	0.90	1.93	2.14	2.03	1.73
CACZ_16	0.16	0.10	0.27	0.16	0.16	0.16	0.31	0.17	0.44	0.34	0.30	0.30	0.79	0.44	0.97	1.06	1.10	0.83

Table 7 (continued)

(b) Medium office annual HVAC energy cost savings intensity ($\$/m^2$).

	new						older						oldest					
	R	**N**	**E**	**S**	**W**	**N E S W**	**R**	**N**	**E**	**S**	**W**	**N E S W**	**R**	**N**	**E**	**S**	**W**	**N E S W**
CACZ_01	0.12	0.04	0.14	0.17	0.25	0.15	0.30	0.03	0.29	0.32	0.48	0.29	0.53	-0.08	1.40	1.05	1.65	1.00
CACZ_02	0.21	0.09	0.21	0.22	0.29	0.20	0.62	0.16	0.41	0.35	0.61	0.38	1.19	0.26	1.17	0.82	1.33	0.88
CACZ_03	0.18	0.06	0.29	0.40	0.34	0.27	0.56	0.09	0.51	0.65	0.55	0.44	1.01	0.13	1.15	1.43	1.21	0.97
CACZ_04	0.23	0.07	0.26	0.29	0.30	0.23	0.69	0.14	0.59	0.53	0.62	0.46	1.24	0.22	1.24	1.14	1.27	0.96
CACZ_05	0.19	0.06	0.21	0.22	0.25	0.18	0.58	0.08	0.45	0.40	0.50	0.36	1.06	0.13	1.09	0.87	1.10	0.78
CACZ_06	0.35	0.11	0.30	0.28	0.34	0.26	0.73	0.19	0.59	0.57	0.68	0.51	0.91	0.36	1.37	1.23	1.40	1.09
CACZ_07	0.34	0.12	0.29	0.33	0.35	0.28	0.73	0.21	0.70	0.63	0.69	0.55	0.90	0.39	1.40	1.33	1.43	1.14
CACZ_08	0.37	0.11	0.28	0.29	0.32	0.25	0.77	0.22	0.62	0.59	0.68	0.54	1.39	0.39	1.40	1.25	1.42	1.12
CACZ_09	0.26	0.12	0.28	0.28	0.33	0.25	0.77	0.23	0.60	0.58	0.70	0.53	1.40	0.41	1.28	1.26	1.49	1.10
CACZ_10	0.25	0.12	0.31	0.33	0.32	0.27	0.75	0.23	0.66	0.70	0.68	0.56	1.42	0.38	1.42	1.29	1.46	1.14
CACZ_11	0.23	0.10	0.29	0.24	0.32	0.24	0.71	0.22	0.60	0.52	0.77	0.52	1.40	0.36	1.50	1.25	1.71	1.19
CACZ_12	0.23	0.10	0.26	0.21	0.32	0.22	0.70	0.18	0.58	0.41	0.73	0.49	1.32	0.33	1.57	1.03	1.65	1.13
CACZ_13	0.24	0.11	0.29	0.24	0.31	0.23	0.73	0.23	0.67	0.51	0.75	0.52	1.40	0.40	1.59	1.12	1.59	1.17
CACZ_14	0.25	0.13	0.27	0.20	0.30	0.23	0.57	0.31	0.62	0.42	0.68	0.49	1.37	0.78	2.17	1.34	2.45	1.68
CACZ_15	0.30	0.17	0.35	0.37	0.39	0.32	0.65	0.36	0.75	0.74	0.85	0.67	1.28	0.97	2.38	2.06	2.95	2.09
CACZ_16	0.13	0.04	0.18	0.08	0.23	0.13	0.30	0.07	0.30	0.14	0.55	0.26	0.74	0.16	1.59	0.57	2.13	1.07

Table 7 (continued)

(c) Retail stand-alone annual HVAC energy cost savings intensity ($\$/m^2$).

	new						older						oldest					
	R	**N**	**E**	**S**	**W**	**N E S W**	**R**	**N**	**E**	**S**	**W**	**N E S W**	**R**	**N**	**E**	**S**	**W**	**N E S W**
CACZ_01	0.11	0.02	0.21	0.29	0.06	0.15	0.52	0.12	0.63	0.87	0.52	0.50	0.99	0.30	1.87	2.62	2.17	1.63
CACZ_02	0.33	0.18	0.38	0.40	0.42	0.34	1.40	0.46	0.90	1.14	1.16	0.90	2.68	0.85	1.92	2.22	2.39	1.81
CACZ_03	0.25	0.11	0.43	0.63	0.48	0.39	1.12	0.29	0.96	1.38	0.94	0.86	2.09	0.60	1.86	2.65	2.01	1.71
CACZ_04	0.37	0.16	0.76	0.48	0.35	0.46	1.42	0.36	1.05	1.30	1.11	0.93	2.65	0.65	2.03	2.58	2.15	1.80
CACZ_05	0.32	0.11	0.65	0.43	0.27	0.37	1.24	0.31	0.92	1.13	1.00	0.83	2.34	0.65	1.80	2.22	2.11	1.65
CACZ_06	0.60	0.23	0.23	0.58	0.61	0.37	1.57	0.48	1.15	1.37	1.29	1.07	1.91	0.93	2.23	2.68	2.69	2.08
CACZ_07	0.57	0.17	0.48	0.54	0.40	0.40	1.44	0.45	0.98	1.34	1.30	0.99	1.79	0.85	2.23	2.62	2.64	2.03
CACZ_08	0.62	0.21	0.16	0.53	0.54	0.33	1.68	0.55	1.26	1.45	1.42	1.14	3.14	0.98	2.31	2.80	2.69	2.16
CACZ_09	0.42	0.22	0.46	0.53	0.42	0.39	1.72	0.56	1.23	1.46	1.41	1.14	3.18	0.98	2.33	2.78	2.82	2.18
CACZ_10	0.48	0.21	0.47	0.55	0.58	0.45	1.78	0.54	1.24	1.55	1.51	1.18	3.36	1.02	2.46	3.02	3.07	2.35
CACZ_11	0.44	0.22	0.49	0.51	0.51	0.42	1.64	0.54	1.11	1.46	1.44	1.12	3.12	1.02	2.49	2.90	2.99	2.28
CACZ_12	0.45	0.20	0.45	0.43	0.49	0.39	1.58	0.52	1.20	1.32	1.35	1.07	2.96	0.95	2.38	2.57	2.80	2.14
CACZ_13	0.43	0.24	0.49	0.47	0.51	0.42	1.72	0.58	1.22	1.41	1.46	1.14	3.24	1.07	2.58	2.68	3.05	2.30
CACZ_14	0.47	0.27	0.52	0.48	0.59	0.45	1.45	0.67	1.23	1.42	1.74	1.24	3.53	1.87	4.06	4.19	5.68	3.89
CACZ_15	0.56	0.30	2.23	0.59	0.55	0.98	1.67	0.77	1.48	1.70	2.00	1.46	3.18	2.10	4.34	4.78	6.47	4.32
CACZ_16	0.18	-0.80	0.40	0.37	0.37	0.05	1.02	0.30	0.95	1.17	1.22	0.88	2.47	1.04	2.99	3.34	4.38	2.80

Table 8. Analog of Table 7 for annual whole-building HVAC energy cost saving fraction (%).

(a) Single-family home annual whole-building HVAC energy cost saving fraction (%).

	new						older						oldest					
	R	**N**	**E**	**S**	**W**	**N E S W**	**R**	**N**	**E**	**S**	**W**	**N E S W**	**R**	**N**	**E**	**S**	**W**	**N E S W**
CACZ_01	5.17	0.90	2.40	1.81	1.16	5.70	7.71	1.18	3.03	2.88	1.68	8.13	7.08	1.41	3.10	4.89	3.46	11.07
CACZ_02	4.44	0.84	2.09	1.66	1.33	5.69	5.42	1.54	3.36	3.57	2.86	11.03	8.10	2.08	4.02	5.05	4.54	14.86
CACZ_03	7.43	0.84	2.50	2.02	1.30	6.34	6.62	1.71	4.34	4.77	3.20	13.46	10.00	2.24	5.07	6.72	4.95	17.63
CACZ_04	3.85	0.95	2.57	2.32	1.68	7.27	6.16	1.59	3.98	4.47	3.16	12.81	9.81	2.27	5.24	6.74	5.15	18.55
CACZ_05	8.47	0.87	2.69	2.23	1.22	6.60	7.20	1.73	4.65	5.45	3.31	14.45	10.45	2.18	2.18	7.37	5.03	18.34
CACZ_06	7.42	1.55	3.20	3.56	2.80	10.89	10.50	1.87	3.81	4.42	3.46	13.30	11.66	3.14	6.05	7.63	6.33	22.44
CACZ_07	8.29	1.66	3.70	4.23	3.31	12.62	11.76	2.01	4.40	5.21	4.02	15.32	13.83	3.53	7.41	9.48	7.69	27.10
CACZ_08	4.42	1.23	2.50	2.63	2.19	8.41	6.36	1.91	3.77	4.35	3.57	13.40	10.74	2.95	5.58	6.92	5.95	20.85
CACZ_09	3.87	1.07	2.25	2.25	1.91	7.36	5.65	1.69	3.39	3.81	3.21	11.93	9.44	2.59	4.93	6.05	5.35	18.39
CACZ_10	3.32	0.82	2.08	1.94	1.51	6.20	5.00	1.33	3.15	3.50	2.70	10.50	8.20	2.01	4.47	5.45	4.51	16.01
CACZ_11	2.45	0.63	1.53	1.32	1.17	4.56	3.84	1.07	2.36	2.55	2.24	8.15	6.17	1.62	3.28	3.94	3.74	12.22
CACZ_12	2.90	0.79	1.99	1.51	1.32	5.48	4.65	1.35	3.06	2.93	2.53	9.67	7.30	1.95	4.06	4.39	4.14	13.98
CACZ_13	2.64	0.66	1.68	1.36	1.21	4.82	4.02	1.11	2.58	2.50	2.21	8.30	6.49	1.68	3.67	3.85	3.65	12.54
CACZ_14	2.79	0.73	1.77	1.40	1.25	5.05	3.59	0.87	2.06	1.79	1.54	6.16	6.93	1.83	3.90	4.15	3.89	13.41
CACZ_15	2.66	0.67	1.57	1.53	1.33	5.06	4.11	0.76	1.72	1.73	1.50	5.66	6.30	1.67	3.54	3.94	3.73	12.73
CACZ_16	2.32	0.59	1.59	0.96	0.97	3.95	3.47	0.78	2.06	1.59	1.41	5.67	5.91	1.38	3.00	3.30	3.41	10.29

Table 8 (continued)

(b) Medium office annual whole-building HVAC energy cost saving fraction (%).

	new						older						oldest					
	R	**N**	**E**	**S**	**W**	**N E S W**	**R**	**N**	**E**	**S**	**W**	**N E S W**	**R**	**N**	**E**	**S**	**W**	**N E S W**
CACZ_01	0.94	0.06	0.20	0.26	0.38	0.89	1.94	0.04	0.38	0.42	0.61	1.47	2.11	-0.07	1.10	0.84	1.29	3.13
CACZ_02	1.24	0.11	0.24	0.26	0.34	0.97	3.09	0.16	0.40	0.35	0.60	1.50	4.05	0.18	0.79	0.56	0.90	2.38
CACZ_03	0.92	0.06	0.29	0.41	0.34	1.10	2.52	0.08	0.45	0.59	0.49	1.57	3.81	0.10	0.86	1.08	0.91	2.93
CACZ_04	1.09	0.07	0.25	0.27	0.28	0.87	2.86	0.12	0.49	0.45	0.52	1.53	4.40	0.16	0.87	0.81	0.89	2.73
CACZ_05	1.04	0.07	0.23	0.24	0.27	0.80	2.74	0.08	0.42	0.38	0.47	1.36	4.21	0.11	0.86	0.70	0.87	2.48
CACZ_06	1.60	0.11	0.27	0.27	0.31	0.97	3.06	0.17	0.49	0.48	0.56	1.69	3.36	0.27	1.01	0.92	1.03	3.23
CACZ_07	1.61	0.11	0.27	0.32	0.33	1.04	3.15	0.19	0.60	0.55	0.59	1.91	3.45	0.30	1.07	1.03	1.09	3.49
CACZ_08	1.64	0.10	0.25	0.26	0.28	0.90	3.06	0.18	0.49	0.48	0.54	1.71	4.73	0.27	0.95	0.85	0.96	3.02
CACZ_09	1.11	0.10	0.24	0.24	0.28	0.86	2.91	0.18	0.45	0.44	0.53	1.59	4.51	0.26	0.82	0.82	0.96	2.83
CACZ_10	1.23	0.12	0.30	0.32	0.31	1.02	3.15	0.19	0.55	0.60	0.56	1.88	4.38	0.24	0.87	0.80	0.89	2.79
CACZ_11	1.04	0.10	0.26	0.22	0.29	0.87	2.70	0.17	0.45	0.40	0.58	1.57	3.75	0.20	0.80	0.67	0.91	2.55
CACZ_12	1.16	0.11	0.26	0.22	0.32	0.90	2.97	0.16	0.49	0.35	0.62	1.65	3.98	0.20	0.94	0.63	0.99	2.70
CACZ_13	1.10	0.10	0.27	0.23	0.28	0.86	2.83	0.18	0.52	0.40	0.58	1.60	3.96	0.23	0.89	0.64	0.89	2.62
CACZ_14	1.00	0.11	0.22	0.16	0.24	0.72	1.94	0.21	0.42	0.29	0.46	1.34	3.10	0.35	0.98	0.61	1.10	3.02
CACZ_15	1.00	0.11	0.24	0.25	0.27	0.86	1.98	0.22	0.45	0.45	0.52	1.62	2.88	0.44	1.06	0.93	1.32	3.75
CACZ_16	0.60	0.04	0.17	0.07	0.22	0.48	1.15	0.05	0.23	0.11	0.42	0.79	1.72	0.08	0.73	0.26	0.97	1.97

Table 8 (continued)

(c) Retail stand-alone annual whole-building HVAC energy cost saving fraction (%).

	new						older						oldest					
	R	**N**	**E**	**S**	**W**	**N E S W**	**R**	**N**	**E**	**S**	**W**	**N E S W**	**R**	**N**	**E**	**S**	**W**	**N E S W**
CACZ_01	1.79	0.05	0.46	0.55	0.11	1.17	7.55	0.22	1.19	1.41	0.84	3.47	10.30	0.40	2.52	3.06	2.50	8.15
CACZ_02	4.00	0.29	0.61	0.55	0.58	2.02	13.06	0.56	1.09	1.19	1.20	4.04	18.00	0.74	1.67	1.67	1.78	5.86
CACZ_03	3.48	0.21	0.79	0.98	0.75	2.61	12.67	0.43	1.41	1.73	1.19	4.71	18.48	0.69	2.15	2.61	1.98	7.31
CACZ_04	4.57	0.27	1.20	0.68	0.48	2.72	13.54	0.45	1.29	1.38	1.18	4.27	19.41	0.63	1.93	2.11	1.75	6.35
CACZ_05	4.43	0.20	1.16	0.66	0.42	2.45	13.56	0.45	1.31	1.38	1.21	4.35	19.71	0.72	1.97	2.08	1.97	6.69
CACZ_06	7.09	0.36	0.37	0.78	0.80	2.10	14.71	0.59	1.39	1.43	1.34	4.82	15.96	1.01	2.41	2.51	2.50	8.40
CACZ_07	7.33	0.29	0.81	0.80	0.58	2.49	14.93	0.61	1.32	1.56	1.50	4.96	16.80	1.04	2.71	2.75	2.73	9.14
CACZ_08	6.87	0.31	0.24	0.66	0.67	1.75	14.56	0.62	1.41	1.40	1.37	4.74	20.92	0.85	2.00	2.08	1.99	6.93
CACZ_09	4.49	0.30	0.64	0.63	0.51	2.03	13.84	0.59	1.29	1.31	1.26	4.41	19.73	0.79	1.87	1.92	1.94	6.51
CACZ_10	5.06	0.29	0.64	0.65	0.68	2.25	13.69	0.54	1.24	1.33	1.29	4.38	18.63	0.73	1.77	1.87	1.89	6.27
CACZ_11	4.40	0.30	0.64	0.58	0.57	2.07	12.07	0.51	1.06	1.21	1.18	3.98	16.53	0.71	1.70	1.72	1.76	5.83
CACZ_12	5.09	0.31	0.66	0.55	0.61	2.14	13.11	0.56	1.30	1.22	1.25	4.30	17.70	0.74	1.84	1.71	1.85	6.15
CACZ_13	4.39	0.32	0.65	0.55	0.57	2.04	12.68	0.56	1.17	1.16	1.20	4.05	17.25	0.74	1.78	1.60	1.80	5.89
CACZ_14	4.03	0.31	0.58	0.47	0.56	1.89	9.67	0.58	1.07	1.06	1.29	4.00	14.78	1.02	2.20	1.96	2.64	7.83
CACZ_15	4.26	0.30	2.16	0.50	0.46	3.54	9.75	0.59	1.12	1.11	1.30	4.12	12.83	1.10	2.27	2.15	2.90	8.40
CACZ_16	1.87	-1.14	0.54	0.44	0.42	0.19	8.48	0.32	1.02	1.09	1.12	3.49	12.94	0.72	2.02	1.96	2.53	7.04

Table 9. Annual HVAC energy cost savings intensity ($/m²) by U.S. climate zone (1A - 8), building vintage (new, older, oldest), and surface(s) modified (R = roof; N = north wall; E = east wall; S = south wall; W = west wall; N E S W = all four walls), tabulated for (a) single-family home, (b) medium office, and (c) retail standalone buildings. Results are mean of values for N-S and E-W orientations of the building's long axis.

(a) Single-family home annual HVAC energy cost savings intensity ($/m²).

	new						older						oldest					
	R	**N**	**E**	**S**	**W**	**N E S W**	**R**	**N**	**E**	**S**	**W**	**N E S W**	**R**	**N**	**E**	**S**	**W**	**N E S W**
USCZ_1A	0.40	0.28	0.48	0.49	0.52	0.44	0.49	0.35	0.60	0.61	0.64	0.55	1.14	0.56	0.94	0.99	1.07	0.89
USCZ_2A	0.26	0.22	0.37	0.33	0.36	0.31	0.39	0.28	0.47	0.42	0.45	0.40	0.80	0.47	0.78	0.78	0.81	0.70
USCZ_2B	0.58	0.33	0.76	0.76	0.65	0.61	0.54	0.31	0.71	0.71	0.60	0.57	1.33	0.57	1.27	1.39	1.21	1.10
USCZ_3A	0.28	0.19	0.35	0.27	0.31	0.28	0.29	0.20	0.36	0.28	0.31	0.28	0.62	0.34	0.62	0.57	0.60	0.52
USCZ_3B	0.30	0.14	0.33	0.23	0.23	0.22	0.44	0.26	0.57	0.47	0.45	0.42	0.99	0.48	1.03	1.01	0.91	0.84
USCZ_3C	0.21	0.07	0.25	0.17	0.09	0.13	0.31	0.11	0.41	0.33	0.12	0.21	1.07	0.31	0.90	1.01	0.53	0.65
USCZ_4A	0.13	0.09	0.17	0.05	0.11	0.10	0.25	0.16	0.30	0.16	0.25	0.21	0.70	0.30	0.56	0.42	0.51	0.43
USCZ_4B	0.24	0.17	0.40	0.26	0.26	0.26	0.35	0.20	0.47	0.31	0.30	0.31	1.01	0.42	0.97	0.91	0.75	0.73
USCZ_4C	0.03	0.00	0.05	0.00	0.00	0.01	0.04	0.01	0.07	0.03	0.03	0.02	0.18	0.06	0.20	0.20	0.14	0.13
USCZ_5A	0.13	0.08	0.17	0.08	0.12	0.11	0.19	0.15	0.27	0.17	0.24	0.20	0.47	0.28	0.52	0.44	0.52	0.42
USCZ_5B	0.11	0.03	0.13	0.04	0.04	0.05	0.17	0.09	0.24	0.16	0.15	0.15	0.52	0.19	0.51	0.47	0.39	0.37
USCZ_6A	0.08	0.03	0.07	-0.06	0.01	0.01	0.09	0.05	0.10	-0.07	0.03	0.02	0.24	0.21	0.32	0.19	0.36	0.24
USCZ_6B	0.04	0.02	0.07	-0.04	-0.01	-0.01	0.11	0.05	0.16	0.05	0.07	0.05	0.39	0.14	0.36	0.27	0.26	0.24
USCZ_7	0.02	0.01	0.02	-0.08	-0.02	-0.03	0.02	-0.00	0.01	-0.10	-0.05	-0.04	0.14	0.06	0.12	-0.04	0.06	0.03
USCZ_8	0.06	0.07	0.13	0.01	0.03	0.05	0.09	0.11	0.20	0.09	0.09	0.10	0.28	0.21	0.42	0.31	0.26	0.27

Table 9 (continued)

(b) Medium office annual HVAC energy cost savings intensity ($/m²).

	new						older						oldest					
	R	**N**	**E**	**S**	**W**	**N E S W**	**R**	**N**	**E**	**S**	**W**	**N E S W**	**R**	**N**	**E**	**S**	**W**	**N E S W**
USCZ_1A	0.38	0.21	0.49	0.45	0.51	0.41	0.40	0.47	1.16	0.93	1.18	0.94	1.05	0.74	1.74	1.28	1.64	1.36
USCZ_2A	0.16	0.08	0.21	0.11	0.18	0.15	0.31	0.22	0.65	0.36	0.65	0.48	0.84	0.55	1.36	1.01	1.29	1.05
USCZ_2B	0.50	0.26	0.60	0.50	0.54	0.48	0.20	0.48	1.38	1.02	1.44	1.08	1.33	0.80	2.24	1.97	2.13	1.78
USCZ_3A	0.21	0.10	0.22	0.11	0.23	0.06	0.37	0.20	0.60	0.27	0.64	0.43	0.93	0.59	1.56	1.25	1.47	1.21
USCZ_3B	0.15	0.07	0.17	0.11	0.15	0.12	0.08	0.17	0.50	0.10	0.55	0.32	0.68	0.16	1.10	0.90	1.06	0.82
USCZ_3C	0.08	-0.03	0.09	0.03	0.11	0.04	0.20	-0.03	0.52	0.27	0.62	0.34	0.40	0.28	1.28	0.90	1.26	0.94
USCZ_4A	0.03	0.00	0.08	-0.02	0.08	0.04	0.10	0.07	0.19	0.00	0.28	0.14	0.64	0.34	1.02	0.80	0.95	0.77
USCZ_4B	0.26	0.10	0.20	0.11	0.17	0.14	0.15	0.09	0.23	-0.09	0.29	0.12	0.64	0.43	1.16	0.74	1.08	0.84
USCZ_4C	0.03	-0.02	0.07	0.03	0.08	0.03	0.11	-0.02	0.16	0.12	0.22	0.12	0.29	0.09	0.50	0.45	0.61	0.40
USCZ_5A	0.01	-0.02	0.04	-0.03	0.05	0.01	0.01	0.01	0.07	-0.08	0.13	0.03	0.26	0.10	0.57	0.23	0.56	0.37
USCZ_5B	-0.03	-0.29	-0.22	-0.28	-0.23	-0.05	0.01	0.01	0.07	-0.06	0.13	0.03	0.30	0.13	0.67	0.42	0.53	0.44
USCZ_6A	0.00	-0.05	0.01	-0.07	0.04	-0.02	-0.04	-0.08	-0.07	-0.22	0.04	-0.08	0.17	0.06	0.74	0.26	0.75	0.46
USCZ_6B	-0.06	-0.06	-0.01	-0.60	-0.00	-0.17	-0.08	-0.08	-0.06	-0.24	0.02	-0.09	0.18	0.08	0.67	0.14	0.53	0.32
USCZ_7	-0.17	-0.09	-0.03	-0.14	-0.01	-0.07	-0.05	-0.06	-0.11	-0.23	-0.03	-0.11	0.08	0.02	0.25	-0.03	0.39	0.16
USCZ_8	0.27	0.08	0.21	-0.01	0.26	0.13	-0.01	-0.08	-0.14	-0.27	-0.02	-0.13	0.01	0.08	0.36	0.29	0.31	0.26

Table 9 (continued)

(c) Retail stand-alone annual HVAC energy cost savings intensity ($/m²).

	new						older						oldest					
	R	**N**	**E**	**S**	**W**	**N E S W**	**R**	**N**	**E**	**S**	**W**	**N E S W**	**R**	**N**	**E**	**S**	**W**	**N E S W**
USCZ_1A*	NA	NA	NA	NA	NA	NA	0.49	0.82	1.42	1.45	1.85	1.36	1.47	0.74	1.34	1.32	2.15	1.37
USCZ_2A	0.28	0.14	0.59	0.80	0.98	0.51	0.27	0.38	0.88	0.78	0.72	0.64	0.98	0.49	1.01	1.06	1.42	0.95
USCZ_2B	0.85	1.72	3.54	4.15	5.11	3.65	0.25	0.60	1.48	1.40	1.55	1.20	1.73	0.68	1.43	1.73	2.20	1.47
USCZ_3A	0.33	0.15	0.52	0.43	0.53	0.42	0.28	0.19	0.74	0.64	0.48	0.51	1.04	0.31	1.00	1.21	1.45	0.99
USCZ_3B	0.21	0.18	0.32	0.42	0.54	0.35	0.13	0.14	0.44	0.30	0.34	0.30	0.85	0.38	0.77	0.95	1.27	0.81
USCZ_3C	0.24	-0.24	0.72	0.72	-0.07	0.54	0.56	-0.12	0.88	0.46	-0.44	0.17	0.64	-0.24	0.56	1.31	0.81	0.59
USCZ_4A	0.08	-0.45	-0.34	0.27	0.28	0.26	0.13	0.06	0.25	0.13	0.08	0.14	0.61	0.13	0.66	0.74	0.43	0.49
USCZ_4B	0.50	0.27	0.57	0.43	0.61	0.47	0.46	0.04	0.37	0.06	0.01	0.13	0.79	0.11	0.69	0.78	0.79	0.58
USCZ_4C	0.13	0.09	0.17	0.22	0.31	0.17	0.16	-0.06	0.05	-0.04	-0.15	-0.04	0.28	-0.08	0.21	0.50	0.16	0.19
USCZ_5A	0.19	0.43	0.61	0.22	0.61	0.29	0.06	0.02	0.11	0.03	0.09	0.05	0.12	0.07	0.13	0.25	0.29	0.17
USCZ_5B	0.16	0.07	0.21	0.15	0.24	0.18	0.08	-0.05	0.05	-0.14	-0.12	-0.06	0.26	0.01	0.12	0.38	0.20	0.17
USCZ_6A	0.29	0.08	0.38	0.20	0.34	0.30	-0.02	-0.04	-0.04	-0.09	-0.06	-0.05	-0.00	-0.07	0.07	0.04	-0.04	0.01
USCZ_6B	0.16	0.08	0.13	0.10	0.27	0.15	-0.06	-0.07	-0.10	-0.26	-0.18	-0.14	-0.05	-0.09	-0.11	-0.03	-0.05	-0.07
USCZ_7	0.11	2.26	0.07	2.90	0.22	0.07	-0.06	-0.04	-0.09	-0.15	-0.11	-0.10	-0.05	-0.04	-0.06	-0.06	-0.08	-0.07
USCZ_8	0.33	0.27	0.63	0.36	0.32	0.37	-0.06	-0.05	-0.07	-0.15	-0.05	-0.07	-0.07	-0.08	-0.06	0.10	-0.10	-0.04

* 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.

Table 10. Analog of Table 9 for annual whole-building HVAC energy cost saving fraction (%).

(a) Single-family home annual whole-building HVAC energy cost saving fraction (%).

	new						older						oldest					
	R	**N**	**E**	**S**	**W**	**N E S W**	**R**	**N**	**E**	**S**	**W**	**N E S W**	**R**	**N**	**E**	**S**	**W**	**N E S W**
USCZ_1A	4.00	1.16	1.98	2.04	2.13	7.28	3.11	0.92	1.57	1.61	1.68	5.74	5.73	1.16	1.95	2.06	2.23	7.39
USCZ_2A	2.96	1.06	1.74	1.55	1.71	5.96	2.91	0.87	1.46	1.31	1.38	4.96	4.68	1.13	1.87	1.88	1.96	6.77
USCZ_2B	3.05	0.72	1.66	1.67	1.41	5.36	2.90	0.69	1.59	1.58	1.33	5.09	5.21	0.93	2.06	2.25	1.95	7.10
USCZ_3A	2.38	0.67	1.22	0.95	1.06	3.81	2.39	0.67	1.23	0.96	1.08	3.86	3.98	0.90	1.64	1.50	1.60	5.49
USCZ_3B	4.43	0.89	2.04	1.44	1.41	5.52	3.68	0.91	1.99	1.64	1.57	5.88	5.98	1.20	2.58	2.53	2.27	8.35
USCZ_3C	5.71	0.81	2.80	1.94	0.99	5.62	4.02	0.59	2.17	1.77	0.66	4.55	8.15	0.98	2.84	3.20	1.68	8.22
USCZ_4A	1.49	0.40	0.81	0.23	0.53	1.86	1.71	0.46	0.85	0.44	0.72	2.37	3.56	0.62	1.17	0.87	1.07	3.57
USCZ_4B	2.75	0.82	1.87	1.24	1.22	4.86	3.41	0.83	1.90	1.28	1.23	5.00	6.56	1.14	2.60	2.46	2.02	7.90
USCZ_4C	0.49	0.03	0.40	-0.01	0.02	0.24	0.40	0.04	0.33	0.16	0.13	0.45	1.46	0.20	0.66	0.65	0.46	1.73
USCZ_5A	1.66	0.43	0.87	0.44	0.65	2.29	1.53	0.47	0.88	0.57	0.78	2.63	2.77	0.70	1.27	1.08	1.27	4.17
USCZ_5B	1.40	0.19	0.69	0.19	0.20	1.14	1.82	0.37	1.06	0.70	0.64	2.60	3.78	0.57	1.51	1.40	1.17	4.42
USCZ_6A	0.67	0.11	0.24	-0.21	0.03	0.09	0.44	0.11	0.19	-0.15	0.06	0.16	0.94	0.33	0.51	0.30	0.58	1.57
USCZ_6B	0.43	0.07	0.34	-0.18	-0.06	-0.16	0.97	0.20	0.60	0.18	0.27	0.79	2.57	0.39	0.98	0.73	0.71	2.59
USCZ_7	0.21	0.04	0.11	-0.37	-0.10	-0.63	0.11	-0.01	0.02	-0.29	-0.13	-0.46	0.67	0.12	0.25	-0.09	0.12	0.25
USCZ_8	0.29	0.13	0.24	0.03	0.06	0.39	0.37	0.19	0.34	0.14	0.16	0.70	0.89	0.28	0.57	0.41	0.34	1.45

Table 10 (continued)

(b) Medium office annual whole-building HVAC energy cost saving fraction (%).

	new						older						oldest					
	R	**N**	**E**	**S**	**W**	**N E S W**	**R**	**N**	**E**	**S**	**W**	**N E S W**	**R**	**N**	**E**	**S**	**W**	**N E S W**
USCZ_1A	2.41	0.28	0.62	0.58	0.66	2.11	1.91	0.45	1.11	0.89	1.12	3.58	3.20	0.46	1.05	0.78	0.99	3.29
USCZ_2A	1.69	0.18	0.44	0.23	0.39	1.25	1.75	0.25	0.74	0.42	0.74	2.18	3.42	0.44	1.09	0.82	1.04	3.38
USCZ_2B	2.47	0.25	0.59	0.50	0.52	1.87	0.79	0.38	1.06	0.79	1.11	3.31	3.18	0.39	1.07	0.95	1.02	3.39
USCZ_3A	1.64	0.16	0.34	0.18	0.36	0.39	1.75	0.18	0.56	0.25	0.60	1.60	3.14	0.40	1.04	0.85	0.99	3.25
USCZ_3B	2.17	0.22	0.49	0.33	0.44	1.44	0.55	0.24	0.69	0.14	0.76	1.79	3.46	0.17	1.11	0.92	1.07	3.30
USCZ_3C	1.40	-0.09	0.30	0.10	0.35	0.55	1.32	-0.04	0.67	0.36	0.80	1.76	2.44	0.36	1.58	1.12	1.50	4.60
USCZ_4A	0.33	0.01	0.16	-0.04	0.16	0.29	0.47	0.07	0.17	0.01	0.26	0.50	2.43	0.25	0.76	0.61	0.71	2.31
USCZ_4B	2.26	0.17	0.35	0.20	0.30	0.95	0.87	0.10	0.27	-0.11	0.35	0.58	2.61	0.36	0.94	0.61	0.88	2.75
USCZ_4C	0.48	-0.07	0.22	0.10	0.24	0.40	0.77	-0.03	0.22	0.18	0.31	0.67	2.00	0.13	0.69	0.63	0.84	2.22
USCZ_5A	0.09	-0.05	0.08	-0.05	0.10	0.07	0.05	0.02	0.07	-0.08	0.13	0.14	1.43	0.11	0.62	0.26	0.62	1.60
USCZ_5B	-0.46	-0.82	-0.63	-0.80	-0.65	-0.58	0.05	0.01	0.10	-0.09	0.20	0.20	1.97	0.18	0.88	0.55	0.70	2.30
USCZ_6A	0.01	-0.08	0.02	-0.10	0.06	-0.11	-0.12	-0.05	-0.04	-0.15	0.03	-0.21	0.71	0.05	0.62	0.22	0.63	1.52
USCZ_6B	-0.56	-0.13	-0.02	-1.25	-0.01	-1.44	-0.41	-0.08	-0.06	-0.24	0.02	-0.36	0.92	0.08	0.69	0.15	0.55	1.32
USCZ_7	-1.35	-0.14	-0.05	-0.22	-0.02	-0.43	-0.21	-0.05	-0.09	-0.19	-0.03	-0.35	0.42	0.03	0.29	-0.04	0.43	0.73
USCZ_8	0.65	0.04	0.10	-0.01	0.12	0.25	-0.01	-0.03	-0.04	-0.08	-0.01	-0.15	0.04	0.05	0.20	0.16	0.17	0.57

Table 10 (continued)

(c) Retail stand-alone annual whole-building HVAC energy cost saving fraction (%).

	new						older						oldest					
	R	**N**	**E**	**S**	**W**	**N E S W**	**R**	**N**	**E**	**S**	**W**	**N E S W**	**R**	**N**	**E**	**S**	**W**	**N E S W**
USCZ_1A*	NA	NA	NA	NA	NA	NA	3.73	0.82	1.42	1.24	1.58	5.03	10.12	0.67	1.20	1.02	1.65	4.54
USCZ_2A	5.55	0.37	1.53	1.78	2.17	4.84	2.78	0.51	1.18	0.90	0.83	3.17	8.56	0.55	1.14	1.02	1.38	4.00
USCZ_2B	5.18	1.36	2.81	2.81	3.47	10.72	1.80	0.56	1.38	1.12	1.24	4.15	10.48	0.54	1.12	1.17	1.48	4.28
USCZ_3A	5.02	0.28	1.03	0.74	0.88	3.04	2.28	0.21	0.80	0.59	0.44	2.05	7.48	0.29	0.94	0.97	1.17	3.44
USCZ_3B	4.76	0.54	0.96	1.09	1.39	3.95	1.78	0.25	0.78	0.45	0.51	1.99	8.85	0.52	1.05	1.10	1.47	4.07
USCZ_3C	5.55	-0.72	2.19	1.89	-0.19	6.13	7.99	-0.20	1.64	0.72	-0.73	1.17	8.25	-0.39	0.95	1.88	1.16	3.68
USCZ_4A	1.48	-1.17	-0.88	0.58	0.59	2.37	1.06	0.07	0.28	0.12	0.07	0.57	4.43	0.12	0.62	0.60	0.35	1.70
USCZ_4B	6.38	0.45	0.94	0.61	0.85	2.86	5.23	0.05	0.55	0.08	0.01	0.71	7.36	0.14	0.83	0.80	0.82	2.62
USCZ_4C	2.83	0.28	0.50	0.55	0.76	1.85	2.05	-0.10	0.08	-0.06	-0.22	-0.24	3.00	-0.11	0.30	0.61	0.19	0.98
USCZ_5A	4.33	1.27	1.81	0.58	1.53	3.24	0.59	0.03	0.14	0.04	0.09	0.25	1.01	0.08	0.14	0.23	0.27	0.69
USCZ_5B	3.36	0.19	0.58	0.37	0.58	1.85	1.04	-0.09	0.08	-0.20	-0.17	-0.35	2.71	0.01	0.17	0.45	0.24	0.86
USCZ_6A	5.14	0.19	0.85	0.39	0.67	2.58	-0.10	-0.03	-0.03	-0.07	-0.05	-0.16	-0.03	-0.06	0.06	0.03	-0.03	0.02
USCZ_6B	2.59	0.17	0.27	0.19	0.49	1.16	-0.49	-0.08	-0.12	-0.25	-0.17	-0.55	-0.38	-0.09	-0.11	-0.03	-0.04	-0.25
USCZ_7	1.47	4.36	0.13	4.80	0.15	0.54	-0.47	-0.04	-0.09	-0.12	-0.10	-0.35	-0.38	-0.04	-0.05	-0.05	-0.07	-0.23
USCZ_8	1.47	0.16	0.36	0.18	0.16	0.79	-0.21	-0.03	-0.04	-0.06	-0.02	-0.13	-0.24	-0.04	-0.03	0.04	-0.04	-0.07

* 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.

The following examples illustrate how to use the savings tables.

3.4.1 Example 1: Cool walls on an isolated 30-year-old single-family home in Fresno, CA

The city of Fresno is within California building climate zone 13 (Table 1 or Figure 2), and a home built 30 years ago (in 1988) is best represented by the "older" vintage (Section 3.1). From Table 7a we obtain the annual HVAC energy cost savings intensity c (\$/m²) for an older single-family home in this climate (CACZ_13):

Table 11. Annual HVAC energy cost savings intensity (\$/m²) in Example 1. Savings in the first four columns (N, E, S, W) result from modifying walls individually, while those in the last column (N E S W) result from modifying all walls simultaneously.

N	E	S	W	N E S W
0.36	0.84	0.82	0.72	0.68

Assume that

- the house is due to be painted;
- the new paint will last for N=10 years;
- the real rate of return is r=3%
- one gallon of paint coats 400 ft²;
- we will apply two coats; and
- we wish to decide whether to choose a light-colored paint (higher-tied cool wall with aged albedo 0.60) or a darker conventional paint (warm wall with aged albedo 0.25).

Table 6 indicates that the PV multiplier for N=10 years and r=3% is b=8.5. The life-cycle HVAC energy cost savings intensity is $b \times c$:

Table 12. Life-cycle HVAC energy cost savings intensity (\$/m²) in Example 1.

N	E	S	W	N E S W
3.06	7.14	6.97	6.12	5.78

We consider two scenarios: (A) the cool paint costs the same as the warm paint, or (B) the cost premium for the cool paint is \$15/gallon.

In Scenario A (or Example 1A), the simple payback time is zero because the cost premium is zero. However, we can still compute life-cycle cost savings intensity.

With zero cost premium, the life-cycle cost savings intensity equals the life-cycle HVAC energy cost savings intensity (Table 12):

Table 13. Life-cycle cost savings intensity ($/m²) in Example 1A.

N	E	S	W	N E S W
3.06	7.14	6.97	6.12	5.78

To obtain savings per ft², divide by 10.76 ft²/m²:

Table 14. Life-cycle cost savings intensity ($/ft²) in Example 1A.

N	E	S	W	N E S W
0.28	0.66	0.65	0.57	0.54

In Scenario B (or Example 1B), the cost premium of $15/gallon yields a two-coat material cost premium of 2 × $15/gallon × 1 gallon/400 ft² × 10.76 ft²/m² = $0.81/m². Dividing this cost premium by the annual HVAC energy cost savings intensity ($/m²) provides the simple payback time in years:

Table 15. Simple payback time (y) in Example 1B.

N	E	S	W	N E S W
2.3	0.96	0.99	1.1	1.2

The life-cycle cost savings is the life-cycle HVAC energy cost savings intensity (Table 12) minus the material cost premium:

Table 16. Life-cycle cost savings intensity ($/m²) in Example 1B.

N	E	S	W	N E S W
2.25	6.33	6.16	5.31	4.97

If you prefer IP units, divide by 10.76 ft²/m²:

Table 17. Life-cycle cost savings intensity ($/ft²) in Example 1B.

N	E	S	W	N E S W
0.21	0.59	0.57	0.49	0.46

Hence, choosing the more reflective paint will be cost effective in either scenario, with zero simple payback time in Scenario A (no cost premium), and a 1 - 2 y simple payback time in Scenario B ($15/gal cost premium).

We can use the wall-specific life-cycle cost savings intensity to estimate the whole-building life cycle cost savings. Say the home is 15 m long (north-south), 10 m wide (east-west), and 6 m high, with a 2 m² door and 15 m² of windows each on the east and west facades, and 10 m² of windows each on the north and south facades. The net wall area (gross wall area minus openings) on the will be 15 m × 6 m – 2 m² - 15 m² = 73 m² on the east façade and on the west façade, and 10 m × 6 m – 10 m² = 50 m² on the north façade and on the south façade.

Table 18. Net wall area (m²) in Example 1.

N	E	S	W	N E S W
50	73	50	73	246

Multiplying each façade's life-cycle cost savings intensity (Table 14 for Scenario A; Table 16 for Scenario B) by its net wall area (Table 18) yields its life-cycle cost savings. In Scenario A, we get

Table 19. Life-cycle cost savings ($) in Example 1A.

N	E	S	W	N E S W
153	521	349	447	1,422

while in Scenario B we get

Table 20. Life-cycle cost savings ($) in Example 1B.

N	E	S	W	N E S W
113	462	308	388	1,223

Note that in each scenario the sum of individual wall savings (N + E + S + W) differs by about 3% from the savings based on the four-wall (N E S W) intensity because the distribution of net wall area in this example does not exactly match that in the modeled prototype.

Rounding to the near $100, the whole-building life-cycle cost savings are $1,400 in Scenario A and $1,200 in Scenario B.

We can find in Table 8 the fraction by which cool roof and cool walls reduce our annual whole-building HVAC energy cost:

Table 21. Annual whole-building HVAC energy cost saving fraction (%) in Example 1.

N	E	S	W	N E S W
1.11	2.58	2.5	2.21	8.3

This result is specific to the geometry of the prototype, and does not consider the net wall area of each façade on the actual home. However, it does indicate that making all four walls cool will lower the building's annual HVAC energy cost by about 8%.

3.4.2 Example 2: Adding neighbors to the home in Example 1

Assume the 6-m tall home in Example 1 is on the west side of a residential street, with its front neighbor across the street (30 m east), its rear neighbor across a pair of back yards (6 m west), and its side neighbors across narrow side yards (3 m north and 3 m south) (Figure 14).

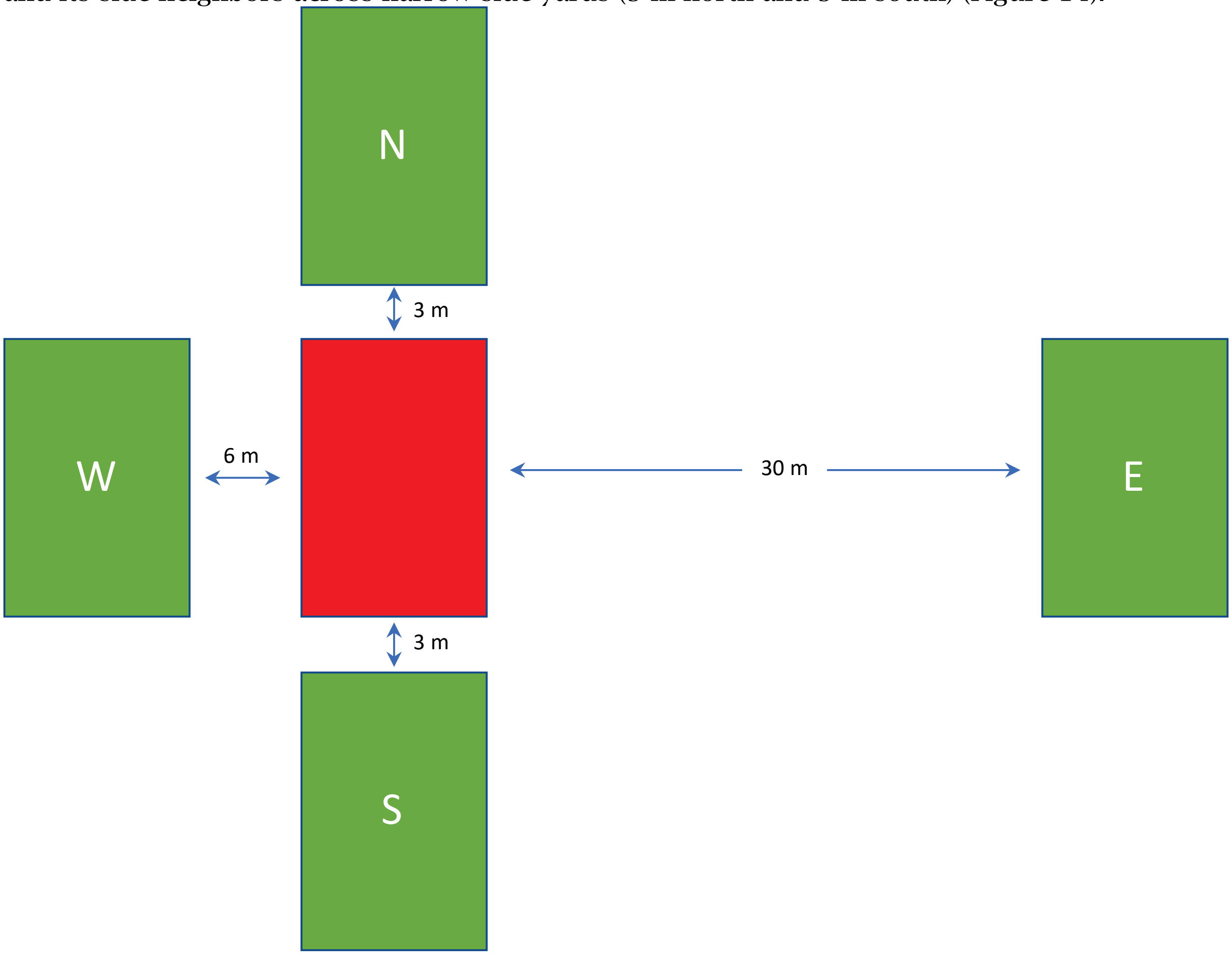

Figure 14. A single-family home (central building, in red) surrounded by its neighbors (in green). Each building is 10 m wide, 15 m long, and 6 m high.

We will show in Section 5 that the shading and reflection by these neighboring buildings will scale the sunlight incident on the walls of the central (modeled) building by the following “solar availability factors” (SAFs):

Table 22. Solar availability factors in Example 2.

N	E	S	W
0.47	0.92	0.50	0.63

Since cool wall savings are proportional to incident sunlight, we multiply each wall's isolated building annual HVAC energy cost savings intensity (Table 11) by its SAF (Table 22) to get its adjusted annual HVAC energy cost savings intensity:

Table 23. Annual HVAC energy cost savings intensity ($/m²) in Example 2.

N	E	S	W
0.17	0.77	0.41	0.45

Note that we do not try to scale the savings intensity in the four-wall case (N E S W).

We can then recalculate the life-cycle HVAC energy cost savings intensity, life-cycle cost savings intensity, and other values evaluated in Example 1, yielding

Table 24. Life-cycle HVAC energy cost savings intensity ($/m²) in Example 2.

N	E	S	W
1.44	6.57	3.49	3.86

Table 25. Life-cycle cost savings intensity ($/m²) in Example 2A.

N	E	S	W
1.44	6.57	3.49	3.86

Table 26. Life-cycle cost savings intensity ($/m²) in Example 2B.

N	E	S	W
0.63	5.76	2.68	3.05

Table 27. Simple payback time (y) in Example 2B.

N	E	S	W
4.8	1.0	2.0	1.8

While the life-cycle cost savings remains positive for all four walls, the Scenario B simple payback time for the north wall has grown to 4.8 y, or nearly half the assumed service life of the paint.

Using the net wall areas computed in Example 1 (Table 18), we get

Table 28. Life-cycle cost savings ($) in Example 2A.

N	E	S	W
72	480	175	282

Table 29. Life-cycle cost savings ($) in Example 2B.

N	E	S	W

32	420	134	223

Interactions with the neighboring buildings reduce the whole building life cycle cost savings by roughly $400, to about $1,000 in Scenario A and $800 in Scenario B.

Finally, we can use the SAFs to adjust the annual whole-building HVAC energy cost saving fraction. Total savings from the four cool walls is reduced to about 5.5% from about 8%.

Table 30. Annual whole-building HVAC energy cost saving fraction (%) in Example 2.

N	E	S	W
0.52	2.37	1.25	1.39

4 Detailed guide to cool-wall effects on an isolated building

Energy cost savings is only one measure of energy efficiency benefit. A wider list of properties related to energy use includes

- site energy (here, electricity or gas) consumed at the building;
- source energy (a.k.a. primary energy) required to produce the site energy;
- energy cost;
- peak power demand, or electric power demand averaged over peak demand hours (e.g., summer afternoons, noon to 6 pm local time); and
- emissions of carbon dioxide (CO_2), carbon dioxide equivalent (CO_2e), nitrogen oxides (NO_x), and sulfur dioxide (SO_2).

Annual savings in each of these properties depends on building category, location, vintage, and orientation, and can be disaggregated by surface(s) modified and by HVAC component (cooling, heating, or fan). There are also four metrics per property: baseline value, whole building absolute savings, whole building fractional savings, and savings intensity.

Since it is impractical to tabulate all these results within this document, we have prepared the Cool Surface Savings Explorer, or "Explorer" for short. The Explorer is an Excel[8] tool that parses the Cool Surface Savings Database, a comma separated value (CSV) text file containing the results of all simulations and calculations performed in Task 2.1 (energy savings for an isolated building).

[8] The tool runs in Excel for Windows, but not in Excel for Mac OS.

Note that the Explorer is *not* a general-purpose simulation tool or savings calculator. It simply extracts previously computed results from the Database.

Note also that our analysis has focused on the most common building categories, such as single-family home, medium office, and retail stand-alone. Results for some highly complex building prototypes, such as large office and large hotel, have not been fully vetted.

4.1 Installing the Explorer

The tool and database are available in a ZIP archive online at http://bit.ly/2Kwvtpu . To install, copy these two files to a local folder.

4.2 Operating the Explorer

Launching the Explorer will open the database and display a “Simulation selector” (hereafter, “Selector”) window (Figure 15).

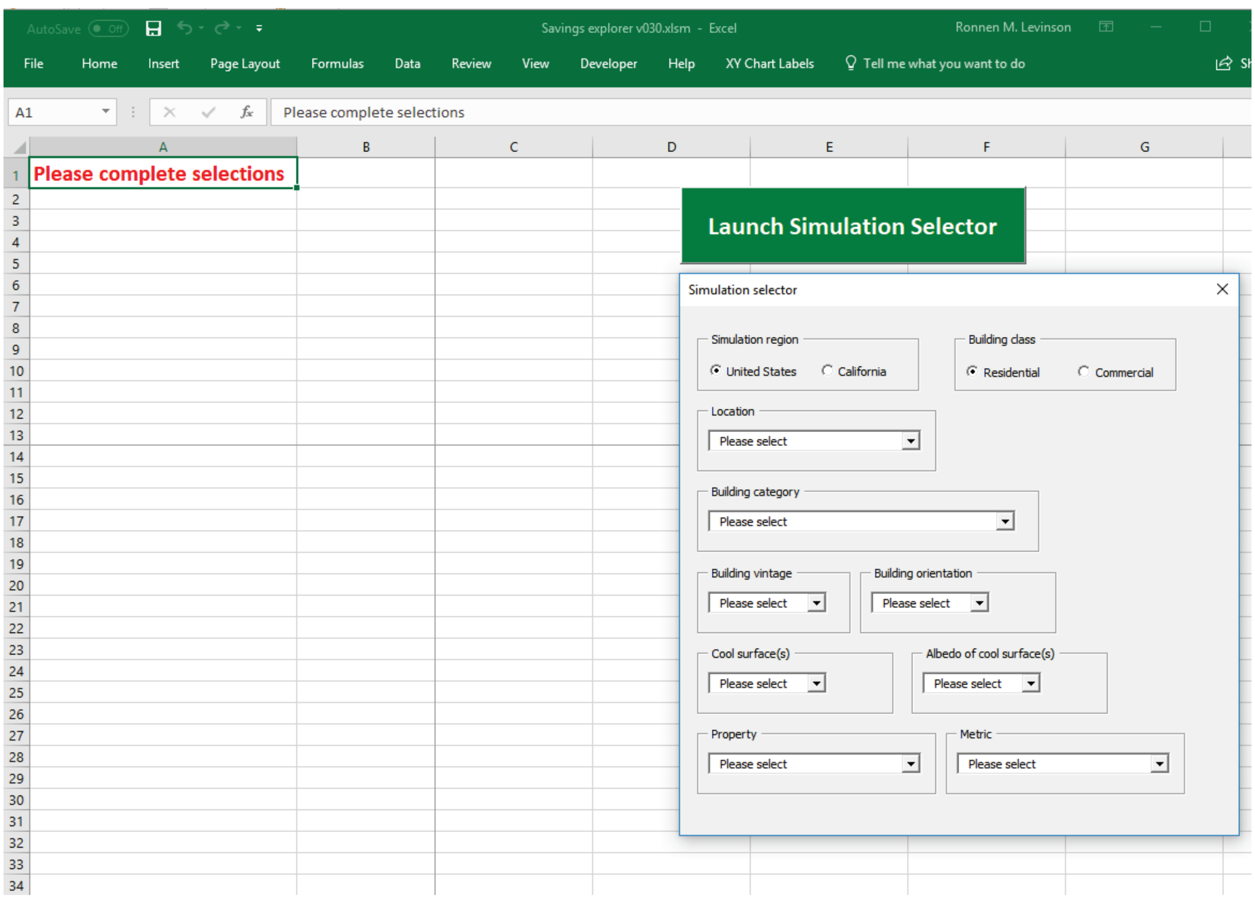

Figure 15. Initial appearance of the Explorer, with Simulation selector window at right (Figure 16).

Within the Selector:

1. Choose the simulation region (United State or California) and the building class (residential or commercial) (Figure 16). Changing the region or class may reset the location or building category to “Please select” because options for location and category depend on region and class.

2. Choose the location. Options vary with simulation region and building class (Figure 17 to Figure 19).

3. Choose the building category. Options vary with simulation region and building class (Figure 20 to Figure 23).

4. Choose the building vintage (Figure 24).

5. Choose the building orientation (Figure 25).

6. Choose the surface(s) to be made cool (Figure 26).

7. Choose the albedo to be assigned to the cool surface(s) (Figure 27).

8. Choose the property to be reported (Figure 28).

9. Choose the metric to be reported (Figure 29).

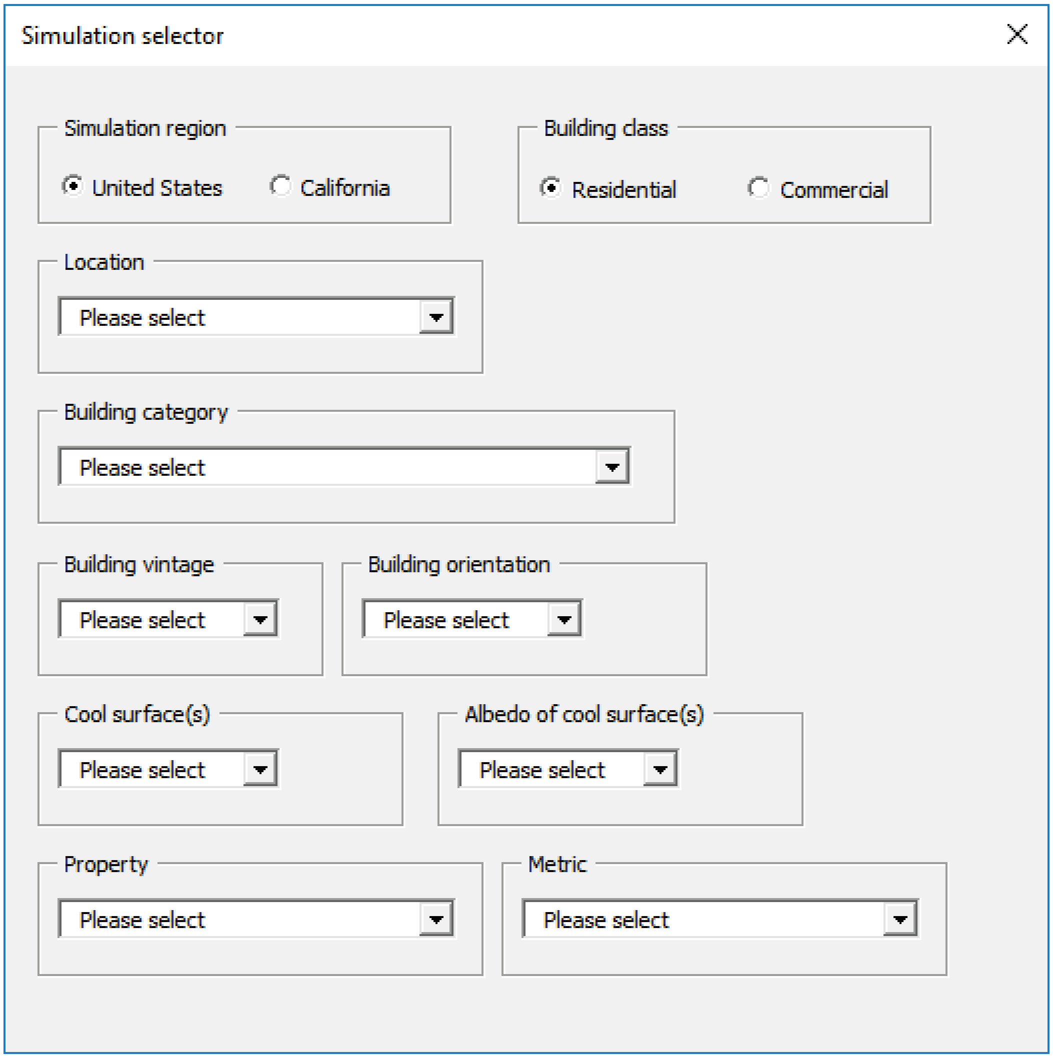

Figure 16. Initial appearance of Simulation selection window. Simulation region defaults to "United States" and building class defaults to "Residential", while all other inputs default to "Please select".

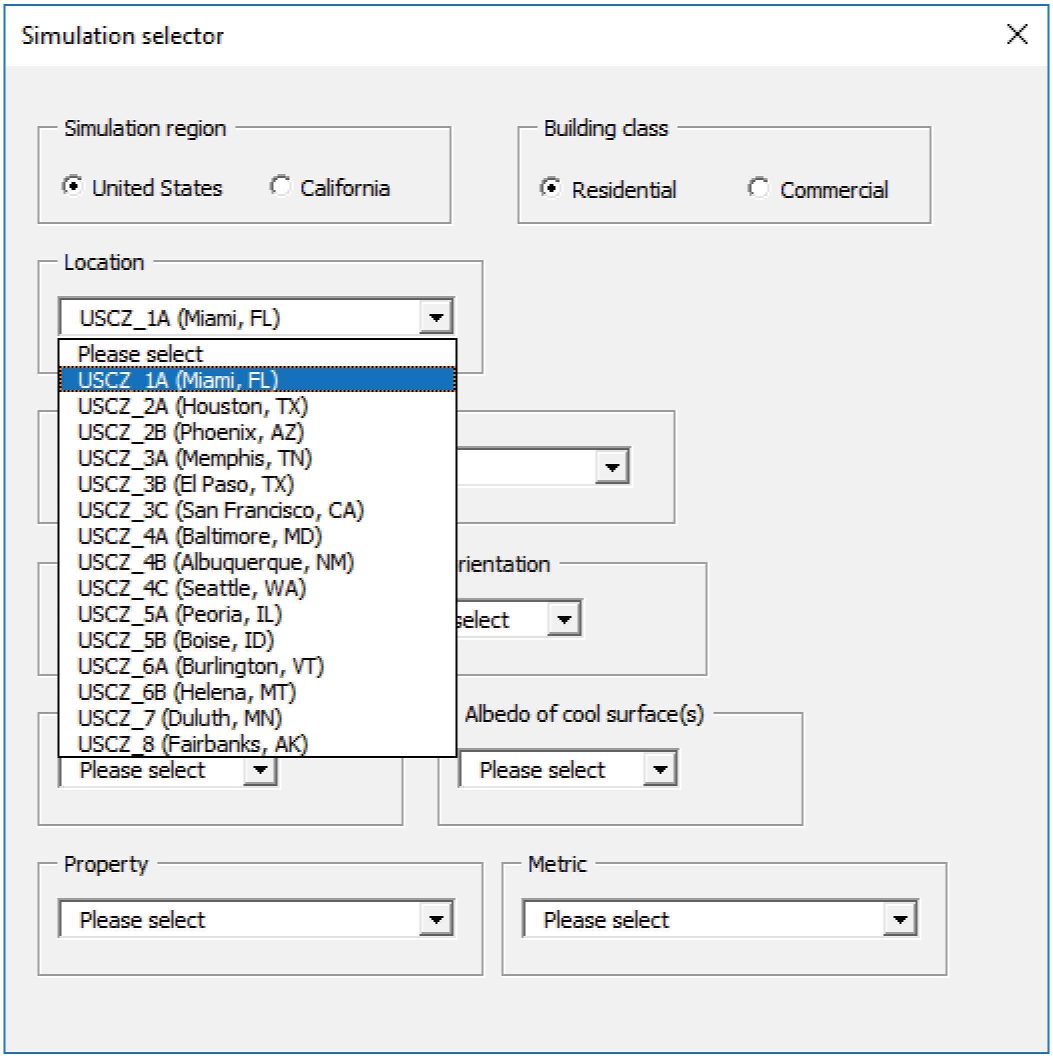

Figure 17. U.S. residential building locations.

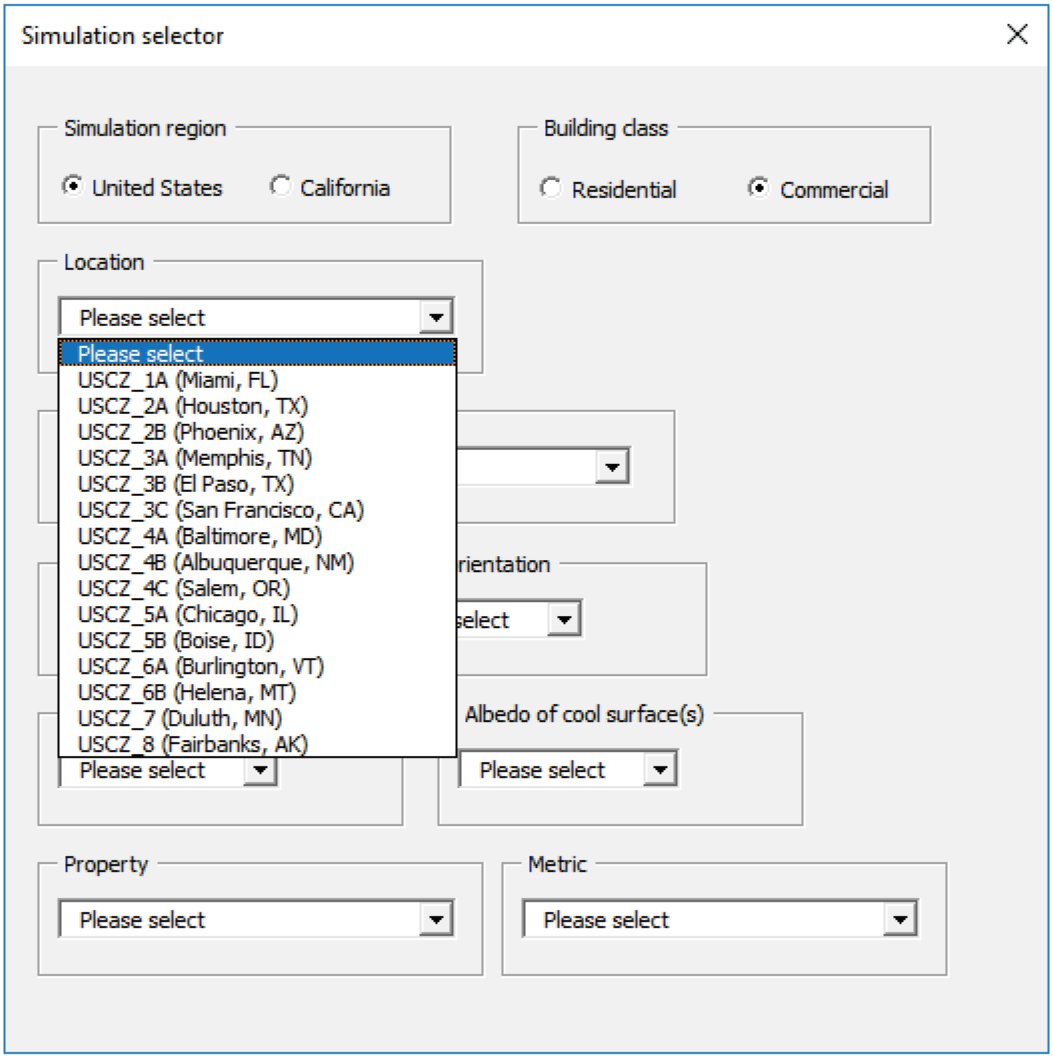

Figure 18. U.S. commercial buildings locations.

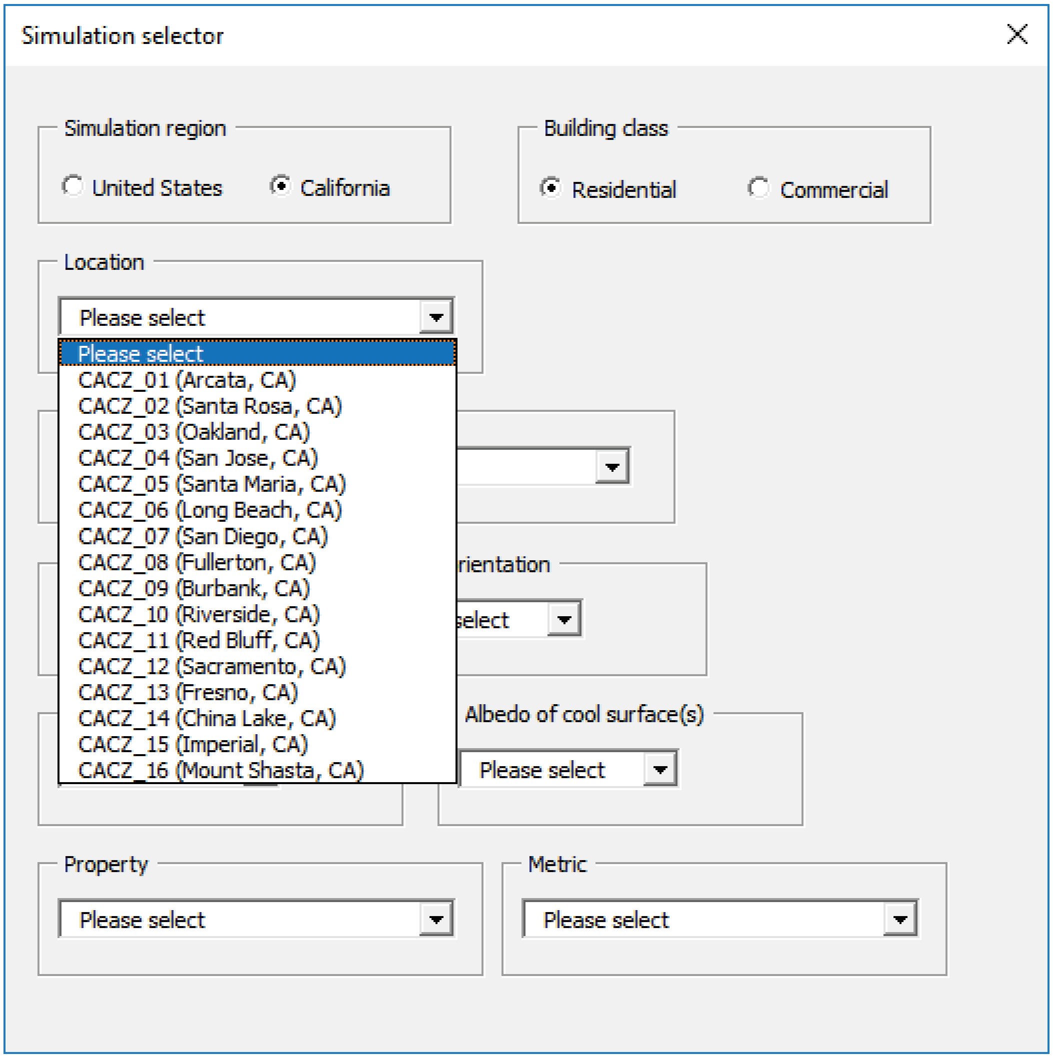

Figure 19. California residential (and commercial) building locations.

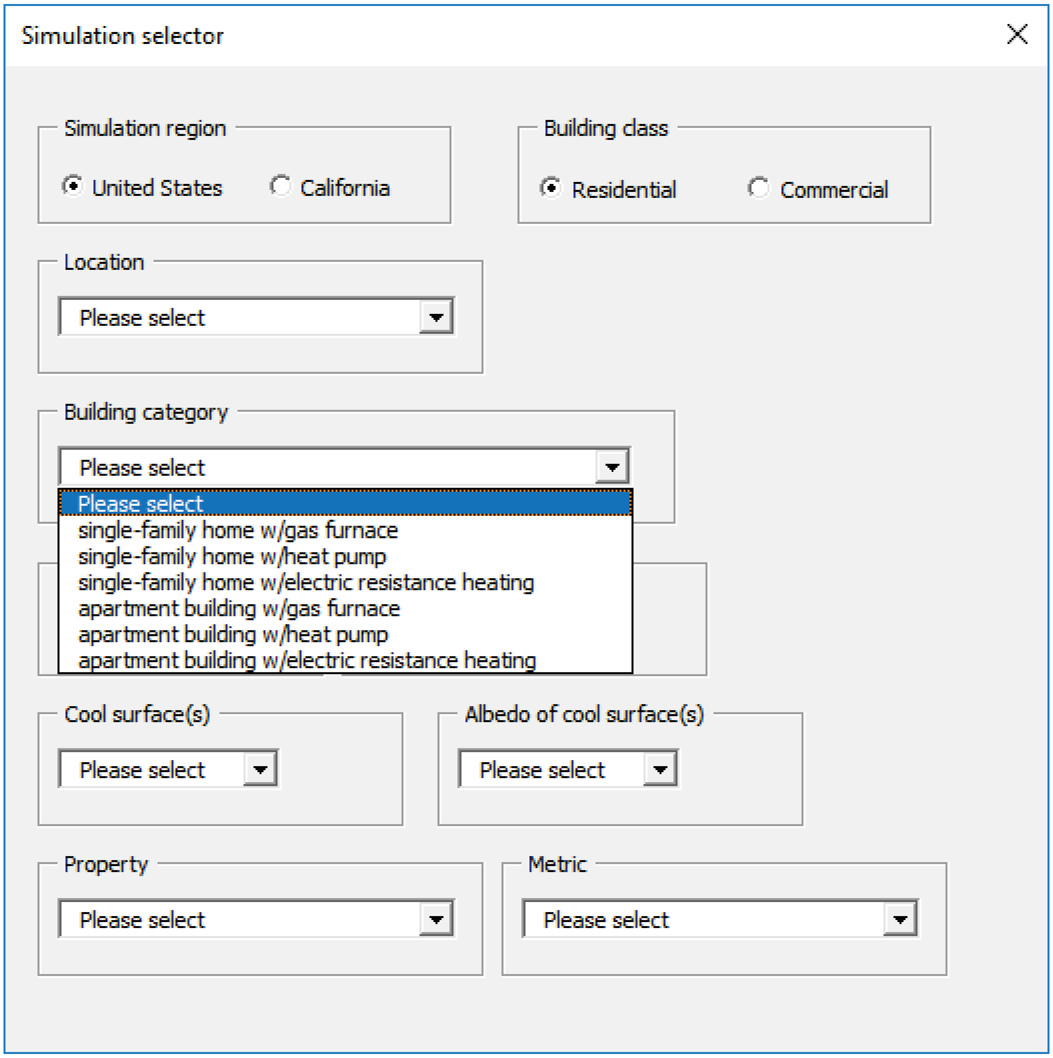

Figure 20. U.S. residential building categories.

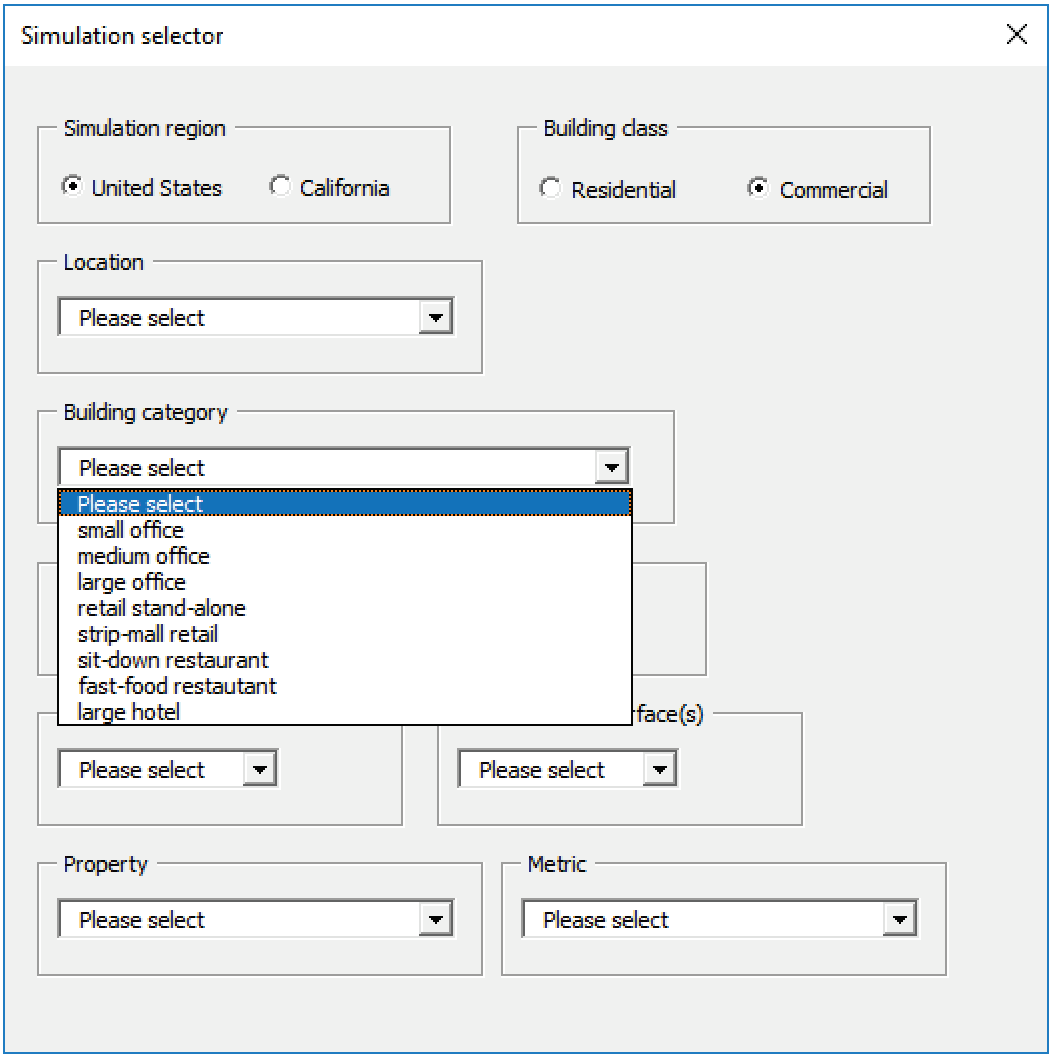

Figure 21. U.S. commercial building categories.

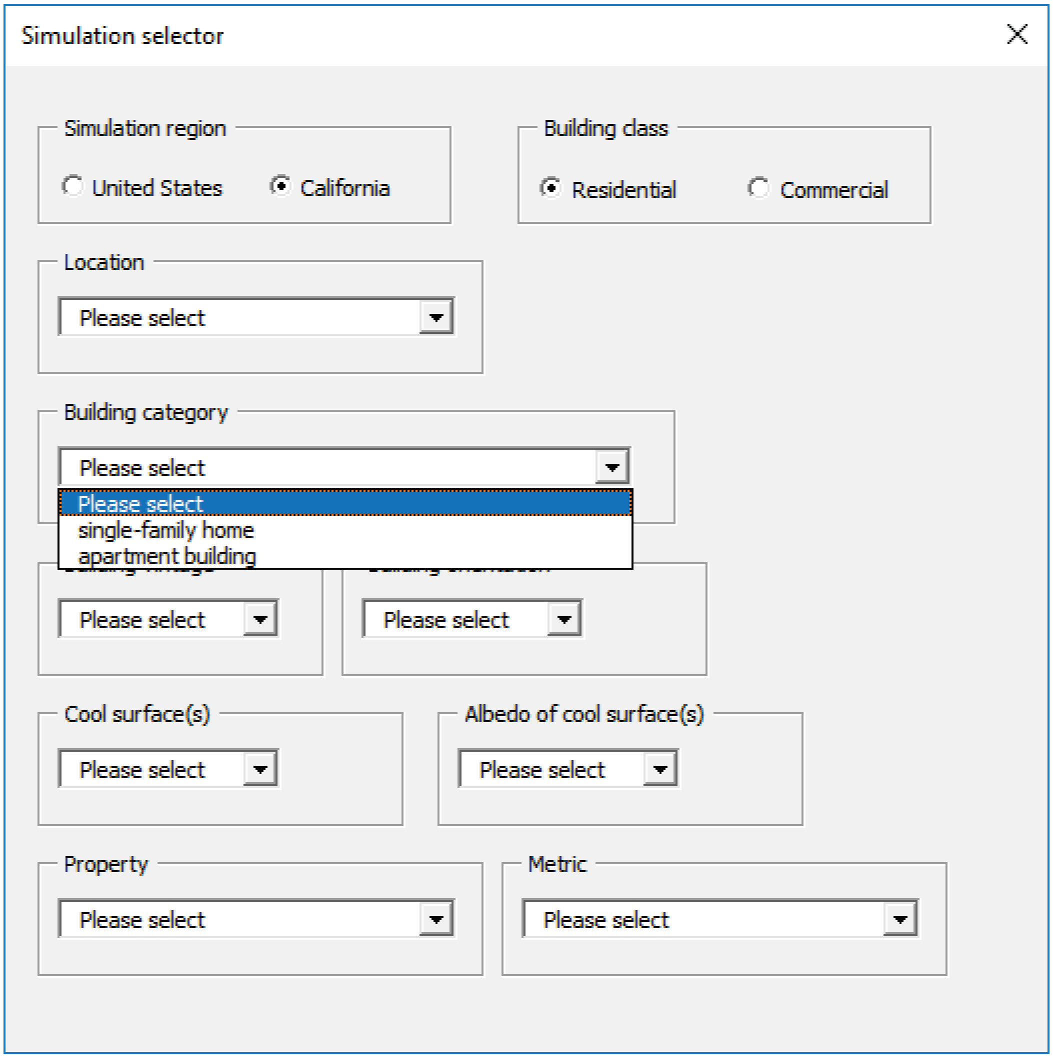

Figure 22. California residential building categories.

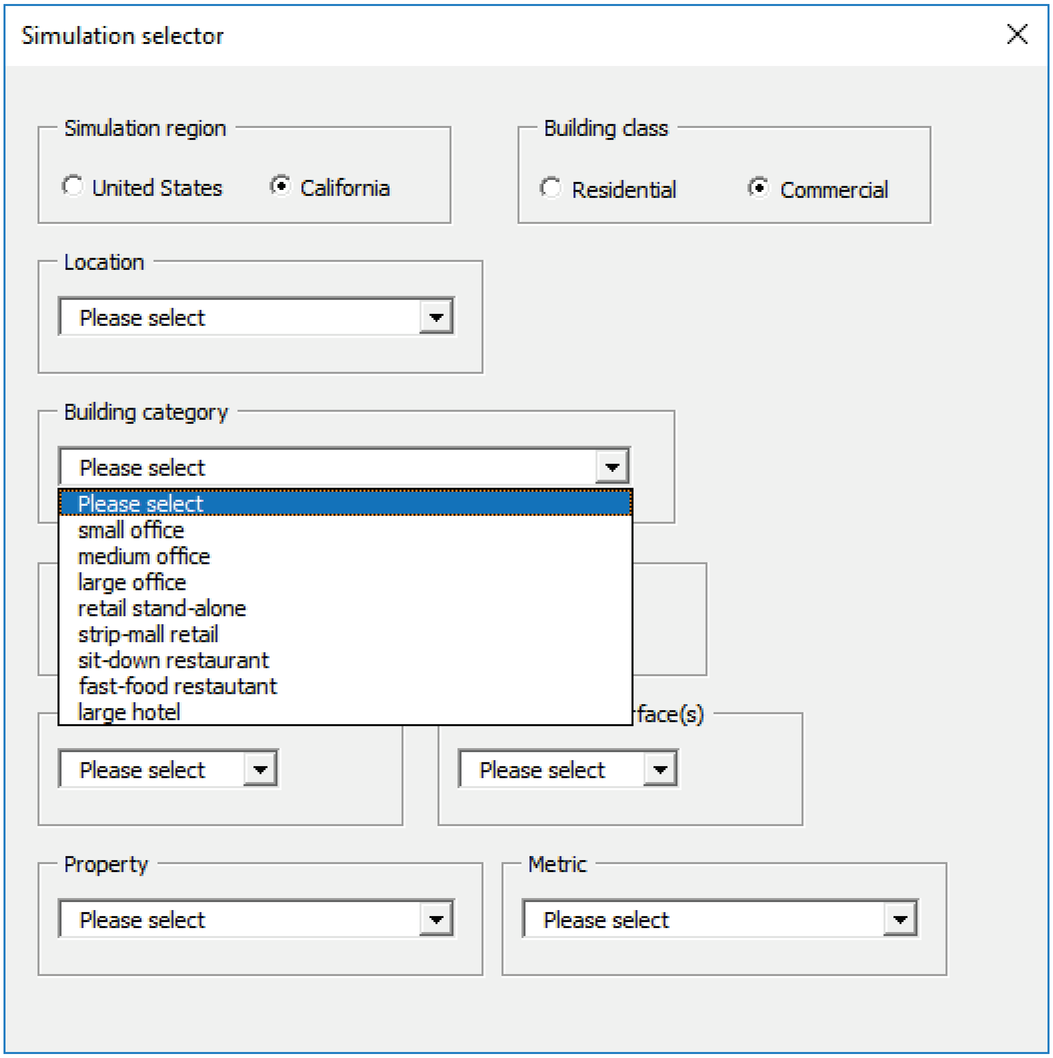

Figure 23. California commercial building categories.

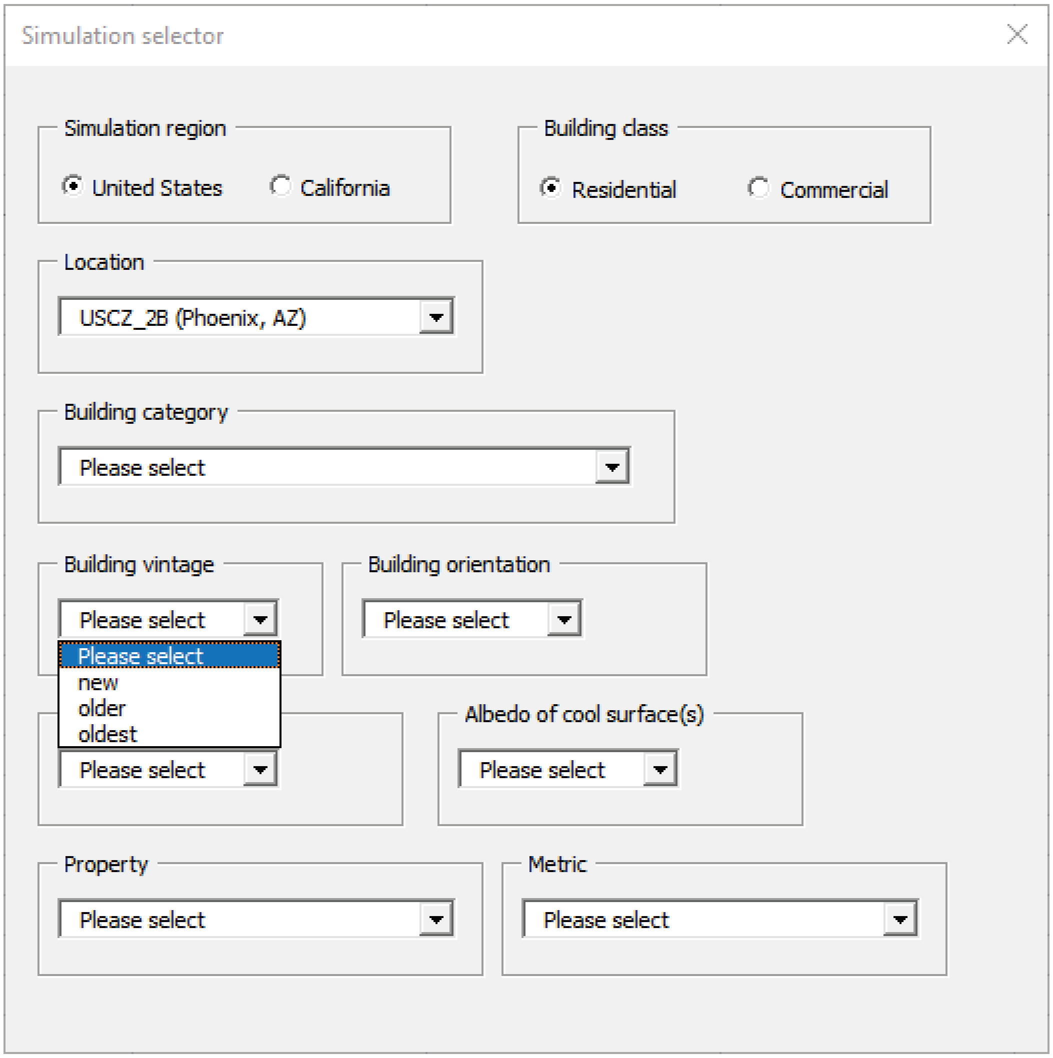

Figure 24. Building vintages.

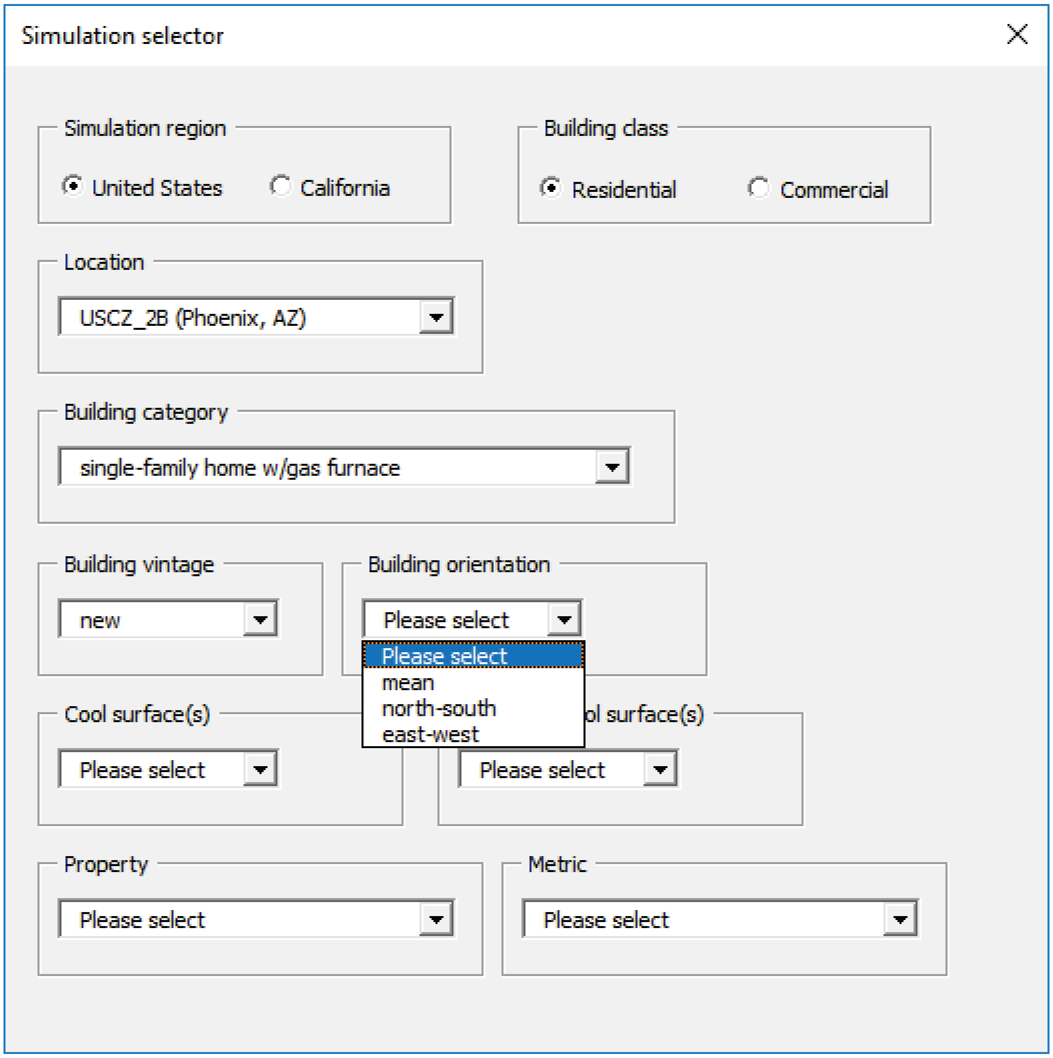

Figure 25. Building orientations.

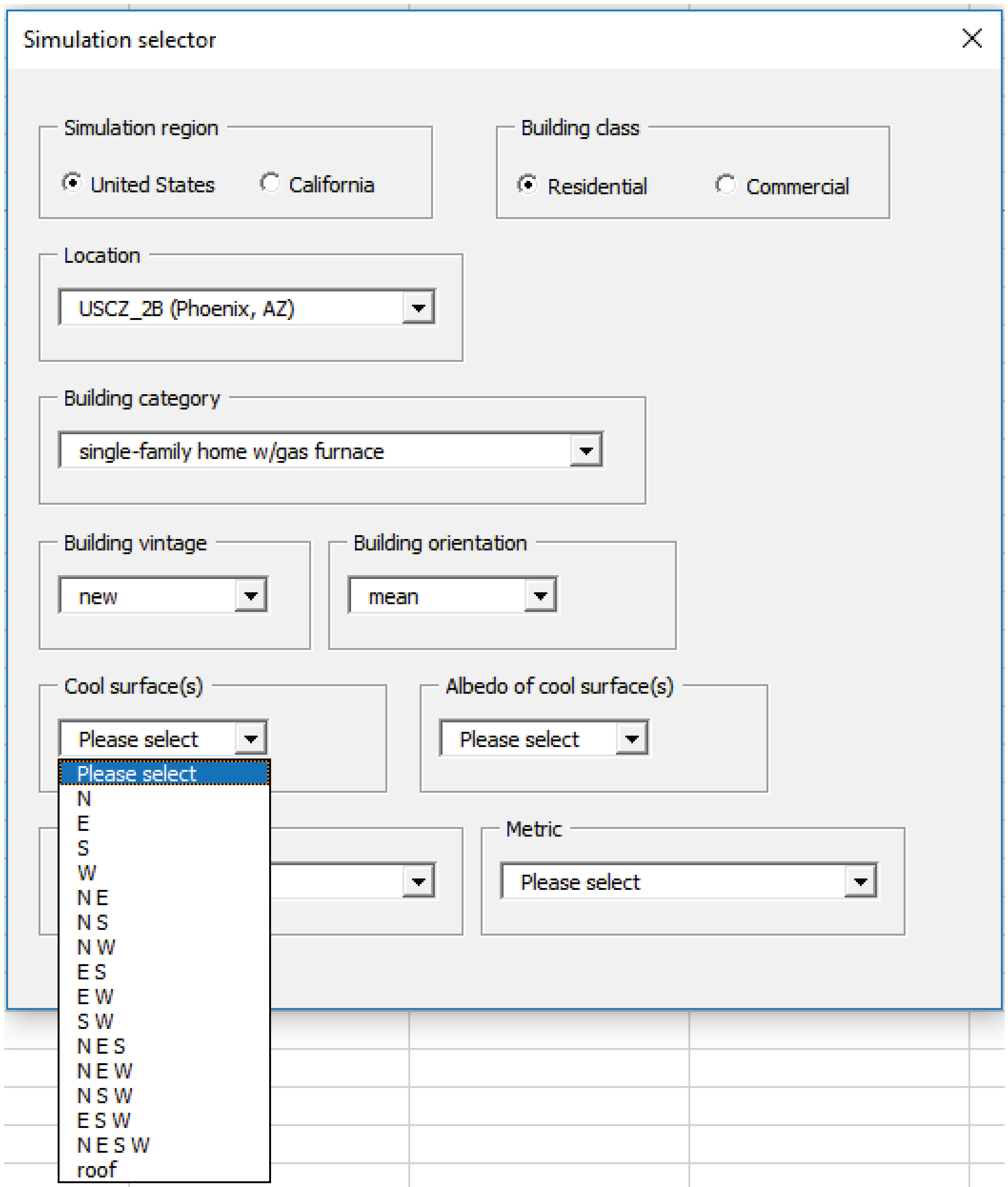

Figure 26. Surfaces that can be made cool.

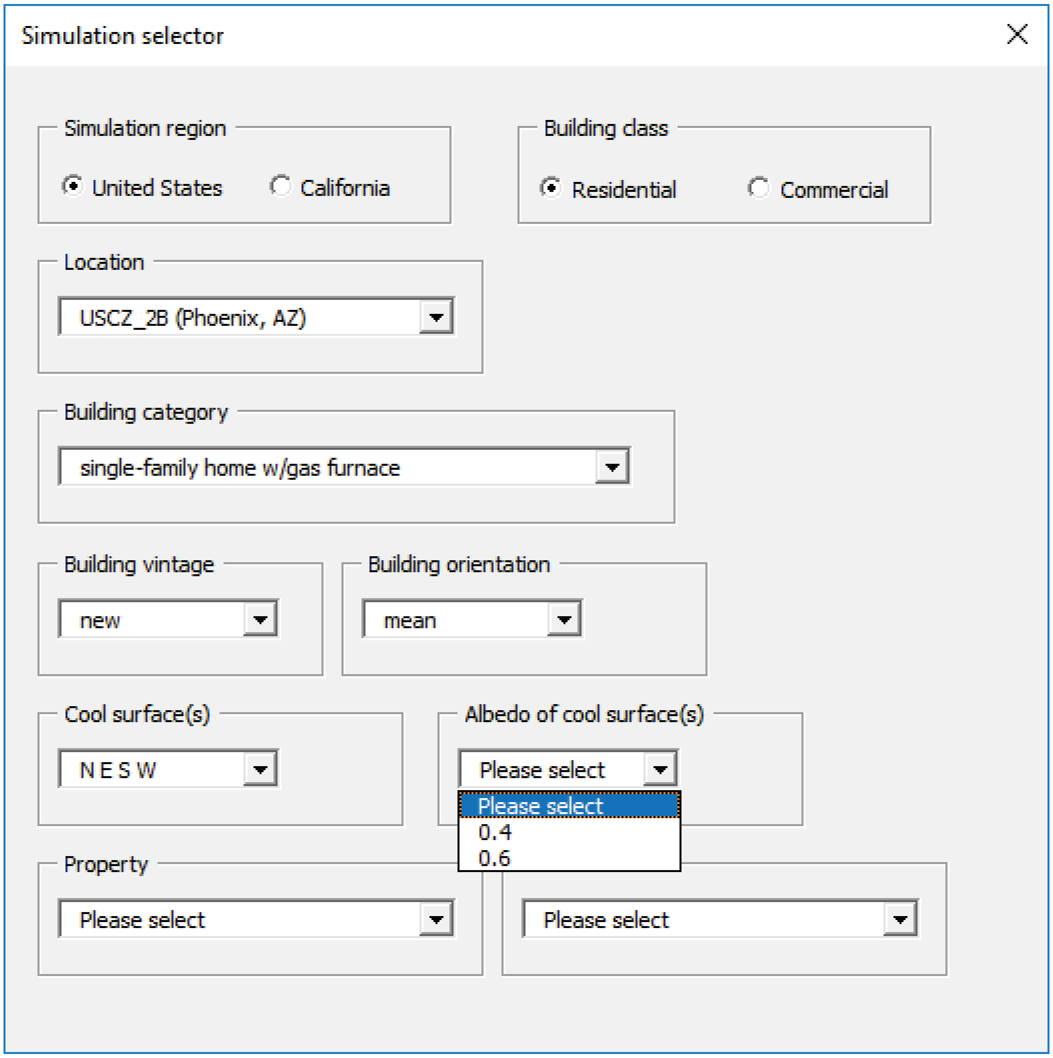

Figure 27. Albedos that can be assigned to the cool surface(s).

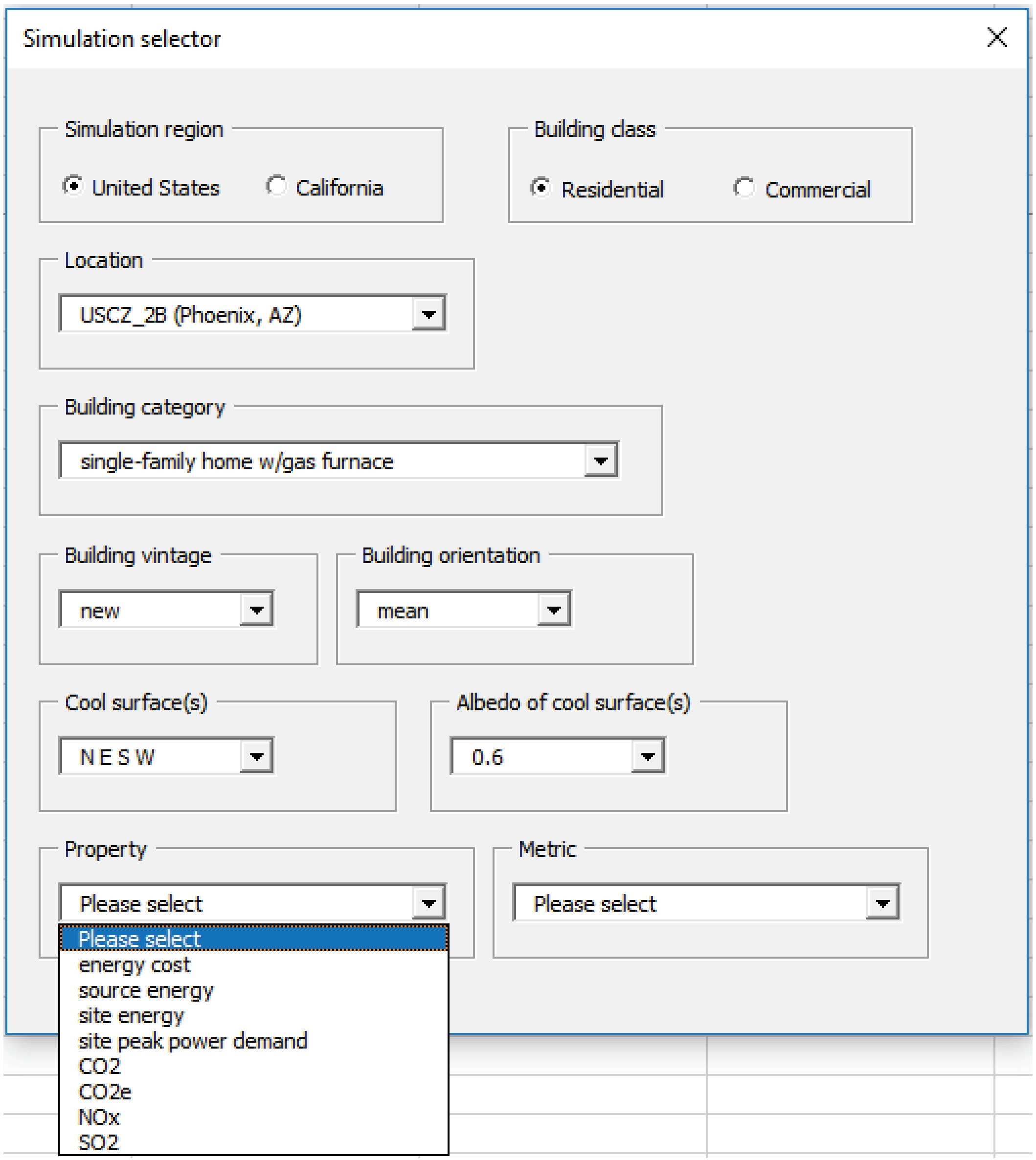

Figure 28. Properties that can be reported.

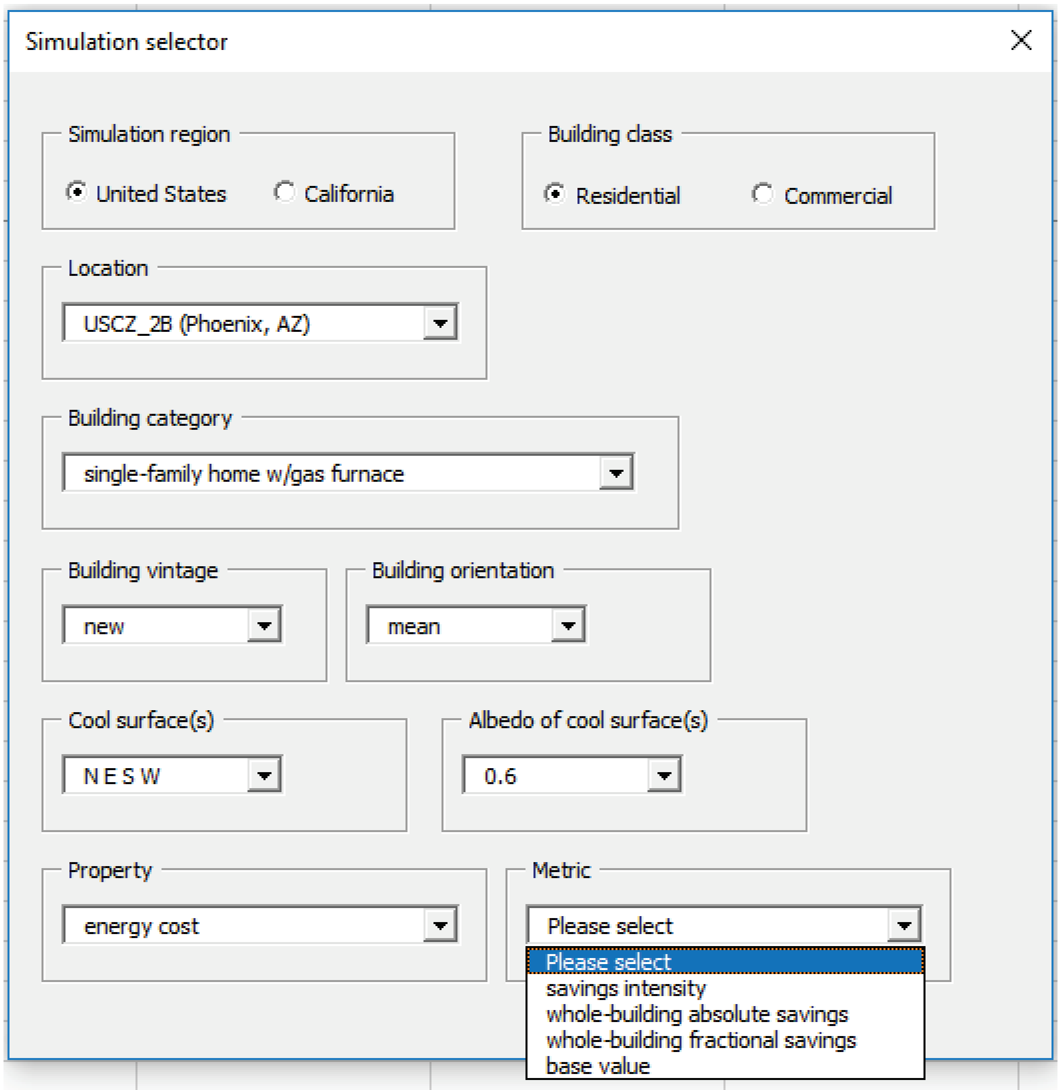

Figure 29. Metrics that can be reported.

Once all selections are complete, the Explorer will then filter the Database and copy simulation parameters and results to columns A and B of the Explorer sheet (Figure 30).

Revising choices within the Selector will update the parameters and results shown in columns A and B. Clearing any selection—i.e., directly or indirectly changing it to “Please select”—will clear the parameters and results displayed in columns A and B.

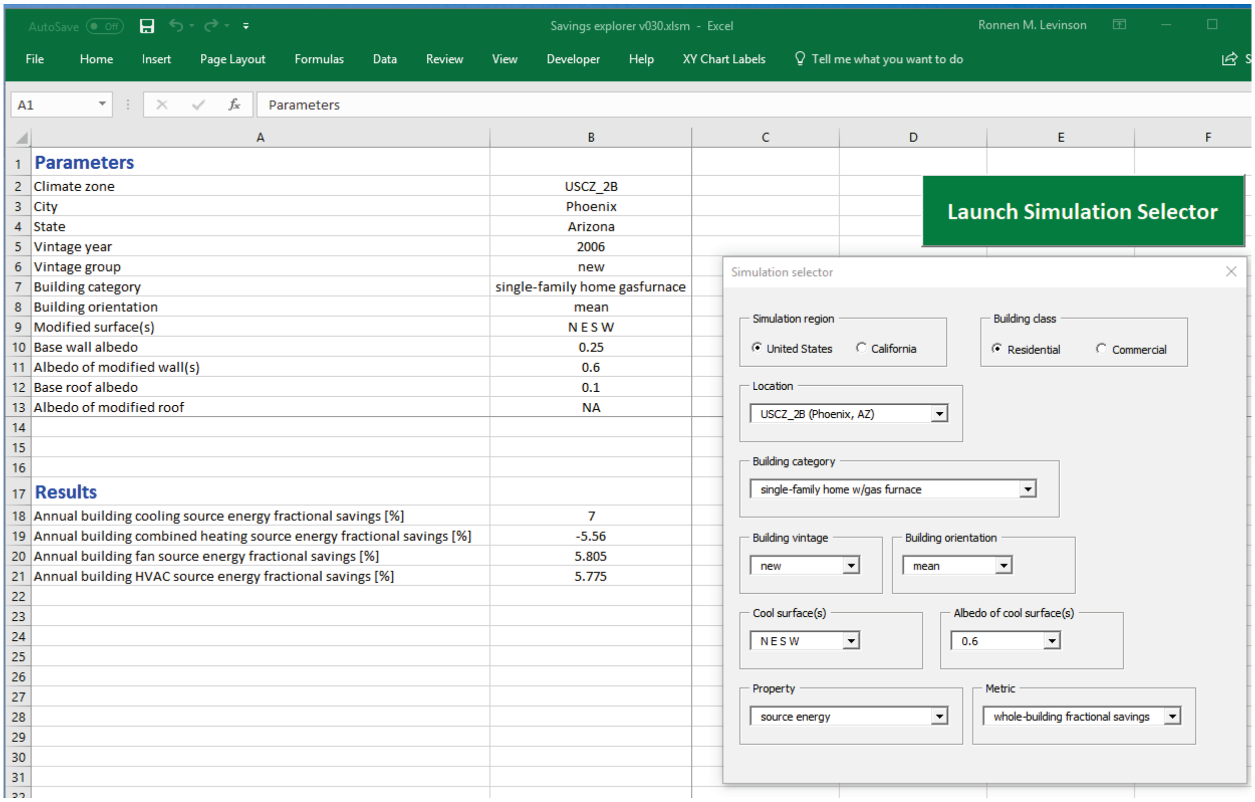

Figure 30. Explorer window displays database entries in columns A and B after parameter selection is complete.

4.2.1 Example 1: Whole-building source energy savings fractions for a new single-family home w/gas furnace in Phoenix, AZ, upon raising albedos of all four walls to 0.60 from 0.25

Configuring the Selector as shown in Figure 31 returns the whole-building energy saving fractions shown in cells A18 – B21 of Figure 32.

Observe that the simulation parameters listed in cells A1 – B13 include some not explicitly specified within the Selector, including vintage year (2006), which is set according to vintage group (new) and state (Arizona); base wall albedo (0.25), which is universal; base roof albedo (0.1), which is set according to building class (residential); and albedo of modified roof (NA), which is not applicable here because the roof's albedo was not modified in this simulation.

Raising wall albedo lowers whole-building cooling, heating, fan, and HVAC (cooling + heating + fan) annual source energy uses by 7.0%, -5.6%, 5.8%, and 5.8%, respectively. Note that "combined heating" sums all modes of heating used in the building (gas and/or electric).

4.2.2 Example 2: Site energy savings intensities for the building considered in Example 1

A useful application of the Explorer is to retrieve the site energy savings, which can be used to calculate energy cost, source energy, or emission savings for energy prices, source energy factors, or emission factors other than those assumed in our study.

Configuring the Selector as shown in Figure 33 returns the site energy savings intensities shown in cells A18 – B21 of Figure 34.

Raising wall albedo yields cooling, gas heating, electric heating, and fan annual site energy savings intensities of 4.791 kWh/m², -0.043 therms/m², 0 kWh/m², and 0.875 kWh/m².

To compute new energy cost, source energy, or emission savings, it is convenient to sum the component annual site electricity savings (cooling, electric heating, and fan) to obtain HVAC annual site electricity savings. Here the HVAC annual electricity savings intensity is 4.791 (cooling) + 0 (electric heating) + 0.875 (fan) = 5.666 kWh/m², and the HVAC annual site gas savings intensity is (gas heating) are -0.043 therms/m².

To obtain annual energy cost savings intensity, we sum the product of the annual site electricity savings intensity and the local electricity price and the product of the annual site gas savings intensity and the local gas price. If electricity costs $0.12/kWh and gas costs $1.50/therm, the HVAC annual energy cost savings intensity will be 5.666 kWh/m² × 0.12/kWh – 0.043 therms/m² × $1.50/therm = $0.615/m².

Computing source energy or emission savings from site energy savings is analogous. Please see the Task 2.1 report: *Simulated HVAC energy savings in an isolated building* for information about energy prices, source energy factors, and emission factors.

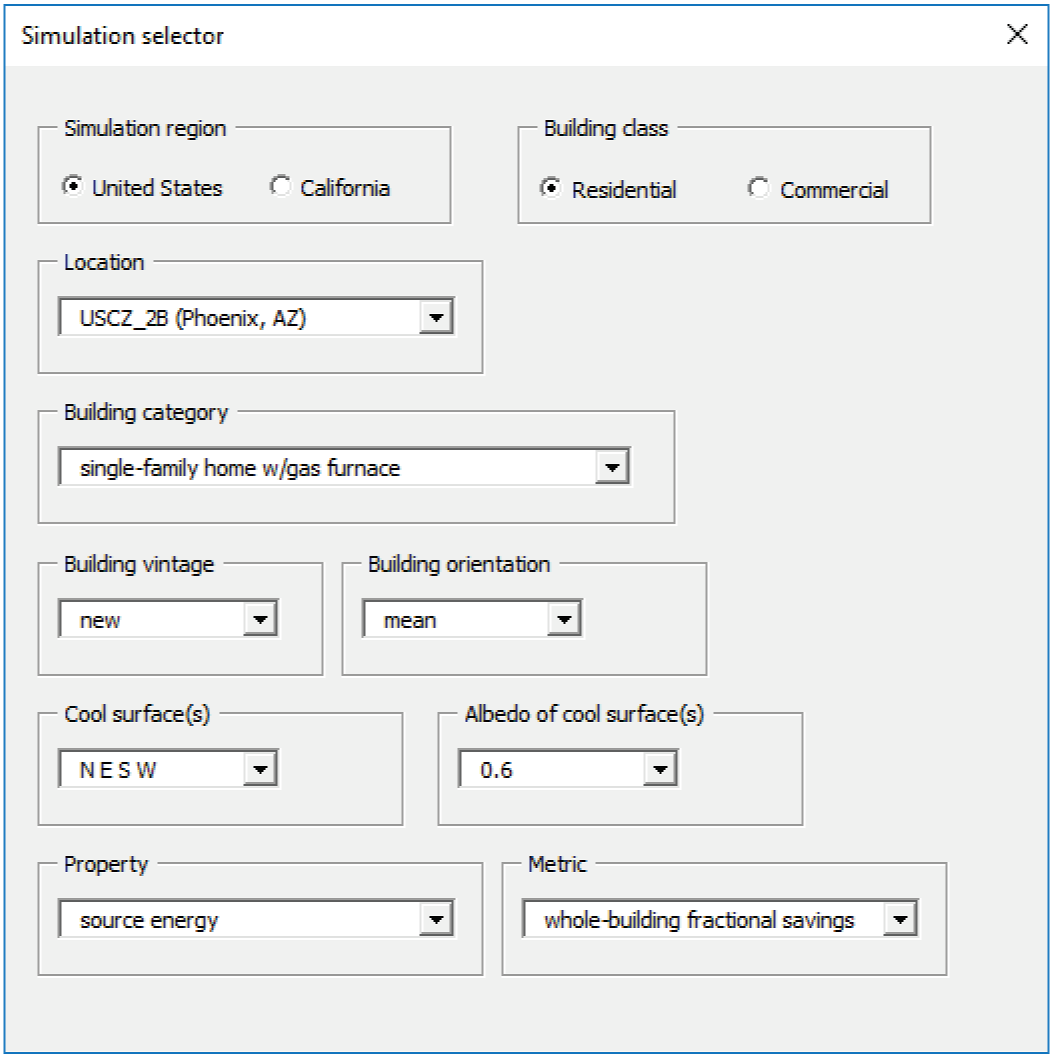

Figure 31. Close-up of Figure 30 showing Selector settings used to obtain whole-building source energy fractional savings for a new single-family home w/gas furnace in Phoenix, AZ (U.S. climate 2B) upon raising the albedo of all walls to 0.60 from the baseline of 0.25. Choosing “mean” building orientation averages results obtained for north-south and east-west orientations of the building’s long axis.

	A	B
1	**Parameters**	
2	Climate zone	USCZ_2B
3	City	Phoenix
4	State	Arizona
5	Vintage year	2006
6	Vintage group	new
7	Building category	single-family home gasfurnace
8	Building orientation	mean
9	Modified surface(s)	N E S W
10	Base wall albedo	0.25
11	Albedo of modified wall(s)	0.6
12	Base roof albedo	0.1
13	Albedo of modified roof	NA
14		
15		
16		
17	**Results**	
18	Annual building cooling source energy fractional savings [%]	7
19	Annual building combined heating source energy fractional savings [%]	-5.56
20	Annual building fan source energy fractional savings [%]	5.805
21	Annual building HVAC source energy fractional savings [%]	5.775

Figure 32. Close-up of Figure 30 showing whole-building source energy fractional savings for a new single-family home w/gas furnace in Phoenix, AZ (U.S. climate 2B) upon raising the albedo of all walls to 0.60 from the baseline of 0.25.

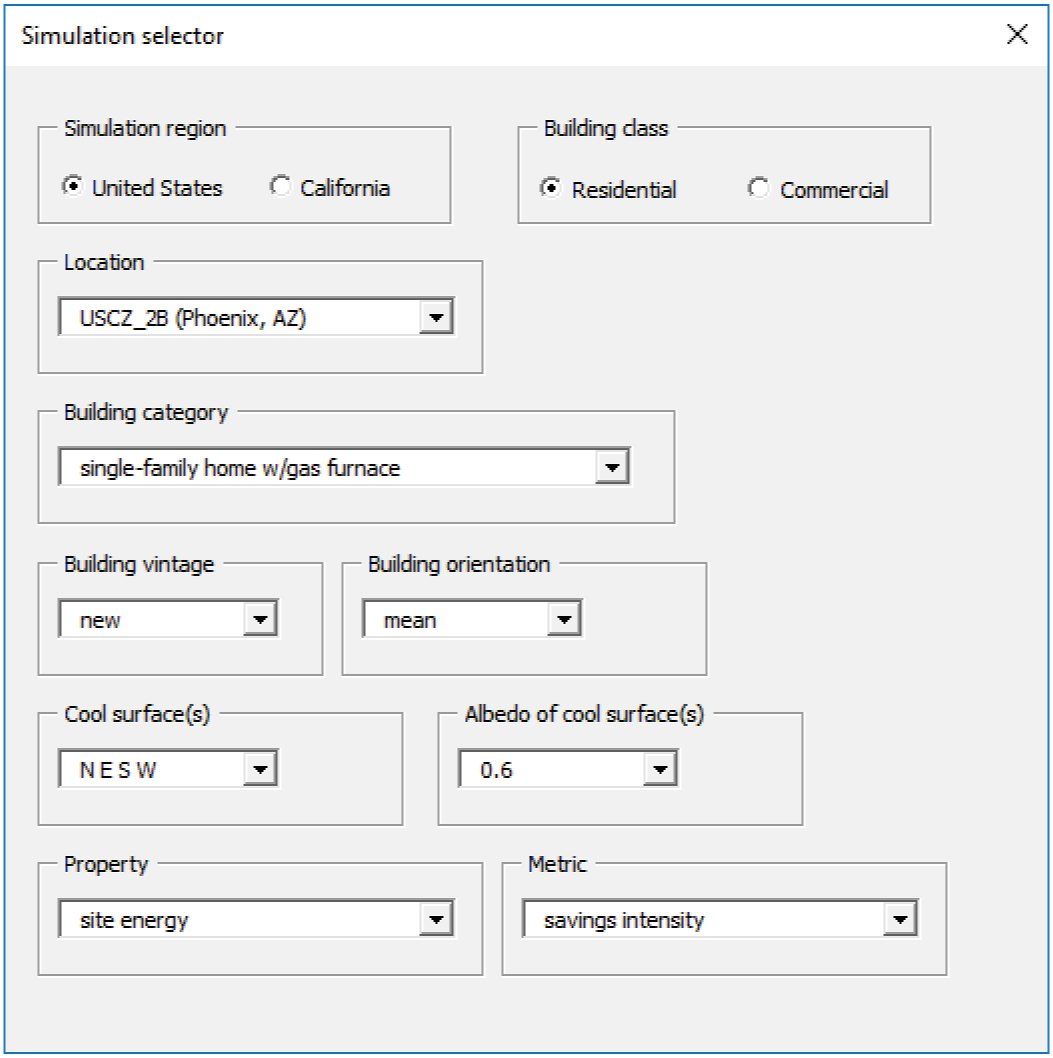

Figure 33. Selector settings to obtain site energy savings intensities for a new single-family home w/gas furnace in Phoenix, AZ (U.S. climate 2B) upon raising the albedo of all walls to 0.60 from the baseline of 0.25.

	A	B
1	**Parameters**	
2	Climate zone	USCZ_2B
3	City	Phoenix
4	State	Arizona
5	Vintage year	2006
6	Vintage group	new
7	Building category	single-family home gasfurnace
8	Building orientation	mean
9	Modified surface(s)	N E S W
10	Base wall albedo	0.25
11	Albedo of modified wall(s)	0.6
12	Base roof albedo	0.1
13	Albedo of modified roof	NA
14		
15		
16		
17	**Results**	
18	Annual cooling site energy absolute savings intensity [kWh/m2]	4.791
19	Annual gas heating site energy absolute savings intensity [therms/m2]	-0.043
20	Annual electric heating site energy absolute savings intensity [kWh/m2]	0
21	Annual fan site energy absolute savings intensity [kWh/m2]	0.875

Figure 34. Site energy savings intensities for a single-family home w/gas furnace in Phoenix, AZ (U.S. climate 2B) upon raising the albedo of all walls to 0.60 from the baseline of 0.25.

5 Adjusting cool wall effects to account for neighboring buildings

The solar availability (incident solar radiation) for a central (modeled) building can be reduced by shadows cast by neighboring buildings, and increased by sunlight reflected from neighboring buildings. The solar availability factor (SAF) of a central building wall, defined as the ratio of sunlight incident on the central building wall in the presence of the neighboring wall to that incident in the absence of the neighboring wall, can be used to scale the cool-wall savings simulated for an isolated central building (no neighbors).

This approach emphasizes simplicity, so that its results can be applied knowing only the canyon aspect ratio R (ratio of building height H to building separation W), city, and month. It assumes that the central building and its neighbors are of equal height, and does not consider shading or reflection by surfaces other than neighboring walls, such as trees. The theory and calculation of SAF is detailed in the Task 2.3 report: *Using solar availability to adjust HVAC energy savings.*

To obtain the solar availability factor for a central wall, first calculate its canyon aspect ratio $R = H/W$. Our guidelines focus on results for the four aspect ratios drawn to scale in Figure 35:

- R=0.2, representing two-story single-family homes across a residential street (H=6 m, W=30 m);
- R=1, representing two-story single-family across small back yards (H=6 m, W=6 m);
- R=2, representing adjacent two-story single-family homes on the same side of a street (H=6 m, W=3 m); and
- R=10, representing adjacent 10-story office buildings on the same side of the street (H=30 m, W=3 m).

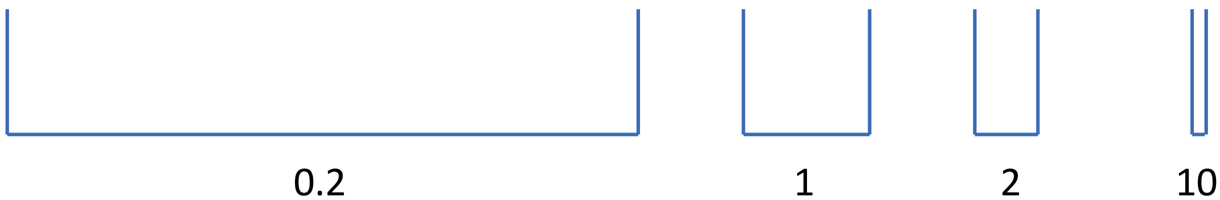

Figure 35. Canyon aspect ratio $R = H/W$ = 0.2, 1, 2, or 10.

Figure 36 illustrates variation with central wall orientation (N, E, S, or W) and aspect ratio (0.2, 1, 2, or 10) of monthly SAF in Fresno, CA when the central and neighboring walls each have albedo 0.25. For greatest accuracy, we would apply the cooling-season mean SAF to cooling energy savings, the heating-season mean SAF to heating energy savings, and the annual mean SAF to fan energy savings. However, that requires inspection of the polar plots and details of the local heating and cooling season.

We can trade accuracy for simplicity by applying the annual average SAF to all savings. This strategy works best when monthly SAF varies little over the course of the year, and less well if there are strong seasonal variations.

Table 31 reports for all 17 climates shown in Figure 18 the annual mean, minimum, maximum, and range (maximum – minimum) values of monthly SAF for conventional central and neighboring walls by climate, central wall orientation, and aspect ratio.

For the Fresno single-family home scenario in Section 3.4.2, we take the annual mean SAF for the east wall (R = 0.2) from Table 31a; the annual mean SAF for the west wall (R = 1) from Table 31b; and the annual mean SAFs for north and south walls (R = 2) from Table 31c. The application of SAF to scale savings is worked in Section 3.4.2.

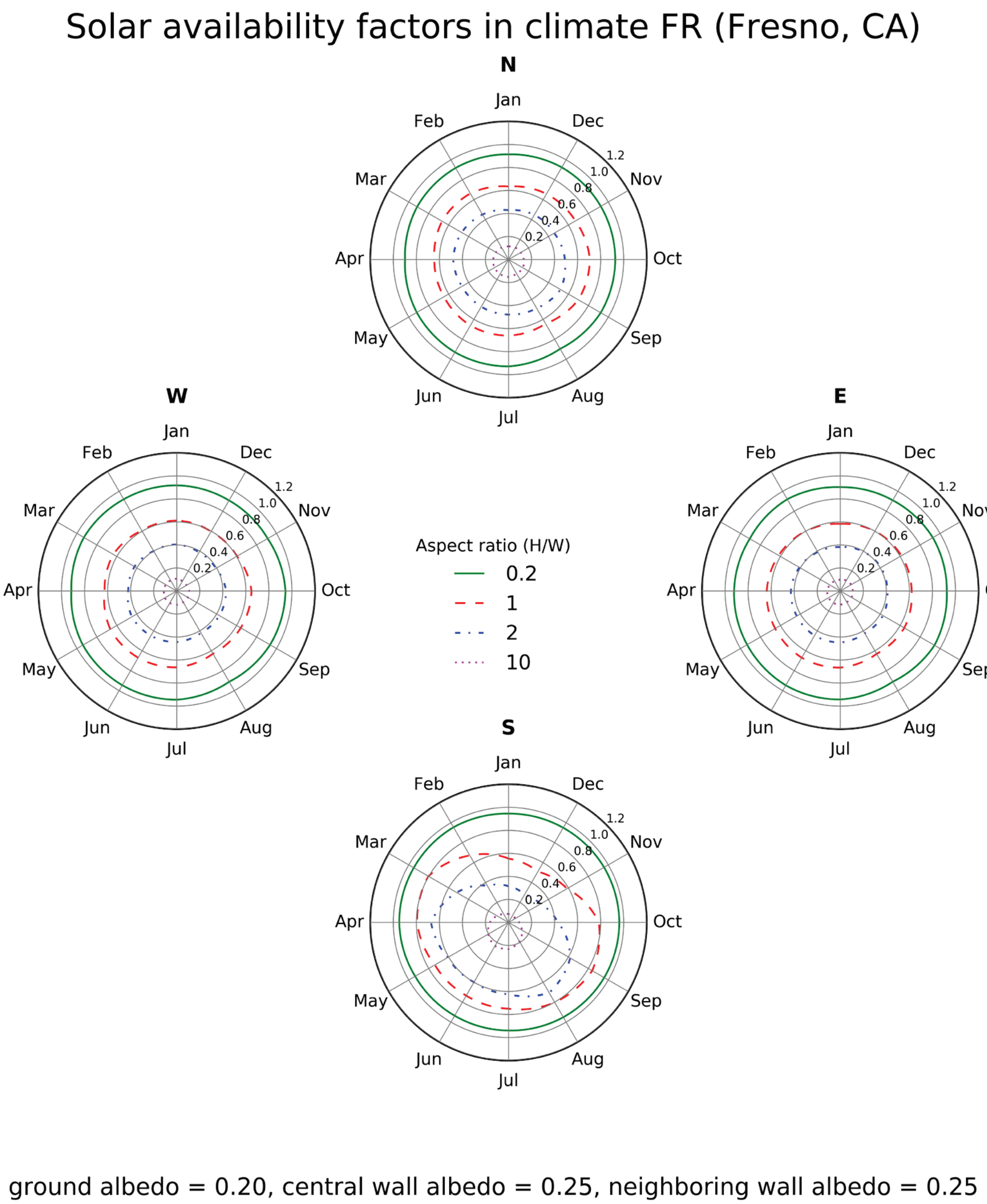

Figure 36. Monthly SAFs for a north (N), east (E), south (S), or west (W) conventional central wall (ρ=0.25) with conventional neighboring wall (ρ=0.25). Results shown for aspect ratios 0.2, 1, 2, and 10 in Fresno, CA.

Table 31. Annual mean, minimum, maximum, and range (maximum – minimum) values of monthly SAF for a north (N), east (E), south (S), or west (W) conventional central wall (ρ=0.25) with a conventional neighboring wall (ρ=0.25). Results shown by climate for aspect ratios of (a) R=0.2, (b) R=1, (c) R=2, and (d) R=10.

(a) aspect ratio R=0.2

	N				E				S				W			
	mean	min	max	range	mean	min	max	range	mean	min	max	range	mean	min	max	range
1A (Miami, FL)	0.91	0.91	0.92	0.02	0.92	0.89	0.94	0.05	0.93	0.91	0.96	0.05	0.91	0.84	0.94	0.10
2A (Houston, TX)	0.91	0.89	0.92	0.03	0.91	0.86	0.94	0.07	0.93	0.91	0.95	0.04	0.91	0.86	0.93	0.07
2B (Phoenix, AZ)	0.92	0.86	0.95	0.09	0.91	0.87	0.95	0.08	0.95	0.93	0.97	0.04	0.92	0.88	0.95	0.06
3A (Memphis, TN)	0.92	0.90	0.93	0.03	0.92	0.85	0.94	0.08	0.94	0.92	0.96	0.04	0.91	0.84	0.94	0.10
3B (El Paso, TX)	0.93	0.91	0.95	0.04	0.94	0.88	0.96	0.07	0.95	0.93	0.97	0.04	0.93	0.90	0.94	0.04
BU (Burbank, CA)	0.92	0.91	0.94	0.03	0.93	0.89	0.94	0.06	0.95	0.93	0.96	0.04	0.93	0.90	0.95	0.05
FR (Fresno, CA)	0.92	0.90	0.93	0.03	0.92	0.90	0.95	0.04	0.95	0.94	0.96	0.03	0.93	0.91	0.95	0.04
3C (San Francisco, CA)	0.91	0.88	0.94	0.06	0.92	0.87	0.94	0.07	0.95	0.93	0.96	0.03	0.92	0.89	0.94	0.05
4A (Baltimore, MD)	0.91	0.88	0.93	0.06	0.90	0.74	0.94	0.19	0.94	0.91	0.96	0.05	0.90	0.83	0.93	0.10
4B (Albuquerque, NM)	0.93	0.88	0.97	0.09	0.92	0.87	0.95	0.08	0.95	0.93	0.97	0.03	0.92	0.89	0.95	0.06
4C (Seattle, WA)	0.91	0.90	0.92	0.03	0.91	0.85	0.94	0.08	0.94	0.91	0.96	0.05	0.90	0.82	0.93	0.12
5A (Chicago, IL)	0.91	0.91	0.93	0.02	0.91	0.86	0.94	0.08	0.94	0.92	0.95	0.03	0.91	0.84	0.94	0.10
5B (Boise, ID)	0.92	0.90	0.94	0.03	0.91	0.86	0.94	0.08	0.95	0.92	0.96	0.04	0.91	0.86	0.95	0.09
6A (Burlington, VT)	0.91	0.87	0.93	0.06	0.90	0.82	0.93	0.11	0.94	0.90	0.95	0.05	0.90	0.85	0.93	0.08
6B (Helena, MT)	0.92	0.88	0.94	0.06	0.91	0.86	0.94	0.08	0.95	0.91	0.96	0.05	0.90	0.80	0.95	0.15
7 (Duluth, MN)	0.91	0.86	0.93	0.07	0.90	0.83	0.94	0.11	0.94	0.91	0.96	0.05	0.90	0.84	0.94	0.10
8 (Fairbanks, AK)	0.88	0.77	0.94	0.16	0.77	0.56	0.92	0.36	0.79	0.24	0.96	0.72	0.91	0.70	0.94	0.24

Table 31 (continued)

(b) aspect ratio R=1

	N				E				S				W			
	mean	min	max	range	mean	min	max	range	mean	min	max	range	mean	min	max	range
1A (Miami, FL)	0.65	0.62	0.69	0.08	0.63	0.59	0.66	0.07	0.70	0.61	0.80	0.19	0.63	0.57	0.66	0.09
2A (Houston, TX)	0.65	0.61	0.69	0.07	0.62	0.57	0.66	0.09	0.70	0.59	0.80	0.21	0.62	0.57	0.66	0.09
2B (Phoenix, AZ)	0.68	0.61	0.75	0.14	0.61	0.56	0.65	0.09	0.72	0.54	0.83	0.30	0.62	0.57	0.67	0.10
3A (Memphis, TN)	0.66	0.63	0.69	0.06	0.62	0.56	0.67	0.10	0.69	0.50	0.80	0.29	0.61	0.55	0.67	0.12
3B (El Paso, TX)	0.69	0.65	0.75	0.10	0.64	0.60	0.69	0.09	0.73	0.57	0.82	0.26	0.63	0.58	0.69	0.11
BU (Burbank, CA)	0.68	0.64	0.72	0.08	0.63	0.59	0.68	0.10	0.71	0.53	0.82	0.29	0.64	0.58	0.69	0.11
FR (Fresno, CA)	0.66	0.63	0.71	0.07	0.63	0.58	0.67	0.09	0.71	0.51	0.84	0.33	0.63	0.60	0.67	0.07
3C (San Francisco, CA)	0.66	0.62	0.69	0.07	0.63	0.56	0.68	0.12	0.70	0.47	0.83	0.36	0.63	0.58	0.66	0.09
4A (Baltimore, MD)	0.65	0.61	0.69	0.08	0.60	0.47	0.65	0.19	0.67	0.44	0.81	0.36	0.60	0.54	0.65	0.12
4B (Albuquerque, NM)	0.70	0.62	0.77	0.15	0.61	0.55	0.67	0.11	0.71	0.51	0.83	0.32	0.62	0.56	0.69	0.13
4C (Seattle, WA)	0.64	0.62	0.67	0.05	0.60	0.55	0.65	0.11	0.64	0.37	0.80	0.42	0.59	0.51	0.65	0.14
5A (Chicago, IL)	0.64	0.63	0.67	0.04	0.60	0.53	0.64	0.12	0.65	0.42	0.80	0.38	0.61	0.53	0.65	0.12
5B (Boise, ID)	0.67	0.64	0.72	0.08	0.59	0.51	0.65	0.13	0.68	0.39	0.85	0.46	0.60	0.53	0.66	0.14
6A (Burlington, VT)	0.63	0.59	0.66	0.07	0.59	0.52	0.64	0.12	0.65	0.39	0.78	0.40	0.59	0.53	0.64	0.11
6B (Helena, MT)	0.66	0.63	0.70	0.06	0.59	0.51	0.64	0.14	0.64	0.34	0.82	0.48	0.58	0.47	0.65	0.18
7 (Duluth, MN)	0.64	0.59	0.67	0.08	0.58	0.50	0.64	0.13	0.63	0.35	0.80	0.45	0.58	0.52	0.63	0.12
8 (Fairbanks, AK)	0.60	0.49	0.66	0.17	0.42	0.25	0.56	0.31	0.47	0.10	0.79	0.69	0.58	0.36	0.64	0.27

Table 31 (continued)

(c) aspect ratio R=2

	N				E				S				W			
	mean	min	max	range	mean	min	max	range	mean	min	max	range	mean	min	max	range
1A (Miami, FL)	0.45	0.43	0.48	0.05	0.42	0.39	0.44	0.06	0.48	0.36	0.62	0.26	0.42	0.38	0.45	0.07
2A (Houston, TX)	0.45	0.43	0.48	0.06	0.42	0.38	0.44	0.07	0.47	0.32	0.63	0.31	0.41	0.37	0.45	0.07
2B (Phoenix, AZ)	0.49	0.44	0.52	0.08	0.41	0.37	0.44	0.07	0.51	0.28	0.70	0.42	0.41	0.36	0.45	0.09
3A (Memphis, TN)	0.46	0.44	0.48	0.03	0.41	0.37	0.45	0.08	0.47	0.27	0.63	0.36	0.41	0.36	0.45	0.10
3B (El Paso, TX)	0.50	0.46	0.53	0.07	0.42	0.39	0.46	0.07	0.51	0.30	0.68	0.38	0.42	0.38	0.47	0.09
BU (Burbank, CA)	0.48	0.45	0.50	0.05	0.42	0.38	0.47	0.08	0.50	0.28	0.67	0.39	0.43	0.38	0.47	0.09
FR (Fresno, CA)	0.47	0.43	0.52	0.09	0.42	0.38	0.45	0.07	0.50	0.28	0.71	0.43	0.42	0.39	0.45	0.06
3C (San Francisco, CA)	0.46	0.44	0.50	0.06	0.42	0.36	0.47	0.11	0.48	0.26	0.66	0.41	0.42	0.37	0.45	0.07
4A (Baltimore, MD)	0.46	0.43	0.47	0.05	0.40	0.30	0.44	0.14	0.45	0.24	0.62	0.38	0.40	0.34	0.44	0.10
4B (Albuquerque, NM)	0.50	0.45	0.54	0.09	0.41	0.36	0.45	0.09	0.50	0.26	0.68	0.42	0.41	0.36	0.47	0.11
4C (Seattle, WA)	0.44	0.42	0.46	0.04	0.40	0.35	0.44	0.09	0.43	0.21	0.65	0.44	0.39	0.33	0.44	0.11
5A (Chicago, IL)	0.45	0.43	0.46	0.02	0.40	0.34	0.43	0.09	0.44	0.23	0.60	0.37	0.40	0.34	0.44	0.10
5B (Boise, ID)	0.47	0.43	0.52	0.09	0.39	0.33	0.43	0.10	0.47	0.21	0.69	0.48	0.39	0.34	0.45	0.10
6A (Burlington, VT)	0.44	0.42	0.46	0.04	0.39	0.33	0.42	0.09	0.44	0.22	0.60	0.38	0.39	0.34	0.43	0.08
6B (Helena, MT)	0.46	0.44	0.49	0.04	0.38	0.32	0.42	0.10	0.44	0.18	0.69	0.50	0.37	0.29	0.43	0.14
7 (Duluth, MN)	0.45	0.43	0.47	0.04	0.38	0.32	0.42	0.10	0.43	0.20	0.63	0.43	0.38	0.33	0.42	0.09
8 (Fairbanks, AK)	0.40	0.33	0.45	0.12	0.26	0.15	0.36	0.20	0.28	0.06	0.51	0.45	0.38	0.23	0.42	0.19

Table 31 (continued)

(d) aspect ratio R=10

	N				E				S				W			
	mean	min	max	range	mean	min	max	range	mean	min	max	range	mean	min	max	range
1A (Miami, FL)	0.13	0.12	0.13	0.01	0.11	0.10	0.11	0.02	0.13	0.08	0.19	0.11	0.11	0.10	0.12	0.02
2A (Houston, TX)	0.13	0.12	0.13	0.01	0.11	0.09	0.11	0.02	0.13	0.07	0.18	0.11	0.11	0.09	0.11	0.02
2B (Phoenix, AZ)	0.14	0.14	0.14	0.01	0.10	0.09	0.11	0.02	0.14	0.06	0.25	0.19	0.10	0.09	0.11	0.03
3A (Memphis, TN)	0.13	0.12	0.13	0.01	0.11	0.10	0.12	0.03	0.13	0.06	0.19	0.13	0.11	0.09	0.12	0.03
3B (El Paso, TX)	0.14	0.14	0.16	0.02	0.11	0.10	0.12	0.03	0.15	0.06	0.25	0.18	0.11	0.10	0.13	0.03
BU (Burbank, CA)	0.14	0.12	0.15	0.02	0.11	0.10	0.13	0.03	0.14	0.06	0.23	0.17	0.11	0.09	0.12	0.03
FR (Fresno, CA)	0.13	0.11	0.15	0.04	0.11	0.10	0.12	0.02	0.14	0.06	0.24	0.17	0.11	0.10	0.12	0.02
3C (San Francisco, CA)	0.13	0.12	0.14	0.02	0.11	0.09	0.12	0.03	0.13	0.06	0.21	0.16	0.11	0.10	0.12	0.02
4A (Baltimore, MD)	0.13	0.12	0.13	0.01	0.10	0.07	0.11	0.04	0.12	0.05	0.19	0.14	0.10	0.09	0.12	0.03
4B (Albuquerque, NM)	0.14	0.13	0.15	0.02	0.10	0.09	0.12	0.03	0.14	0.06	0.25	0.19	0.11	0.09	0.13	0.04
4C (Seattle, WA)	0.12	0.11	0.13	0.02	0.10	0.09	0.11	0.03	0.10	0.05	0.16	0.11	0.10	0.09	0.12	0.03
5A (Chicago, IL)	0.12	0.11	0.13	0.01	0.10	0.09	0.11	0.03	0.11	0.05	0.18	0.13	0.10	0.09	0.12	0.03
5B (Boise, ID)	0.13	0.11	0.14	0.03	0.10	0.09	0.11	0.03	0.11	0.05	0.20	0.15	0.10	0.08	0.12	0.03
6A (Burlington, VT)	0.12	0.11	0.12	0.01	0.10	0.09	0.11	0.03	0.11	0.05	0.16	0.11	0.10	0.08	0.11	0.03
6B (Helena, MT)	0.13	0.12	0.14	0.02	0.09	0.08	0.10	0.02	0.10	0.04	0.18	0.14	0.09	0.08	0.11	0.03
7 (Duluth, MN)	0.12	0.11	0.13	0.01	0.10	0.08	0.11	0.03	0.10	0.04	0.16	0.12	0.10	0.08	0.11	0.03
8 (Fairbanks, AK)	0.11	0.09	0.12	0.03	0.06	0.04	0.09	0.05	0.06	0.02	0.12	0.10	0.10	0.06	0.11	0.05

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