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Potential benefits of cool roofs on commercial buildings: conserving energy, saving money, and reducing emission of greenhouse gases and air pollutants

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Abstract Cool roofs—roofs that stay cool in the sun by minimizing solar absorption and maximizing thermal emission—lessen the flow of heat from the roof into the building, reducing the need for space cooling energy in conditioned buildings. Cool roofs may also increase the need for heating energy in cold climates. For a commercial building, the decrease in annual cooling load is typically much greater than the increase in annual heating load. This study combines building energy simulations, local energy prices, local electricity emission factors, and local estimates of building density to characterize local, state average, and national average cooling energy savings, heating energy penalties, energy cost savings, and emission reductions per unit conditioned roof area. The annual heating and cooling energy uses of four commercial building prototypes—new office (1980+), old office (pre-1980), new retail (1980+), and old retail (pre-1980)—were simulated in 236 US cities. Substituting a weathered cool white roof (solar reflectance 0.55) for a weathered conventional gray roof (solar reflectance 0.20) yielded annually a cooling energy saving per unit conditioned roof area ranging from 3.30 kWh/m^2 in Alaska to 7.69 kWh/m^2 in Arizona (5.02 kWh/m^2 nationwide); a heating energy penalty ranging from 0.003 therm/m^2 in Hawaii to 0.14 therm/m^2 in Wyoming (0.065 therm/m^2 nationwide); and an energy cost saving ranging from \$0.126/m^2 in West Virginia to \$1.14/m^2 in Arizona (\$0.356/m^2 nationwide). It also offered annually a CO_2 reduction ranging from 1.07 kg/m^2 in Alaska to 4.97 kg/m^2 in Hawaii (3.02 kg/m^2 nationwide); an NO_x reduction ranging from 1.70 g/m^2 in New York to 11.7 g/m^2 in Hawaii (4.81 g/m^2 nationwide); an SO_2 reduction ranging from 1.79 g/m^2 in California to 26.1 g/m^2 in Alabama (12.4 g/m^2 nationwide); and an Hg reduction ranging from 1.08 μg/m^2 in Alaska to 105 μg/m^2 in Alabama (61.2 μg/m^2 nationwide). Retrofitting 80% of the 2.58 billion square meters of commercial building conditioned roof area in the USA would yield an annual cooling energy saving of 10.4 TWh; an annual heating energy penalty of 133 million therms; and an annual energy cost saving of \$735 million. It would also offer an annual CO_2 reduction of 6.23 Mt, offsetting the annual CO_2 emissions of 1.20 million typical cars or 25.4 typical peak power plants; an annual NO_x reduction of 9.93 kt, offsetting the annual NO_x emissions of 0.57 million cars or 65.7 peak power plants; an annual SO_2 reduction of 25.6 kt, offsetting the annual SO_2 emissions of 815 peak power plants; and an annual Hg reduction of 126 kg.

Keywords Air pollution · Building energy simulation · Carbon dioxide · Cool roof · Cooling energy · Energy cost · Greenhouse gas · Heating energy · Mercury · Nitrogen oxides · Solar reflectance · Sulfur dioxide

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Introduction

Roofs that have high solar reflectance (high ability to reflect sunlight, spectrum 0.3–2.5 μm) and high thermal emittance (high ability to emit thermal radiation, spectrum 4–80 μm) stay cool in the sun. Low roof temperatures lessen the flow of heat from the roof into the building, reducing the need for electricity for space cooling in conditioned buildings. Cool roofs may also increase the need for heating energy in cold climates. Since building heat gain through the roof peaks in mid-to-late afternoon, when summer electricity use is highest, cool roofs can reduce peak electricity demand. Measurements in several warm weather climates, including California, Florida, and Texas, typically yielded summertime daily air conditioning savings and peak demand reductions of 10% to 30%, though values have been as low as 2% and as high as 40% (Konopacki et al. 1998). Measured energy savings and peak demand reductions are summarized by Levinson et al. (2005).

The extents to which replacing a conventional (hot) roof with a cool roof will reduce the need for cooling energy and/or increase the need for heating energy depend on building construction, building operation, and climate. Prior research has indicated that net annual energy cost savings are greatest for buildings located in climates with long cooling seasons and short heating seasons, particularly those buildings that have distribution ducts in the plenum (Akbari et al. 1998, 1999; Konopacki and Akbari 1998).

The combustion of fossil fuels in a power plant or building furnace produces greenhouse gases and air pollutants, including but not limited to carbon dioxide (CO_2), nitrogen oxides (NO_x), sulfur dioxide (SO_2), and mercury (Hg). Emission reductions achieved through the use of cool roofs vary with both energy saved and the local mix of fuels used to generate electricity. For example, conserving equal amounts of cooling electricity reduces Hg emissions more in a region served by coal-fired power plants than in an area with natural gas power generation. The net annual energy cost saving also depends on regionally varying energy prices.

The influence of cool roof installation on a building's energy use is proportional to its "conditioned roof area" (CRA), or area of roof over conditioned space. While cooling energy savings and heating energy penalties per unit CRA can be estimated through building energy simulations, local rates of energy savings and penalties per unit land area (LA) depend on building density, or ratio of conditioned roof area to land area. Regional sums, such as state cooling energy savings, are the land area integrals of these per-LA rates.

This study combines building energy simulations, local energy prices, local electricity emission factors (mass of greenhouse gas or air pollutant emitted per unit energy supplied to the grid), and local estimates of building density to characterize local per-CRA and per-LA annual rates of cooling energy saving, heating energy penalty, energy cost saving, and emission reduction in the USA. We also report regional CRAs and regional average per-CRA rates—ratios of regional saving or penalty (land area integral of per-LA rate) to regional CRA—for each US state and for the nation.

Theory

Cooling and heating load changes per unit conditioned roof area

Consider a building with electric cooling and natural gas (hereafter, simply "gas") heating. Installing a cool roof will reduce the building's solar heat gain, decreasing its annual cooling load (amount of heat that must be removed by its cooling equipment) while increasing its annual heating load (amount of heat that must be supplied by its furnace).

The influence of a cool roof on the building's conditioning energy use is quantified in this study by comparing simulations of the building's cooling energy and heating energy uses with a cool roof to those with a conventional roof. Replacing a conventional roof by a more solar-reflective cool roof reduces roof solar heat gain by $\Delta\rho \times A \times I$, where $\Delta\rho$ is the increase in roof solar reflectance, A is the roof area, and I is the solar irradiance. We expect that the local reduction in annual cooling load will be roughly proportional to $\Delta\rho \times A \times R^{-1} \times \overline{I}(x,y) \times C(x,y)$, where R is the thermal resistance of the roof assembly; $\overline{I}(x,y)$ is the local annual mean global horizontal solar irradiance (Fig. 1); $C(x,y)$ is the local number of annual cooling degree days (Fig. 2a); and (x,y) locates the building in a projected (flat) Earth coordinate system. Similarly,

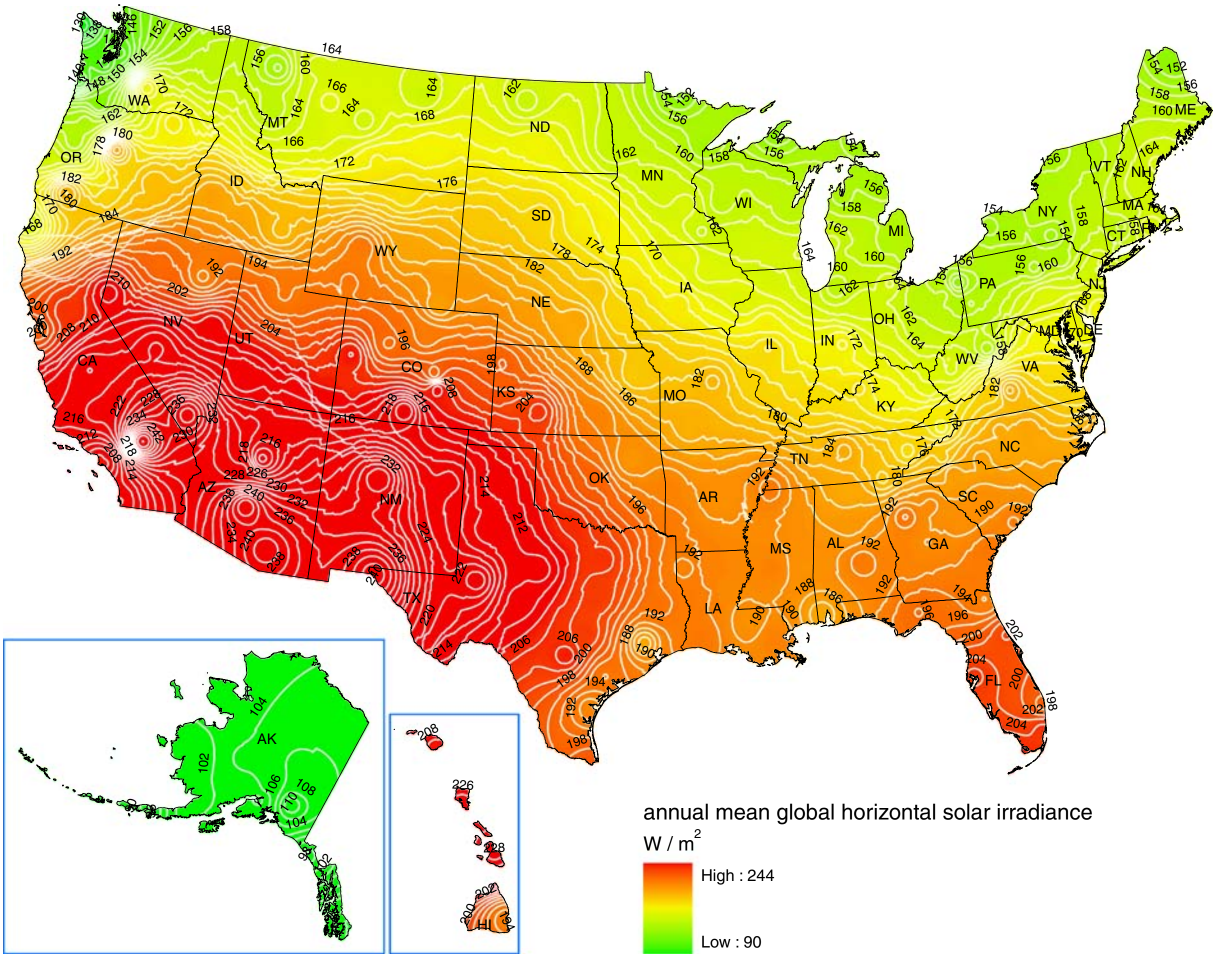


Fig. 1 Annual mean global horizontal solar irradiance (W/m^2) computed from NREL TMY2 typical meteorological year data (NREL 2007)

we expect the local increase in annual heating load to be roughly proportional to $\Delta\rho \times A \times R^{-1} \times \bar{I}(x, y) \times H(x, y)$, where $H(x, y)$ is the local number of annual heating degree days (Fig. 2b).

Cool roof changes to a building's annual cooling and heating loads depend on the thermal resistance and thermal capacity of the roof assembly; the operating schedules of the building and its HVAC system; the efficiencies of the HVAC equipment; and the climate. A cool roof can decrease annual cooling load even in climates with zero nominal (base 18°C) cooling degree days if air conditioning is required to remove the building's solar heat gain and/or internally generated heat. Note also that since there is negligible heat transfer between floors in a conditioned building, roof solar heat gain affects the heat balance of only the top floor in a multi-storey conditioned building. Thus, cool roof energy savings and penalties are proportional to roof area rather than to floor area.

Since the thermal conductivity of roof insulation typically rises with temperature, a cool roof surface can lower the temperature and thus increase the thermal resistance of roof insulation (Levinson et al. 1996). The DOE-2.1E building energy simulations performed for this study incorporate a roof assembly heat transfer module that accounts for this effect (Gartland et al. 1996).

The ratio of annual heating load increase to annual cooling load decrease is a simple measure of the influence of cool roof installation on a building's annual heat balance. If the installation of a cool roof reduces annual cooling energy (electricity) use per CRA by $e(x, y)$ [kWh/area; 1 kWh=3.6 MJ] and increases annual heating energy (gas) use per CRA by

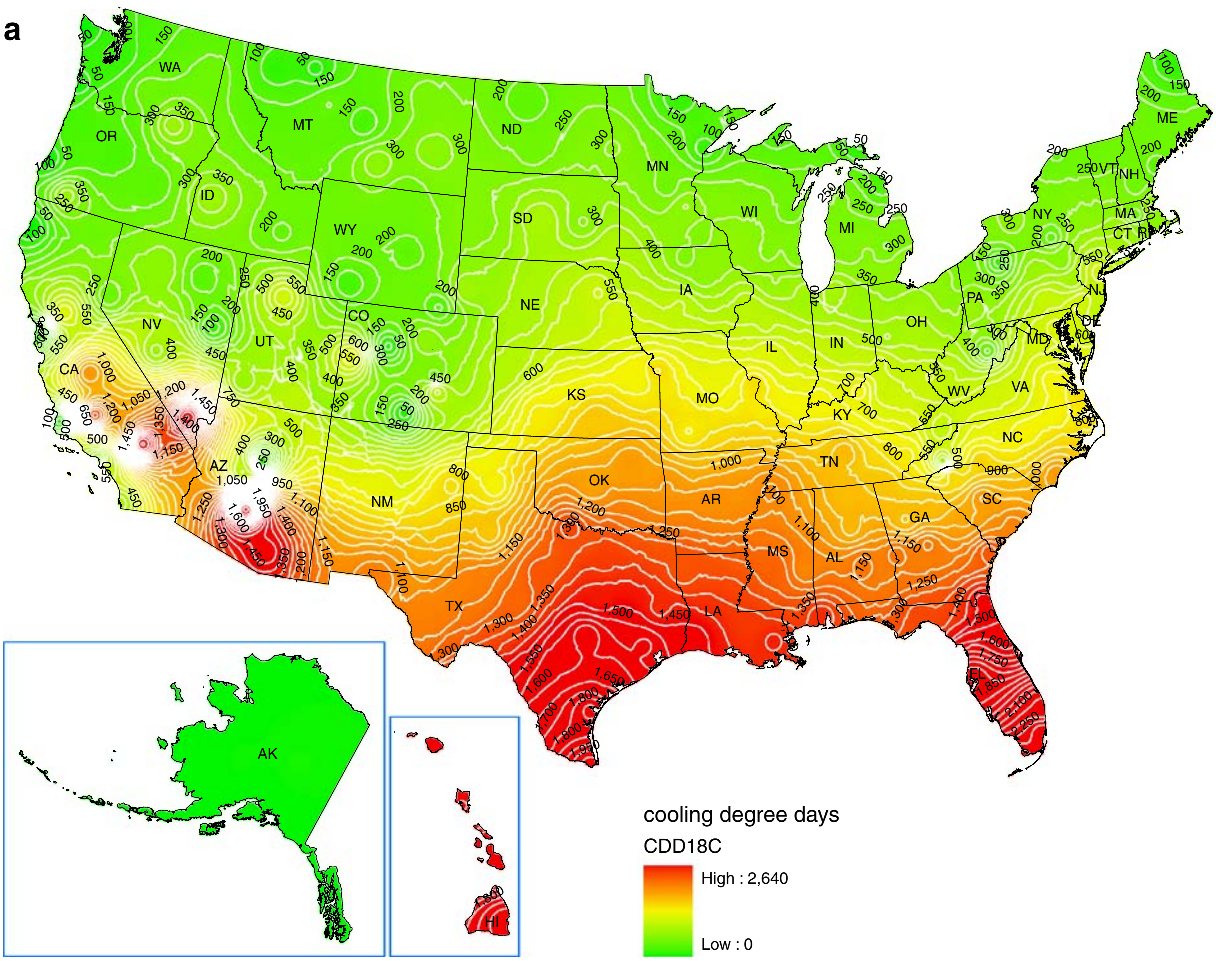


Fig. 2 Maps of **a** annual cooling degree days (CDD18C) and **b** annual heating degree days (HDD18C) computed from NREL TMY2 typical meteorological year data (NREL 2007)

$g(x,\ y)$ [therm/area; 1 therm=105.5 MJ], the dimensionless "load change" ratio is

$$\ell(x,y) = \frac{\eta_\mathrm{h}^{-1}\, g(x,y)}{e(x,y) \times EER \times 0.01\ \mathrm{therm/kBTU}}, \qquad (1)$$

where η_h is the dimensionless efficiency of the heating equipment and *EER* (energy efficiency ratio) is the dimensional coefficient of performance of the cooling equipment [BTU/(h·W); 1 BTU=1.055 kJ].

Fractional cooling energy savings and heating energy penalties

Any single building component is typically responsible for only a small fraction of the building's total energy consumption. For example, increasing the solar reflectance of a roof's surface from $\rho_0 = 0.20$ to $\rho_1 = 0.55$ will reduce the roof's solar heat gain by $(\rho_1 - \rho_0)/(1 - \rho_0) = 44\%$, but will decrease the cooling energy use and increase the heating energy use of a single-storey office or retail building by only about 5–10%. Fractional cool roof cooling energy savings and heating energy penalties are even smaller for multi-storey buildings. However, the cost of a roof reflectance upgrade is also only a small fraction of the total cost of a building. It is simplest to evaluate the economics of a cool roof upgrade by comparing the present value of the building's lifetime energy cost savings to the cost of the upgrade.

Energy cost saving per unit conditioned roof area

The installation of a cool roof yields a per-CRA annual energy cost saving (monetary value of cooling

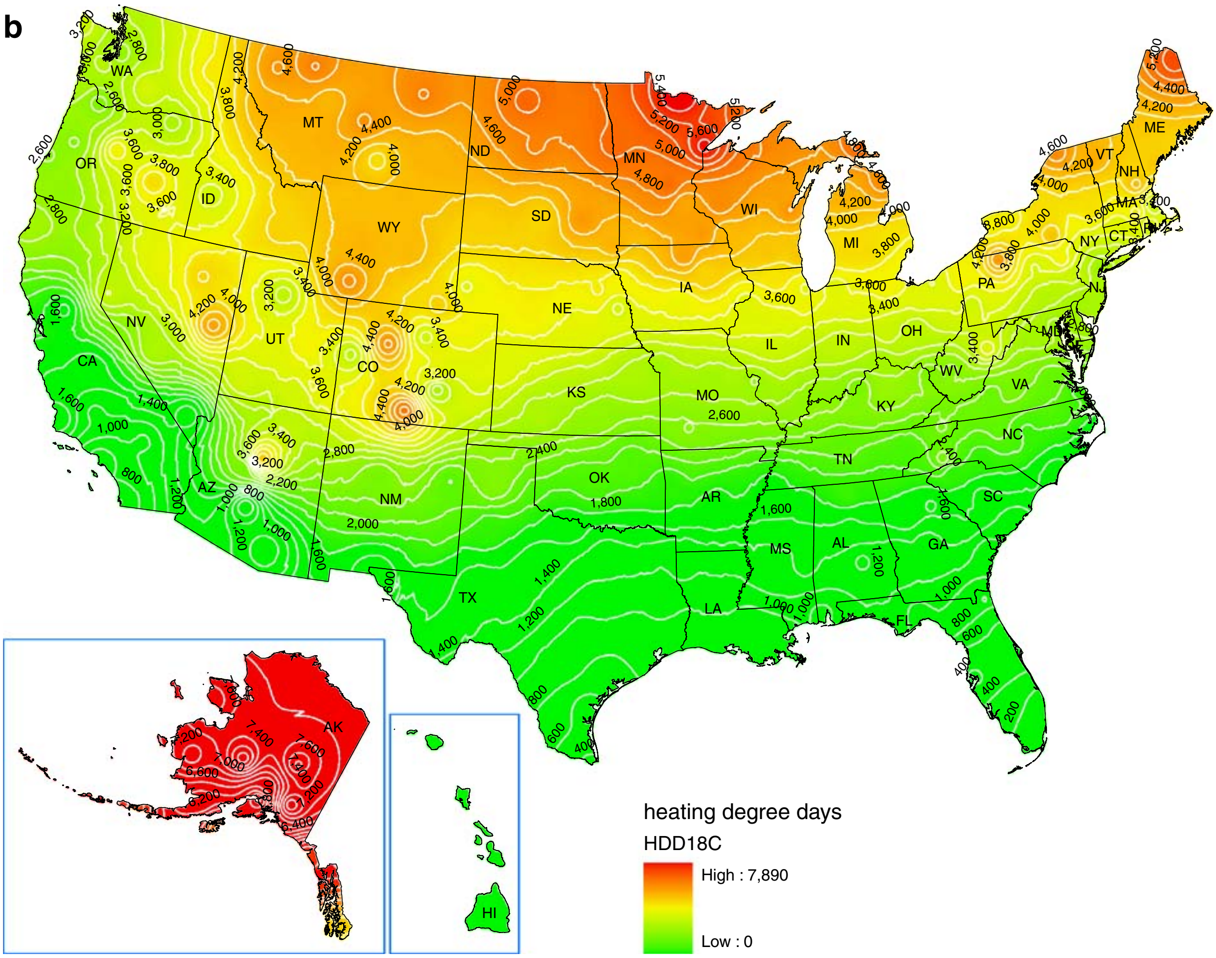


Fig. 2 (continued)

energy saving less monetary value of annual heating energy penalty) of

$$c(x,y) = e(x,y)\ d_{\mathrm{e}}(x,y) - g(x,y)\ d_{\mathrm{g}}(x,y) \tag{2}$$

where $d_{\mathrm{e}}(x,y)$ and $d_{\mathrm{g}}(x,y)$ are the annual average prices of electricity and gas, respectively. This relationship is approximate, since energy prices vary over the course of year.

Life cycle cost saving per unit conditioned roof area

The life cycle cost saving of a cool roof is equal to the present value of its lifetime energy cost savings minus any initial cost premium. The cost premium for choosing a cool white roofing product rather than a conventional roofing product is typically 0 to \$2.20/ m^2 (Levinson et al. 2005). The present value of the lifetime energy cost saving is computed by treating each year's cost savings as an ordinary annuity. Given a real (inflation-adjusted) annual rate of return r, the present value (PV) of N years of constant annual energy cost saving $c(x,\ y)$ is $b \times c(x,\ y)$, where

$$b = \sum_{i=1}^{N} (1+r)^{-i} = \left[1 - (1+r)^{-N}\right] \Big/ r. \tag{3}$$

The PV multiplier b increases with roof lifetime N and decreases with real annual rate of return r (Table 1).

Emission reductions per unit conditioned roof area

If a power plant emits greenhouse gas or air-pollutant i at an annual average rate of $f_{\mathrm{e},i}(x,\ y)$ mass units per unit electrical energy supplied to the grid and a gas

Table 1 Present value multiplier b (ratio of present value of lifetime energy cost saving to annual energy cost saving) computed from Eq. 3 for various combinations of roof lifetime N and real (inflation-adjusted) annual rate of return r

Roof lifetime N (years)	Real annual rate of return r		
	3%	5%	7%
15	11.9	10.4	9.1
20	14.9	12.5	10.6
25	17.4	14.1	11.7
30	19.6	15.4	12.4

furnace emits the same substance at a rate of $f_{g,i}$ mass units per unit gas energy consumed, the installation of a cool roof will reduce the annual per-CRA mass of substance i emitted by

$$p_i(x,y) = e(x,y)\,\eta_t^{-1} f_{e,i}(x,y) - g(x,y) f_{g,i}, \tag{4}$$

where η_t is the electrical grid's transmission efficiency (ratio of output to input).

Extrapolation of energy savings and penalties

The influence of a cool roof on energy use depends not only on the building's location (a proxy for climate) but also on its construction and operation. Energy use simulations are typically conducted for a limited number n of building prototypes, often far fewer than the m classes of buildings present in some region of interest.

If two co-located buildings "1" and "2" differ only in weekly occupancy time t, roof assembly thermal resistance R, cooling energy efficiency ratio EER, and/or heating efficiency η_h, we expect that

$$\frac{e_1(x,y)}{e_2(x,y)} \cong \frac{t_1}{t_2} \times \frac{EER_2}{EER_1} \times \frac{R_2}{R_1} \tag{5}$$

and

$$\frac{g_1(x,y)}{g_2(x,y)} \cong \frac{t_1}{t_2} \times \frac{\eta_{h,2}}{\eta_{h,1}} \times \frac{R_2}{R_1}. \tag{6}$$

We assume that the per-CRA annual cooling energy saving or heating energy penalty of each building class j can be expressed as a linear combination of the per-CRA annual cooling energy savings or heating energy penalties of the prototypes $k = 1 \ldots n$. That is,

$$e_{\text{class},j}(x,y) = \sum_{k=1}^{n} v_{j,k}\, e_{\text{prototype},k}(x,y) \tag{7}$$

and

$$g_{\text{class},j}(x,y) = \sum_{k=1}^{n} w_{j,k}\, g_{\text{prototype},k}(x,y) \tag{8}$$

where $v_{j,k}$ and $w_{j,k}$ are location-independent coefficients relating the cooling energy savings and heating energy penalties (respectively) of the building classes to those of the prototypes. In matrix form,

$$E_{\text{class}}(x,y) = V\, E_{\text{prototype}}(x,y) \tag{9}$$

and

$$G_{\text{class}}(x,y) = W\, G_{\text{prototype}}(x,y) \tag{10}$$

where

$$E_{\text{class}}(x,y) \equiv \begin{bmatrix} e_{\text{class},1}(x,y) \\ \vdots \\ e_{\text{class},m}(x,y) \end{bmatrix}, \quad E_{\text{prototype}}(x,y) \equiv \begin{bmatrix} e_{\text{prototype},1}(x,y) \\ \vdots \\ e_{\text{prototype},n}(x,y) \end{bmatrix}; \tag{11}$$

$$G_{\text{class}}(x,y) \equiv \begin{bmatrix} g_{\text{class},1}(x,y) \\ \vdots \\ g_{\text{class},m}(x,y) \end{bmatrix}, \quad G_{\text{prototype}}(x,y) \equiv \begin{bmatrix} g_{\text{prototype},1}(x,y) \\ \vdots \\ g_{\text{prototype},n}(x,y) \end{bmatrix}; \tag{12}$$

and

$$V \equiv \begin{bmatrix} v_{1,1} \cdots v_{1,n} \\ \vdots \ \ddots \ \vdots \\ v_{m,1} \cdots v_{m,n} \end{bmatrix}, W \equiv \begin{bmatrix} w_{1,1} \cdots w_{1,n} \\ \vdots \ \ddots \ \vdots \\ w_{m,1} \cdots w_{m,n} \end{bmatrix}. \tag{13}$$

If the energetics of building class j are related to the energetics of a single prototype k, the matrices V and W will be sparse, with only one nonzero entry per row.

Rates per unit land area

The rates of cooling energy saving, heating energy penalty, energy cost saving, and emission reduction per unit LA depend on the density and type distribution of the local building stock. Let matrix

$$U(x,y) \equiv \begin{bmatrix} u_1(x,y) \\ \vdots \\ u_m(x,y) \end{bmatrix} \tag{14}$$

where $u_j(x,y)$ is the ratio of CRA to LA for building class j. Since building inventory statistics typically characterize broad areas, such as US census divisions (Fig. 3), we use county-level population density $h(x,y)$ (Fig. 4) to better estimate local ratios of CRA to LA. That is, if $r_j(x,y)$ is the ratio of CRA of building class j to population in the census division containing point (x,y), we assume that

$$U(x,y) = h(x,y)\, R(x,y) \tag{15}$$

where

$$R(x,y) \equiv \begin{bmatrix} r_1(x,y) \\ \vdots \\ r_m(x,y) \end{bmatrix}. \tag{16}$$

The per-LA rates of annual cooling energy saving and heating energy penalty are then

$$\begin{aligned} \hat{e}(x,y) &= U(x,y)^{\mathrm{T}} E_{\mathrm{class}}(x,y) \\ &= \left[U(x,y)^{\mathrm{T}} V\right] E_{\mathrm{prototype}}(x,y) \end{aligned} \tag{17}$$

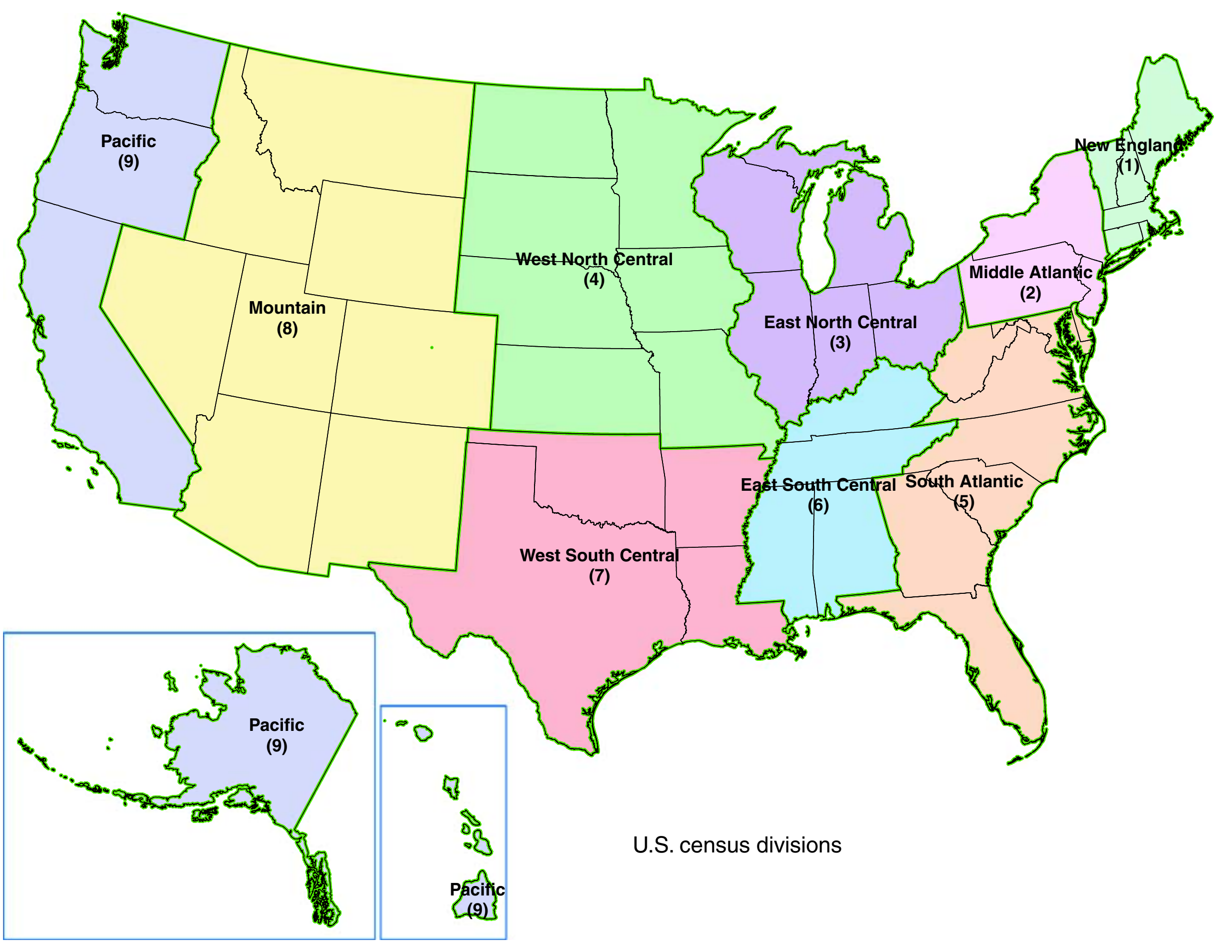


Fig. 3 Boundaries of the nine US census divisions (ESRI 2007b)

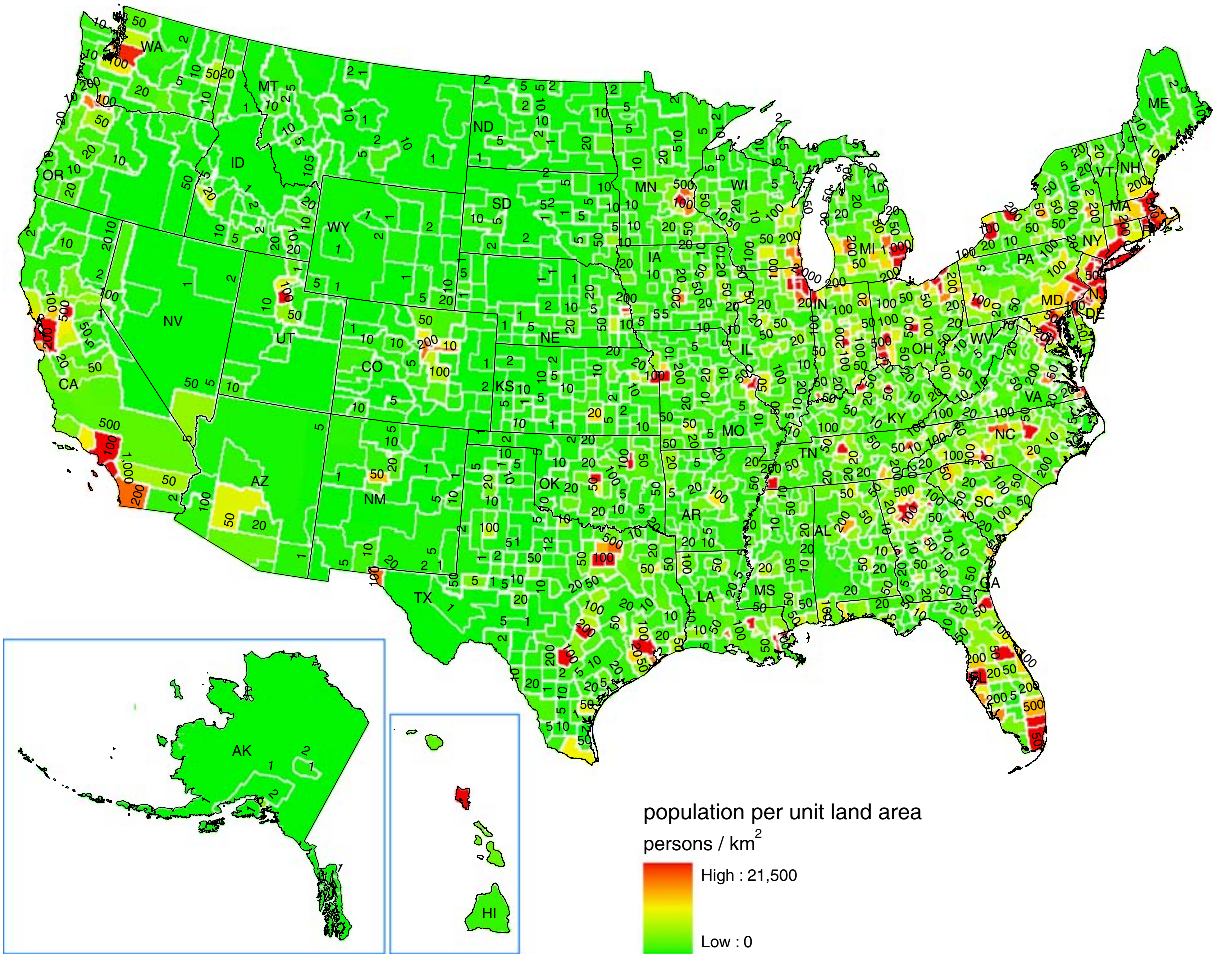


Fig. 4 US population density (persons/km^2) from the 2004 US Census (ESRI 2007b)

and

$$\hat{g}(x,y) = U(x,y)^{\mathrm{T}} G_{\mathrm{class}}(x,y)$$
$$= \left[U(x,y)^{\mathrm{T}} W\right] G_{\mathrm{prototype}}(x,y) \qquad (18)$$

respectively. These yield per-LA annual rates of energy cost saving and emission reduction

$$\hat{c}(x,y) = \hat{e}(x,y)\, d_{\mathrm{e}}(x,y) - \hat{g}(x,y)\, d_{\mathrm{g}}(x,y) \qquad (19)$$

and

$$\hat{p}_i(x,y) = \hat{e}(x,y)\, \eta_{\mathrm{t}}^{-1} f_{\mathrm{e},i}(x,y) - \hat{g}(x,y) f_{\mathrm{g},i} \qquad (20)$$

respectively.

The local per-LA annual rates $\hat{e}(x,y)$, $\hat{g}(x,y)$, $\hat{c}(x,y)$, and $\hat{p}_i(x,y)$ can be integrated over any region of interest, such as a US state, to obtain the region's aggregate annual cooling energy saving, heating energy penalty, energy cost saving, and emission reduction. Dividing each regional sum by aggregate regional CRA yields the regional-average per-CRA rate.

Methodology

Estimating prototype energy saving and heating penalty per unit conditioned roof area

In a year 2005 study (Akbari and Konopacki 2005), one of the authors used the DOE-2.1E building energy model (DOE-2 2007) to simulate for a typical meteorological year (NREL 2007) the hourly heating and cooling energy uses of four prototype single-storey commercial buildings, including both new (1980^+) and old (pre-1980) offices and retail stores. The general characteristics of the office and retail store prototypes were based on survey data from the California Energy Commission (CEC 1994). Location-specific properties such as roof and wall construction, window characteristics, and building schedules were obtained from the US Energy Information Administration (EIA 1979, 1983, 1994a). Additional office and retail store attributes were derived from building characteristic surveys conducted in both northern and southern California (Akbari et al. 1989, 1991, 1993).

Each building was simulated with several different levels of roof insulation thermal resistance. The prototypes used in the current study—new office, old office, new retail, and old retail—are identical to the prototypes described in the prior study, except that in the current study, the roof insulations in the new and old buildings are assigned thermal resistances of 3.3 m^2 K W^{-1} [R-19] and 1.2 m^2 K W^{-1} [R-7], respectively. The prototypes are partly characterized in Table 2 and fully detailed in the year 2005 study.

Akbari and Konopacki (2005) simulated the annual heating and cooling energy uses of each prototype twice: first, with a weathered conventional gray roof (solar reflectance 0.20, thermal emittance 0.90) and then with a weathered cool white roof (solar reflectance 0.60, thermal emittance 0.90). Prototype energy uses were evaluated in each of 236 US cities (Fig. 5) to yield per-CRA cooling energy saving (annual cooling energy use with a conventional roof minus annual cooling energy use with a cool roof) and per-CRA heating energy penalty (annual heating energy use with a cool roof minus annual heating energy use with a conventional roof) when roof solar reflectance is increased by 0.40 (to 0.60 from 0.20). The simulations are fully detailed in the year 2005 study.

While it is reasonable to assign a solar reflectance of 0.60 to a weathered white roof, lowering this value to 0.55 makes estimates of cool roof energy saving more conservative and consistent with the nonresidential cool roof analysis we performed for California's Title 24 building energy efficiency standards (Levinson et al. 2005). A building's cooling energy saving and heating energy penalty are each proportional to the increase in the solar reflectance of its roof (Konopacki et al. 1997). Hence, we scaled these results by a factor of $0.35/0.40=0.875$ to estimate the per-CRA cooling energy saving and heating energy penalty when roof solar reflectance is raised by 0.35 (to 0.55 from 0.20). All savings, penalties, and emission reductions in this study are based on increasing the weathered solar reflectance of a roof to 0.55 from 0.20.

The geographic information system (GIS) application ESRI ArcGIS Desktop 9.1 (ESRI 2007a) was used to create spatial maps of per-CRA annual cooling energy saving $e_k(x,y)$ and heating energy penalty $g_k(x,y)$ for each prototype k. Each map is a raster of 5×5-km cells spanning the USA; cell values were populated by inverse-distance-weighted interpolation between values simulated in each of the 236

Table 2 Major characteristics of the prototype buildings whose annual cooling and heating energy uses were simulated with cool and conventional roofs

Geometry	New office (1980^+)	Old office (pre-1980)	New retail store (1980^+)	Old retail store (pre-1980)
	Single-storey, non-directional, five zones		Single-storey, non-directional, one zone (conditioned)	
Roof area and floor area (m^2)	455		753	
Roof construction	Built-up materials on flat deck			
Thermal resistance of roof insulation[a] (m^2 K/W)	3.3 [R-19]	1.2 [R-7]	3.3 [R-19]	1.2 [R-7]
Thermal resistance of wall insulation (m^2 K/W)	2.3 [R-13]	1.1 [R-6]	2.3 [R-13]	0.7 [R-4]
Cooling equipment	Package a/c, direct expansion, air cooled			
Cooling energy efficiency ratio (BTU/[h·W])	10	8	10	8
Heating equipment	Gas furnace			
Heating efficiency (%)	74	70	74	70
Operating hours	Weekdays 6A-7P		Weekdays 8A-9P, weekends 10A-5P	

[a] Roof insulation levels differ from those of prototypes described by Akbari and Konopacki (2005)

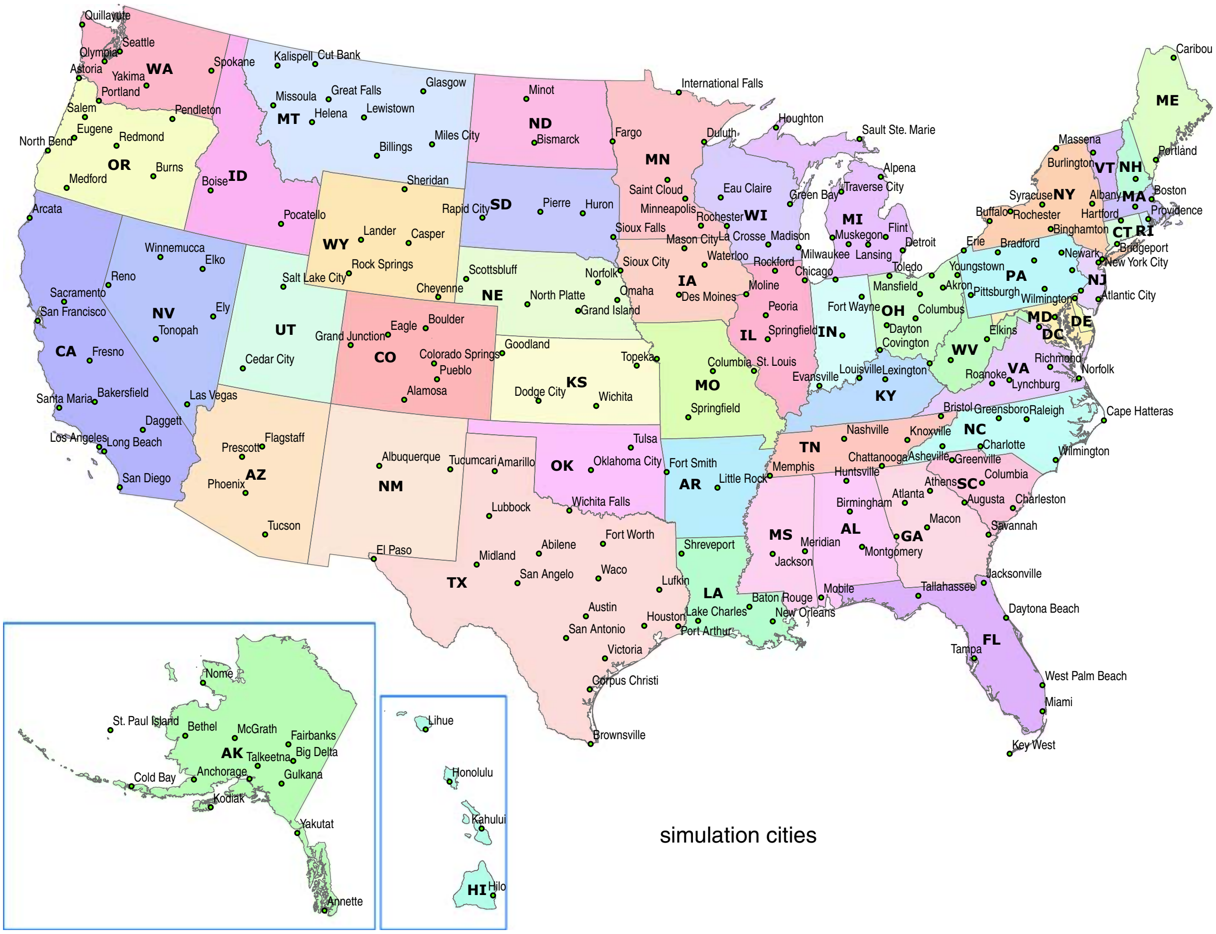


Fig. 5 Locations of the 236 US cities in which building energy use was simulated with conventional and cool roofs

cities. Each city was placed in the *x*–*y* plane via NAD 1983 Lambert Conformal Conic projection of its latitude and longitude.

All raster maps produced in this study share the same domain, cell size, and projection.

Estimating prototype load change ratios

Equation 1 was used to compute the load change ratio $\ell_k(x, y)$ (dimensionless ratio of annual heating load increase to annual cooling load decrease) of each prototype k.

Estimating prototype energy cost saving per unit conditioned roof area

Year 2005 average commercial sector prices of electricity and natural gas in each US state (and in the District of Columbia, which we treat as a state) were obtained from the Energy Information Administration (EIA 2006a, 2007a). Raster maps of electricity price $d_e(x, y)$ and gas price $d_g(x, y)$ were generated by assigning the appropriate EIA price to each state's raster cells (Fig. 6).

A raster map of per-CRA annual energy cost saving $c_k(x, y)$ was created for each prototype k via Eq. 2.

Estimating prototype emission reduction per unit conditioned roof area

Table 3 presents year 2004 electricity emission factors (mass of greenhouse gas or air pollutant emitted per unit electrical energy supplied to the grid) for CO_2, NO_x, SO_2, and Hg obtained from eGRID2006v2.1, the latest version of the Emissions & Generation

Table 3 Electricity emission factors (mass of greenhouse gas or air pollutant emitted per unit energy supplied to the grid) and generation resource mixes for each subregion of the US EPA eGRID dataset

Subregion	Emission factor				Generation resource mix							
	CO_2 (kg/kWh)	NO_x (g/kWh)	SO_2 (g/kWh)	Hg (μg/kWh)	Coal (%)	Oil (%)	Gas (%)	Other fossil (%)	Nuclear (%)	Hydro (%)	Non-hydro renewable (%)	Unknown (%)
AKGD	0.570	1.35	0.60	0.8	12.3	7.3	68.0	0.0	0.0	12.4	0.0	0.0
AKMS	0.218	2.96	0.30	0.0	0.0	28.8	3.6	0.0	0.0	66.9	0.7	0.0
AZNM	0.569	0.94	0.65	11.5	40.4	0.0	31.5	0.0	21.2	4.5	2.4	0.0
CAMX	0.399	0.34	0.25	1.0	12.6	1.1	46.4	0.9	14.2	15.1	9.7	0.1
ERCT	0.644	0.44	1.43	13.2	37.7	0.5	45.9	1.3	13.2	0.3	1.0	0.2
FRCC	0.602	1.02	1.64	4.1	26.4	18.3	36.5	0.3	15.5	0.0	2.0	1.0
HIMS	0.661	3.17	2.71	0.0	3.6	77.2	4.1	0.0	0.0	3.0	12.1	0.0
HIOA	0.784	1.16	1.59	7.3	18.0	77.4	0.0	1.9	0.0	0.0	2.7	0.0
MROE	0.843	1.47	3.40	13.9	71.3	2.4	5.2	0.1	13.2	3.9	3.9	0.1
MROW	0.823	1.73	2.66	19.6	74.6	0.6	1.8	0.1	16.0	4.7	2.1	0.0
NEWE	0.412	0.44	1.06	3.9	14.5	9.4	36.7	1.0	27.6	5.1	5.7	0.0
NWPP	0.418	0.73	0.57	4.4	34.4	0.3	10.6	0.1	3.6	49.0	2.0	0.0
NYCW	0.418	0.40	0.31	2.9	0.0	20.4	29.8	0.3	48.6	0.0	0.8	0.0
NYLI	0.641	0.83	2.43	2.6	0.0	58.2	35.5	1.8	0.0	0.0	4.5	0.0
NYUP	0.372	0.45	1.90	6.4	25.4	6.6	13.2	0.3	27.1	26.0	1.4	0.0
RFCE	0.497	0.77	3.64	18.7	44.9	3.5	9.6	0.7	38.4	1.6	1.4	0.0
RFCM	0.745	1.11	3.09	14.9	67.0	0.9	15.5	0.3	14.3	0.0	2.0	0.0
RFCW	0.706	1.28	4.62	19.8	72.8	0.5	1.5	0.7	23.2	0.7	0.4	0.1
RMPA	0.923	1.41	0.92	7.4	80.6	0.0	13.5	0.0	0.0	5.3	0.5	0.0
SPNO	0.894	1.80	2.74	12.4	78.1	1.3	4.6	0.1	15.2	0.1	0.5	0.0
SPSO	0.799	1.15	1.79	17.6	58.8	0.2	34.1	0.3	0.0	4.2	2.3	0.1
SRMV	0.515	0.66	1.03	5.0	23.4	5.0	39.3	1.1	26.6	1.6	2.4	0.5
SRMW	0.837	1.14	3.15	18.5	84.7	0.3	2.0	0.1	11.7	1.2	0.1	0.0
SRSO	0.676	0.98	3.83	15.8	64.0	0.6	10.1	0.1	18.6	3.1	3.5	0.0
SRTV	0.678	1.17	3.27	11.5	65.8	1.7	2.4	0.0	20.4	8.8	0.9	0.0
SRVC	0.520	0.84	2.66	9.9	51.0	1.7	3.8	0.2	39.5	1.7	2.0	0.1

Resource Grid Integrated Database released by the US Environmental Protection Agency (EPA 2007). eGRID assigns the land within each US ZIP code to one of 26 subregions (Fig. 7). A raster map of electricity emission factor $f_{e,i}(x,y)$ for each substance i was created by assigning the subregion's emission factor to the raster cells within that subregion (Fig. 8).

Table 4 shows the non-regional natural gas emission factors $f_{g,i}$ (mass of greenhouse gas or air pollutant emitted per unit gas energy consumed) obtained from the US EPA (EPA 2005). We chose an NO_x factor in the middle of the range of NO_x factors listed for a variety of combustion systems. The EPA provides only a single natural gas emission factor each for CO_2, SO_2, and Hg.

A map of per-CRA emission reduction $p_{i,k}(x,y)$ was created for each combination of substance i and prototype k using Eq. 4.

Estimating conditioned roof area per unit land area

The 2003 Commercial Buildings Energy Consumption Survey (CBECS) public use microdata files

Table 4 Non-regional natural gas combustion emission factors (mass of greenhouse gas or air pollutant emitted per unit energy consumed)

CO_2 (kg/therm)	NO_x (g/therm)	SO_2 (g/therm)	Hg (μg/therm)
5.281	4.14	0.026	11.4

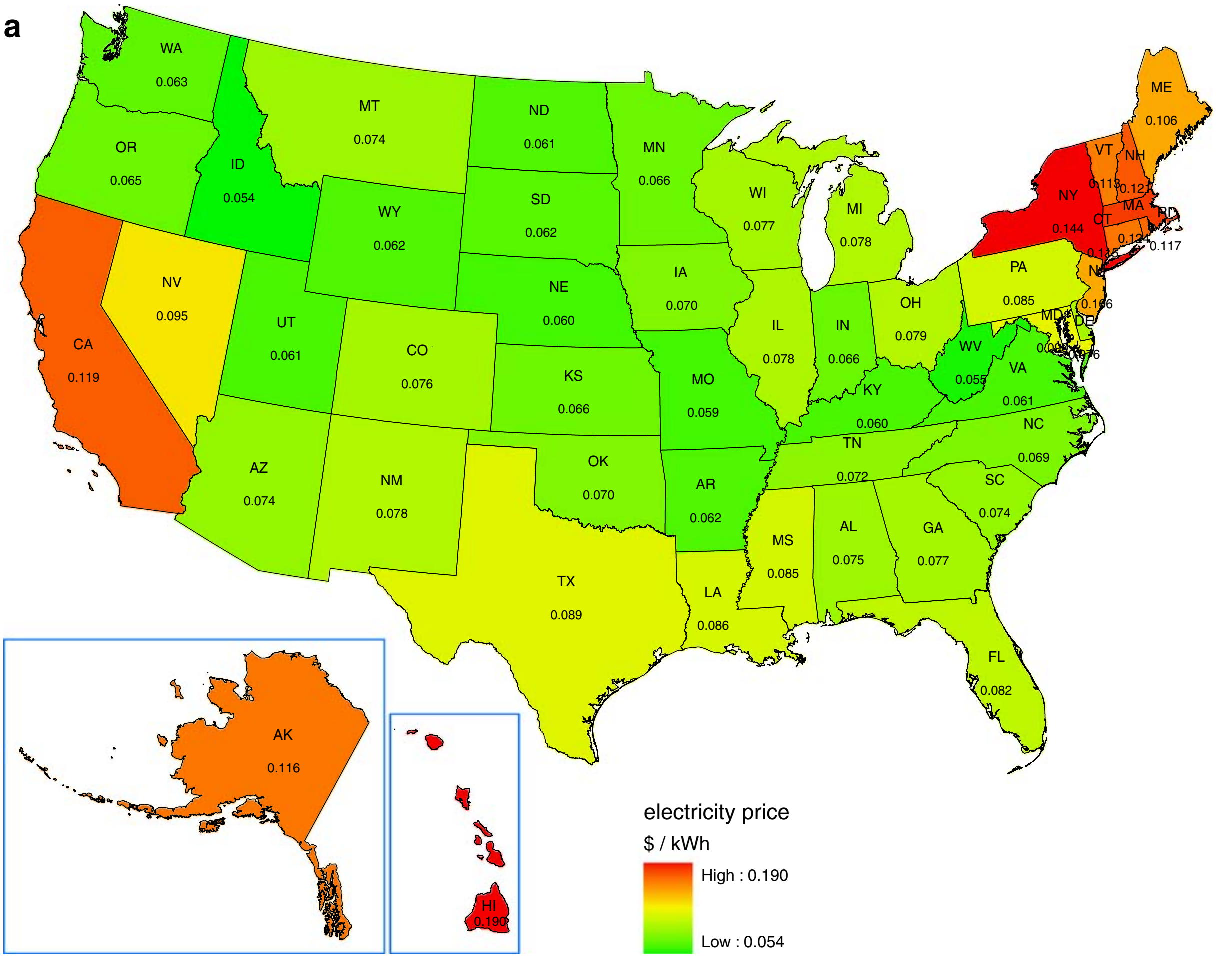


Fig. 6 Year 2005 average commercial sector prices in each US state of **a** electricity [$d_e(x, y)$, \$/kWh] (EIA 2006a) and **b** natural gas [$d_g(x, y)$, \$/therm] (EIA 2007a)

(EIA 2006b) describe a sample of 5,215 US commercial buildings. The CBECS database was used to characterize building inventory by US census division (Fig. 3), since its records locate each building only by census division.

The roof area of each building was estimated by dividing its total floor area by the number of floors. The database reports the exact number of floors in a building only if it is less than 15. If the number of floors was recorded as "15 to 25," we assigned 20 floors (the range mean); if the number of floors was recorded as "over 25," we assigned 40 floors (a guess).

We calculated the adjusted conditioned roof area of each building as the product of its roof area, fraction of floor space that is cooled, and adjusted sampling weight. The third term is the reciprocal of the probability of that building being selected into the sample, adjusted for non-response bias. The adjusted conditioned roof area is the contribution made by the sample building to conditioned roof area in the census division.

We estimated the CRA in each state by multiplying the CRA in the census division containing the state by the ratio of the state population to the census-division population. National CRA is simply the sum of all state CRAs (or, equivalently, the sum of all census-division CRAs).

CBECS assigns to each building one of 20 principle building activities (PBAs), such as "office," "education," or "food service." Using PBA and age category (new or old) to define each building class, we calculated for each combination of census division d and building class j the ratio $r_{j,d}$ of conditioned roof area to census-division population (Table 5). A raster map of the CRA-to-LA ratio $u_j(x, y)$ for each building class j was created by

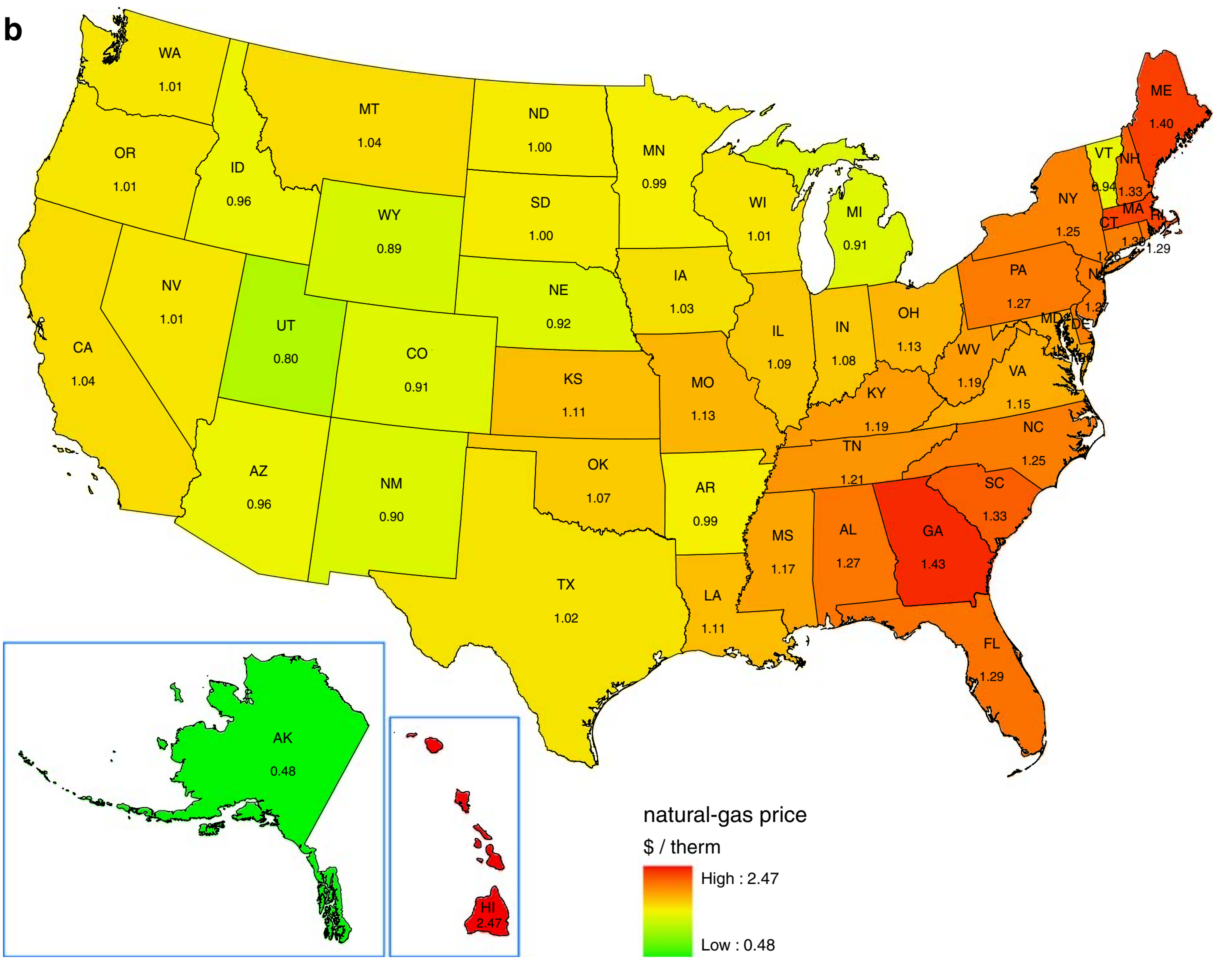


Fig. 6 (continued)

assigning each division's per capita CRA for building class j, $r_j(x, y)$ to the cells within that division, then multiplying each per capita CRA raster map $r_j(x, y)$ by the county population density raster map $h(x, y)$ shown in Fig. 4.

Relating per-CRA energy savings and penalties of building classes to those of building prototypes

The per-CRA cooling energy savings and heating energy penalties of 10 office-like building classes—new/old office, new/old laboratory, new/old non-refrigerated warehouse, new/old public order and safety, and new/old outpatient health care—were assumed to equal those of the new/old office prototypes. Similarly, the per-CRA energy savings and penalties of 12 store-like building classes—new/old food sales, new/old food service, new/old strip shopping mall, new/old enclosed mall, new/old retail other than mall, and new/old service—were assumed to equal those of the new/old retail prototypes.

The per-CRA savings and penalties of new/old religious worship buildings were assumed to be 40% of those of the new/old office prototypes on the grounds that the former are operated about 2 days a week, while the latter are operated 5 days a week. Likewise, the per-CRA savings and penalties of new/old public assembly buildings were assumed to be 60% of those of the new/old office prototypes on the basis that the former are operated about 3 days a week. Four difficult-to-characterize building classes—new/old vacant and new/old other—were conservatively assigned zero per-CRA savings and penalties.

The ratios of per-CRA savings and penalties for the 10 remaining building classes—new/old refriger-

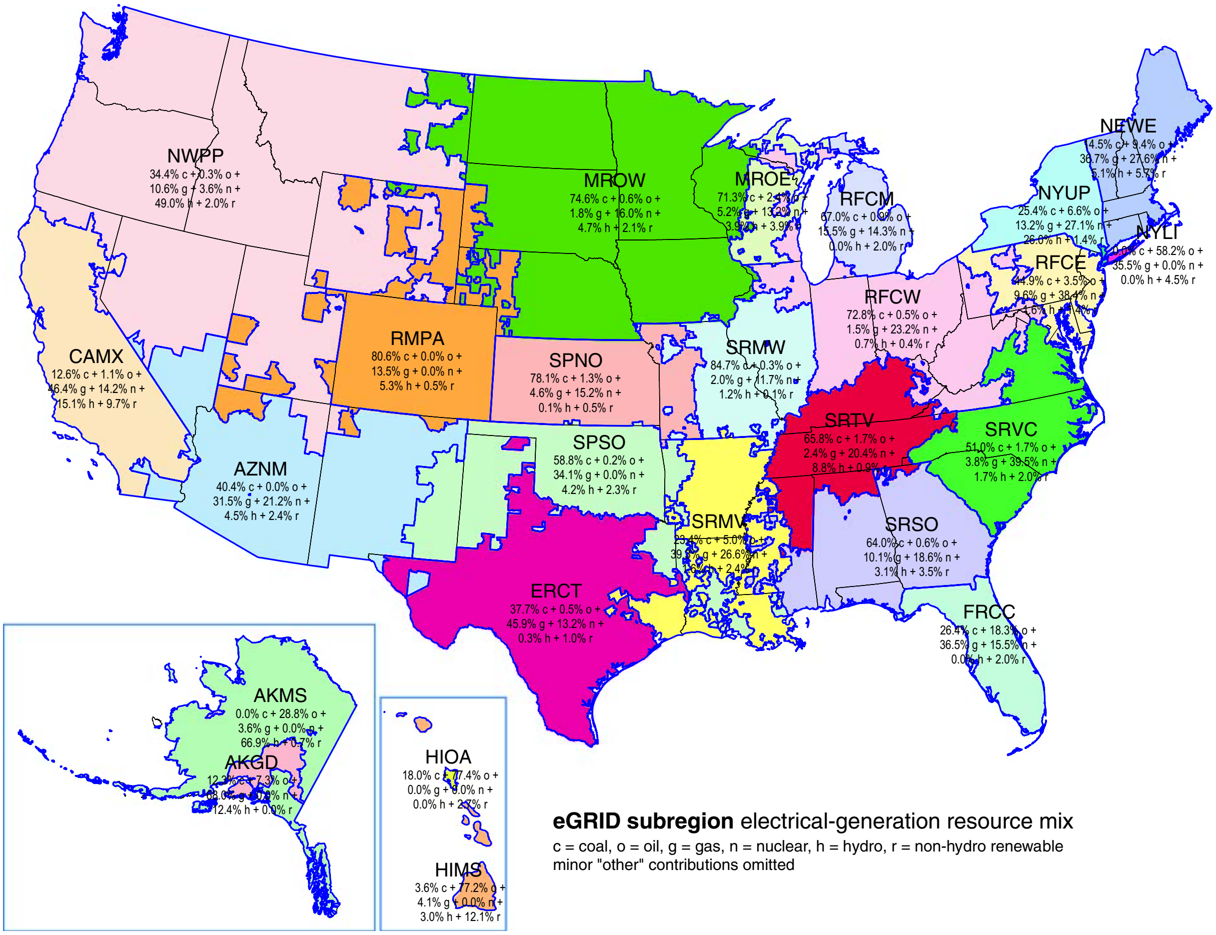


Fig. 7 Electrical generation resources mixes of the 26 subregions in the US Environmental Protection Agency Emissions & Generation Resource Grid Integrated Database eGRID2006v2.1 (EPA 2007)

ated warehouse, new/old education, new/old inpatient health care, new/old nursing, and new/old lodging—to those of the new/old office prototypes were obtained from simulations performed in an earlier study (Akbari et al. 1999). Specifically, the ratios of savings and penalties for each building class to those of an office building (new or old, as appropriate) were approximated by the mean ratios of savings and penalties simulated in 11 US cities for each building class to the savings and penalties simulated in the same 11 cities for an office building.

The matrices V and W relating per-CRA building class cooling energy savings and heating energy penalties to those simulated in the current study for new office, old office, new retail, and old retail prototypes are presented in Tables 6 and 7.

Estimating state- and national-average saving and penalty rates per unit conditioned roof area

US raster maps of per-LA cooling energy saving $\hat{e}(x,y)$, heating energy penalty $\hat{g}(x,y)$, energy cost saving $\hat{c}(x,y)$, and emission reduction $\hat{p}(x,y)$ were computed from Eqs. 17, 18, 19, and 20.

Per-LA rates of cooling energy saving, heating energy penalty, energy cost saving, and emission reduction were integrated over the land area bounded by each US state to compute state totals. Each state total (e.g., cooling energy saving in kilowatt-hours) was divided by the state's CRA to estimate state-average per-CRA rates (e.g., cooling energy saving per CRA, kilowatt-hours per square meter). US-average per-CRA rates were computed by dividing national totals

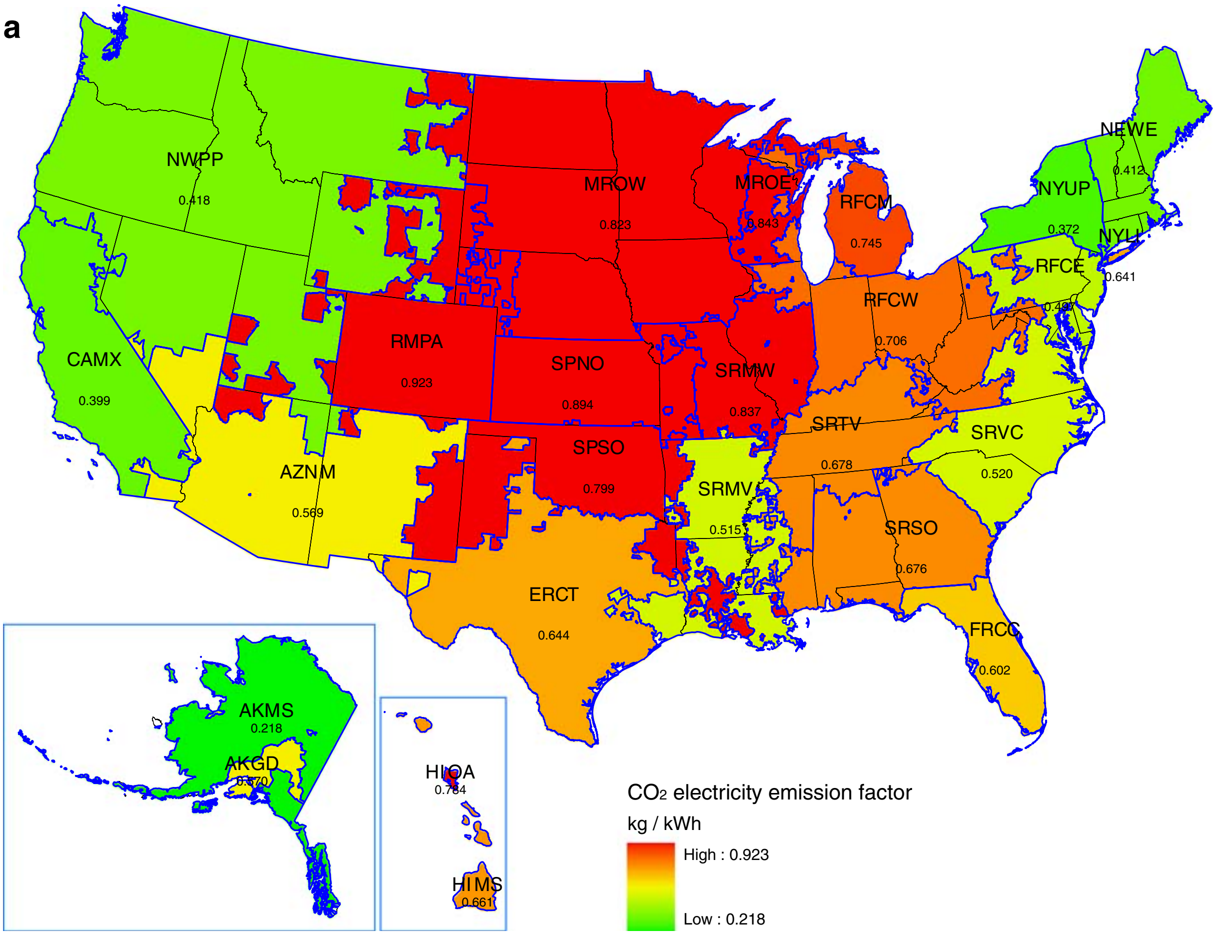


Fig. 8 Year 2004 average electricity emission factor $f_{e,i}(x, y)$ (mass of greenhouse gas or air pollutant emitted mass per unit energy supplied to the grid) for each of four substances i: **a** carbon dioxide (CO_2), kg/kWh; **b** nitrogen oxides (NO_x), g/kWh; **c** sulfur dioxide (SO_2), g/kWh; and **d** mercury (Hg), μg/kWh (EPA 2007)

(sums of state totals) by national CRA (sum of state CRAs).

State- and national-average per-CRA rates should not be applied to specific buildings because energy savings and penalties vary with both climate and building type. However, these average rates can be used to estimate and compare regional savings, penalties, and reductions.

Results

Prototype cooling energy saving and heating energy penalty per unit conditioned roof area

Annual cooling energy saving per CRA $e(x, y)$ ranged from 0.1 to 4.1 kWh/m^2 for new office, 0.5 to 11.5 kWh/m^2 for old office, 0 to 4.7 kWh/m^2 for new retail, and 0.8 to 15.0 kWh/m^2 for old retail (Fig. 9). New office cooling savings were at least 1 kWh/m^2 everywhere except in very cold and sparsely populated regions of Alaska. As predicted by Eq. 5, old office, new retail, and old retail cooling energy savings were about 3.4, 1.2, and 4.1 times those of the new office prototype. Annual heating energy penalty per CRA $g(x, y)$ ranged from 0 to 0.104 therm/m^2 for new office, 0 to 0.235 therm/m^2 for old office, 0 to 0.122 therm/m^2 for new retail, and 0 to 0.264 therm/m^2 for old retail (Fig. 10).

The dimensionless "load change" ratio $\ell(x, y)$—increase in annual heating load divided by decrease in annual cooling load—calculated from Eq. 1 was less than unity everywhere except in the aforementioned cold and sparsely populated regions of Alaska

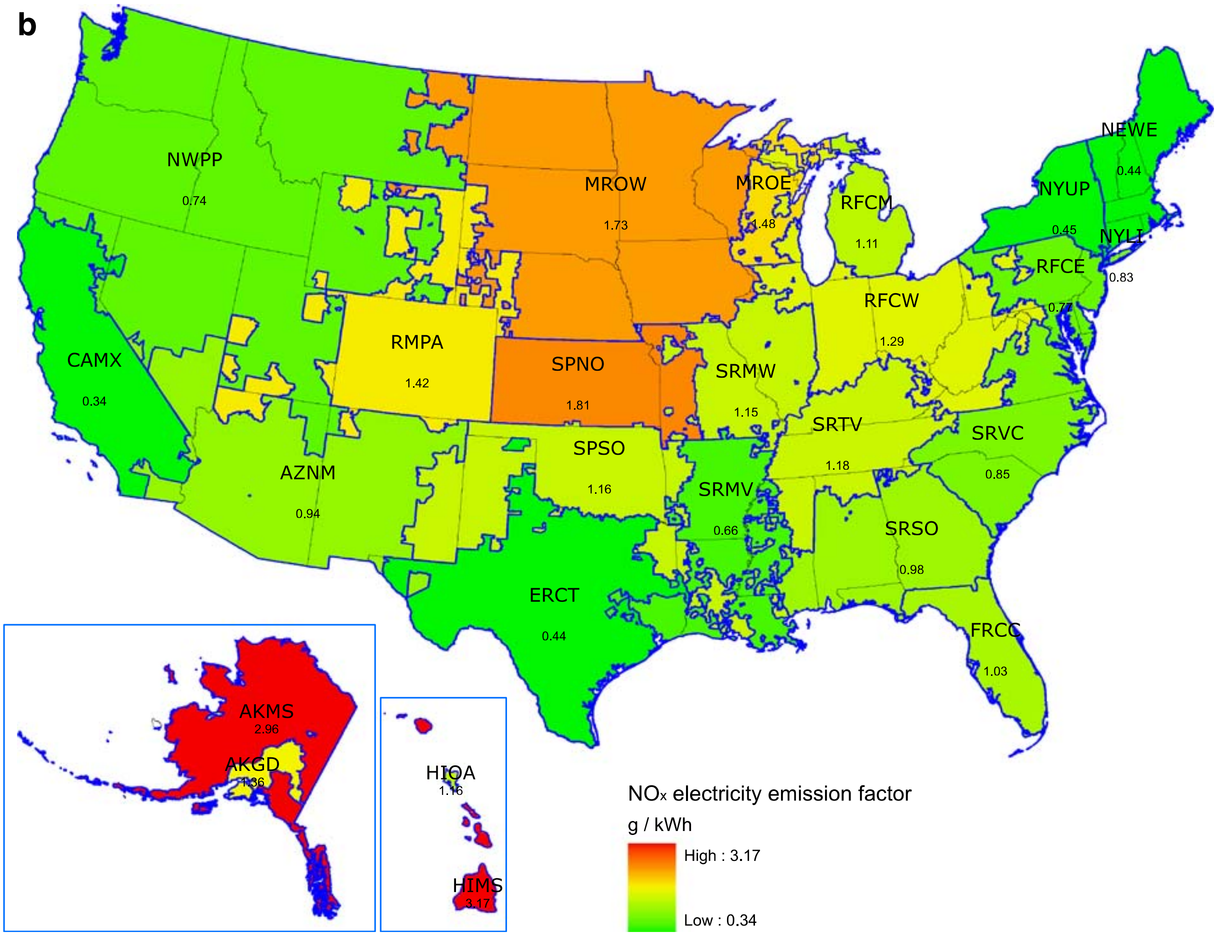


Fig. 8 (continued)

(Fig. 11). In most of the mainland USA, load change ratios for new office, old office, new retail, and old retail buildings were less than 0.5, 0.4, 0.4, and 0.3 respectively. That is, a cool roof almost always reduced the annual cooling load more than it increased the annual heating load.

Cooling energy savings generally increased southward, while heating penalties and load change ratios generally increased northward. Exceptions in the mainland USA were induced by variations in local annual mean global horizontal solar irradiance (greatest in the southwest; see Fig. 1), local annual cooling degree days (greatest in the southwest, Texas, and Florida; see Fig. 2a), and/or local annual heating degree days (high not only in the far north, but also in cold mountainous areas; see Fig. 2b).

Prototype energy cost saving per unit conditioned roof area

Annual energy cost saving (monetary value of cooling energy saving less monetary value of heating energy penalty) per CRA $c(x,y)$ ranged from −0.04 to \$0.63/m^2 for new office, −0.04 to \$1.72/m^2 for old office, −0.04 to \$0.82/m^2 for new retail, and −0.03 to \$2.34/m^2 for old retail (Fig. 12). Energy cost saving was greatest in Hawaii, which has high cooling-energy saving, virtually no heating energy penalty, and the most expensive electricity in the USA. The next highest rate of energy cost saving (about half that in Hawaii) was available in California's Central Valley. Savings were positive nearly everywhere—even in Alaska, where expensive electricity and

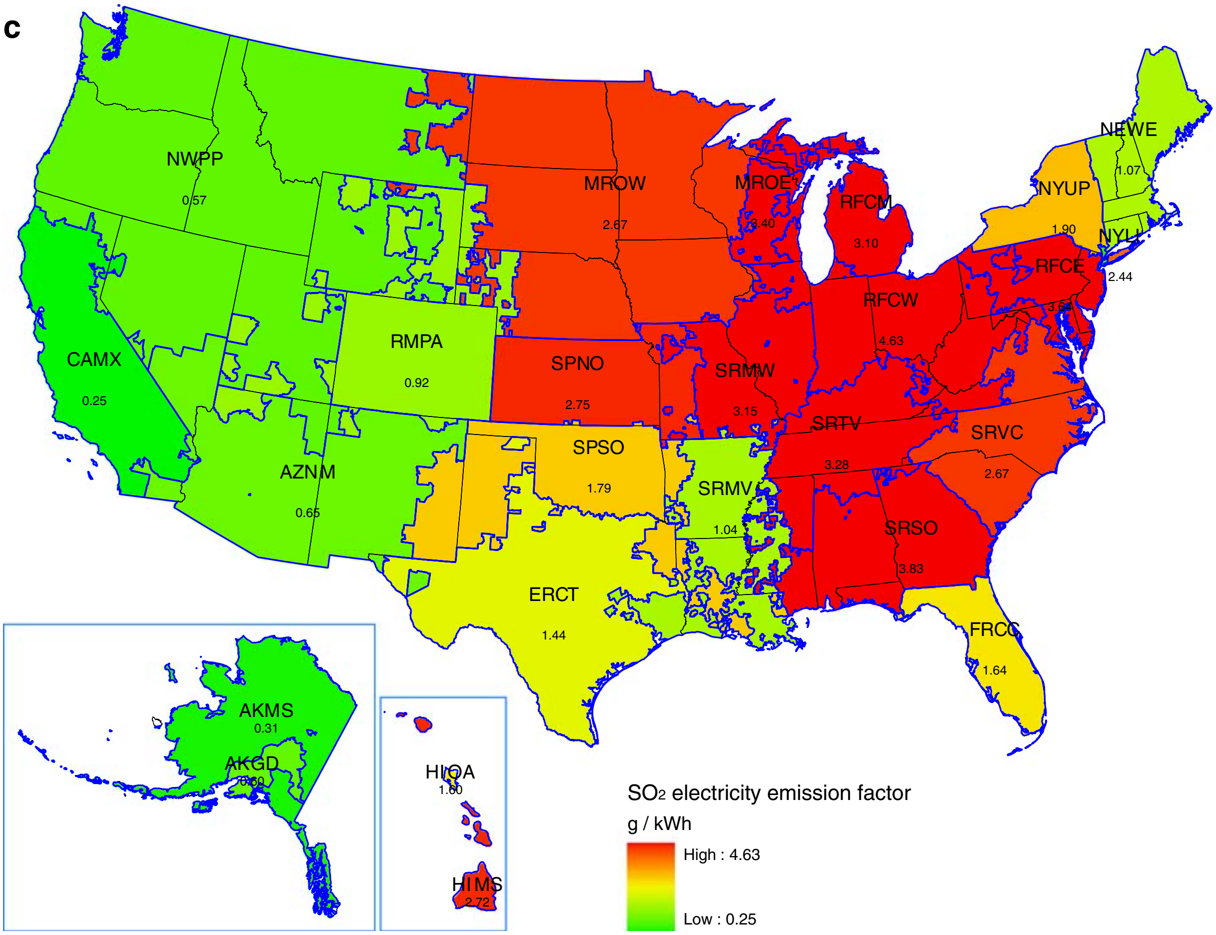


Fig. 8 (continued)

cheap natural gas made energy cost savings comparable to those in central-latitude mountain states, such as Utah and Colorado.

While energy cost saving generally increased southward, there were large east–west variations induced by wide differences in energy prices (Fig. 6).

Present values of energy cost savings can be obtained by using the PV multiplier b appropriate to the roof's lifetime and the real annual rate of return (Table 1).

Prototype emission reductions per unit conditioned roof area

Annual CO_2 reduction per CRA $p_{CO_2}(x,y)$ ranged from −0.52 to 3.86 kg/m^2 for new office, −1.0 to 11.5 kg/m^2 for old office, −0.50 to 4.76 kg/m^2 for new retail, and −1.2 to 14.0 kg/m^2 for old retail (Fig. 13). Reductions were positive everywhere except in very cold and sparsely populated regions of Alaska with a low cooling energy saving and a low CO_2 electricity emission factor. Outside of Alaska, reductions were lowest in the northeast, which tends to have cool weather and/or hydro power. CO_2 reductions generally increased southward, but were quite high in the northern central states due to high CO_2 electricity emission factors.

Annual NO_x reduction per CRA $p_{NO_x}(x,y)$ ranged from −0.1 to 11.8 g/m^2 for new office, 0.9 to 32.0 g/m^2 for old office, −0.4 to 15.3 g/m^2 for new retail, and 1.5 to 43.4 g/m^2 for old retail (Fig. 14). NO_x reductions were positive nearly everywhere, with

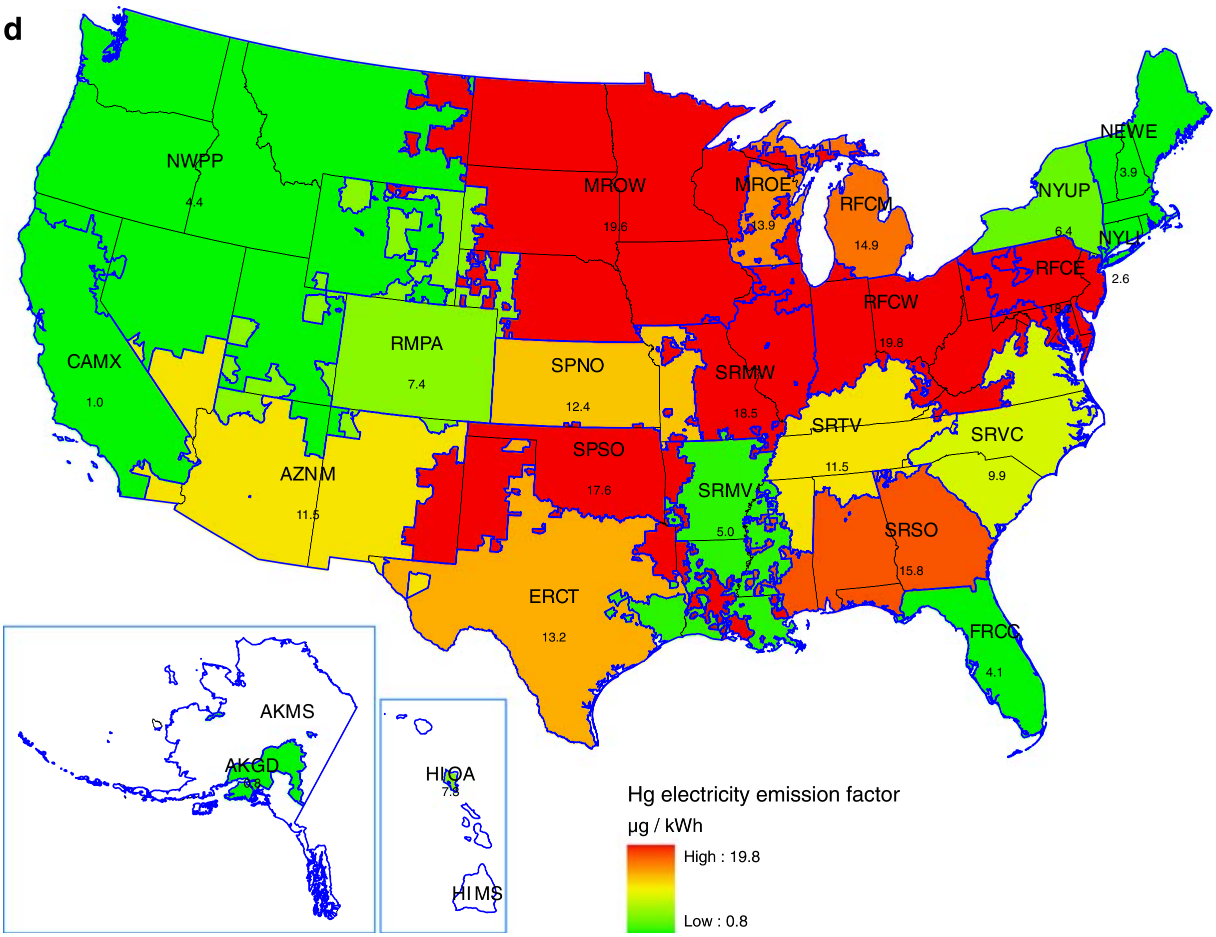


Fig. 8 (continued)

remarkably high values in the midwest driven by high NO_x electricity emission factors (Fig. 8b).

Annual SO_2 reduction per CRA $p_{SO_2}(x, y)$ ranged from 0 to 17.1 g/m^2 for new office, 0.2 to 45.3 g/m^2 for old office, 0 to 17.4 g/m^2 for new retail, and 0.3 to 61.3 g/m^2 for old retail (Fig. 15). Reductions were nonnegative everywhere, but much higher in the east (except New York and New England) than in the west. This strong variation was driven by SO_2 electricity emission factors that are an order of magnitude larger in the east than in the west (Fig. 8c).

Annual Hg reduction per CRA $p_{Hg}(x, y)$ ranged from −0.3 to 70.4 µg/m^2 for new office, 1 to 193 µg/m^2 for old office, −0.2 to 75.6 µg/m^2 for new retail, and 2 to 262 µg/m^2 for old retail (Fig. 16; reductions were not computed in parts of Alaska and Hawaii for which the eGRID database did not specify Hg electricity emission factors). Reductions were positive everywhere except in sparsely populated regions of Alaska with low cooling energy saving and low Hg electricity emission factor. Variations in Hg reduction were driven primarily by Hg electricity emission factor, which is high when coal dominates the generation resource mix.

State- and national-average rates per unit conditioned roof area

Per-LA raster maps are not shown here because spatial variations in the per-LA rates of annual cooling energy saving, heating energy penalty, energy

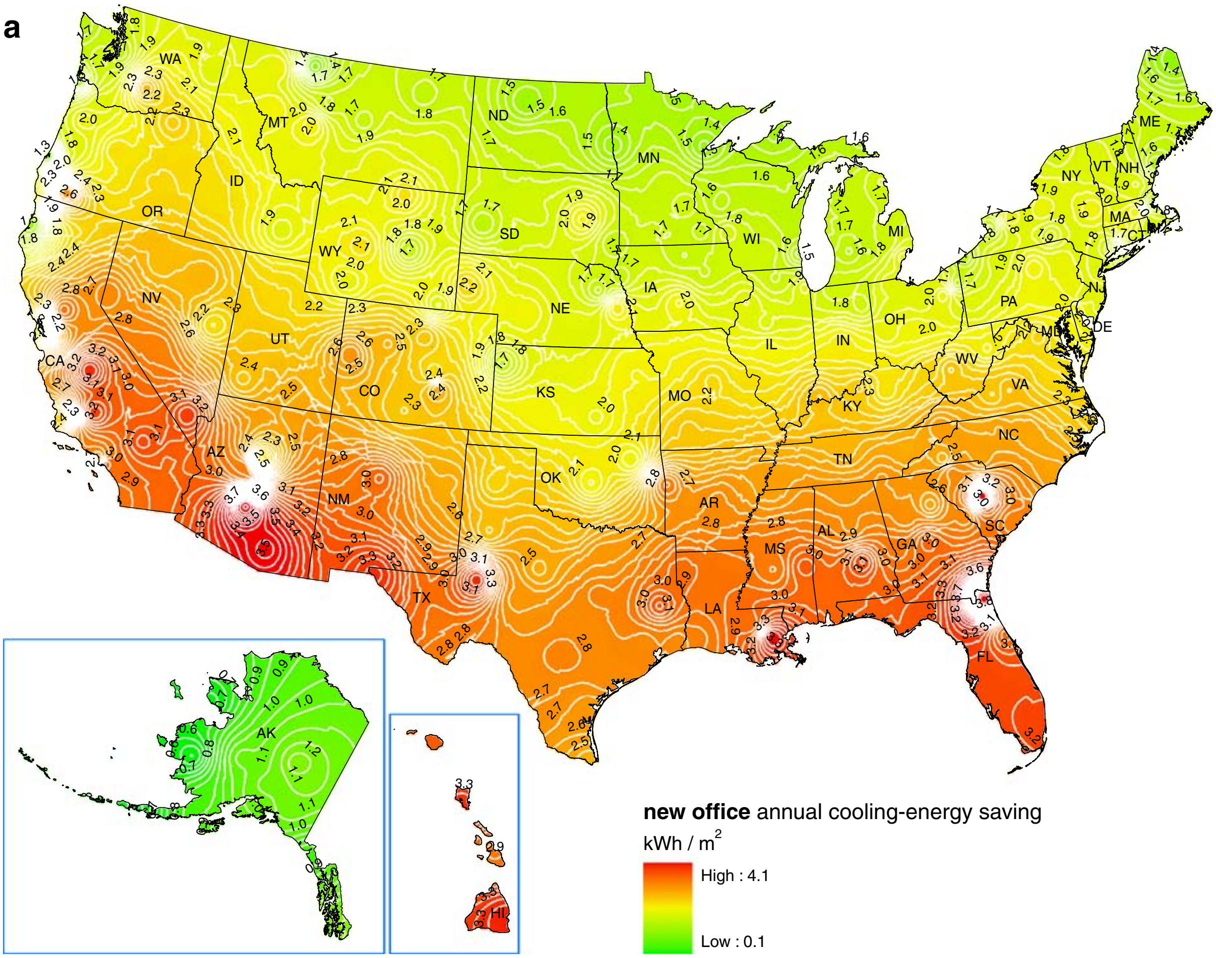


Fig. 9 Annual cooling energy saving per unit conditioned roof area $e_k(x, y)$ (kWh/m^2) for each of four building prototypes k: **a** new office, **b** old office, **c** new retail, and **d** old retail

cost saving, and emission reduction are all dominated by the four-order-of-magnitude range in US population density (Fig. 4), which swamps the one- to two-order-of-magnitude range in per-CRA rates (Figs. 9, 10, 11, 12, 13, 14, 15, and 16). Instead, state- and national-average values of per-CRA annual cooling energy saving (kWh/m^2), heating energy penalty (therm/m^2), energy cost saving ($/m^2), CO_2 reduction (kg/m^2), NO_x reduction (g/m^2), SO_2 reduction (g/m^2), and Hg reduction (μg/m^2) are presented in Table 8. Also included for reference are state and national year 2004 census populations (millions), state and national roof areas (million m^2), state and national conditioned roof areas (million m^2), and year 2005 state commercial sector prices of electricity ($/kWh) and natural gas ($/therm).

State- and national-average annual savings, penalties, and reductions per unit conditioned roof area vary as follows:

- Cooling energy saving ranged from 3.30 kWh/m^2 in Alaska to 7.69 kWh/m^2 in Arizona, averaging 5.02 kWh/m^2 nationwide.
- Heating energy penalty ranged from 0.003 therm/m^2 in Hawaii to 0.141 therm/m^2 in Wyoming, averaging 0.065 therm/m^2 nationwide.
- Energy cost saving ranged from $0.126/m^2 in West Virginia to $1.14/m^2 in Arizona, averaging $0.356/m^2 nationwide.
- CO_2 reduction ranged from 1.07 kg/m^2 in Alaska to 4.97 kg/m^2 in Hawaii, averaging 3.02 kg/m^2 nationwide.

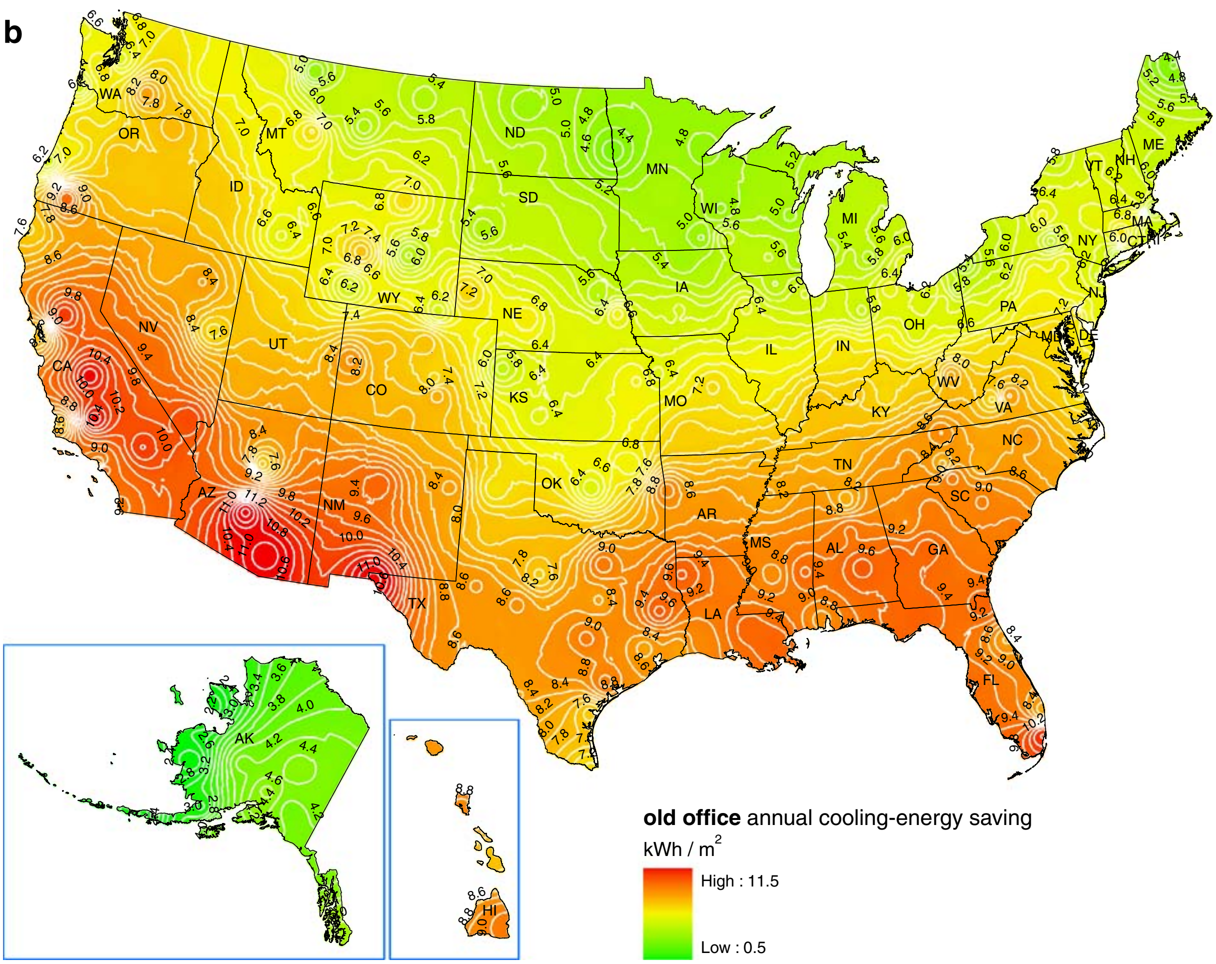


Fig. 9 (continued)

- NO_x reduction ranged from 1.70 g/m^2 in New York to 11.7 g/m^2 in Hawaii, averaging 4.81 g/m^2 nationwide.
- SO_2 reduction ranged from 1.79 g/m^2 in California to 26.1 g/m^2 in Alabama, averaging 12.4 g/m^2 nationwide.
- Hg reduction (excluding that in parts of Alaska and Hawaii for which eGRID Hg electricity emission factors were unavailable) ranged from 1.08 μg/m^2 in Alaska to 105 μg/m^2 in Alabama, averaging 61.2 μg/m^2 nationwide.

Each state's aggregate savings, penalties, and reductions can be estimated by multiplying average per-CRA rates by the product of state CRA and the fraction of CRA to be made cool. National aggregate values can be computed in a similar fashion.

The present values of state and national energy cost savings can be calculated using the PV multipliers in Table 1.

Discussion

Geographic differences in per-CRA rates

Spatial variations in the per-CRA annual rates of cooling energy saving and heating energy penalty correspond reasonably well to those in annual cooling and heating degree days. That is, the influence of cool roof installation on energy use maps well to climate. However, per-CRA values of annual energy cost saving and emission reduction can depend as much on regional differences in energy prices and electricity emission factors as on climate.

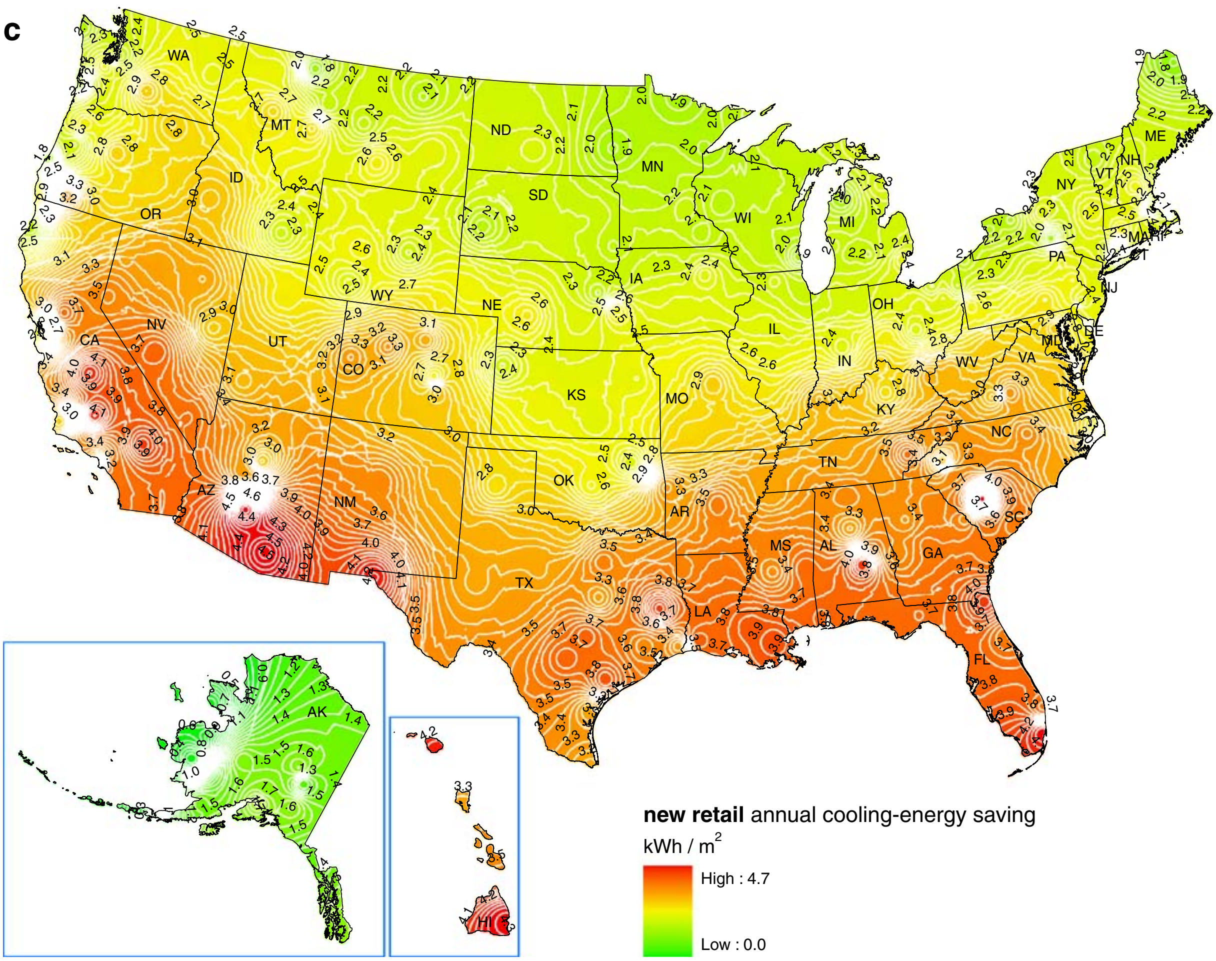


Fig. 9 (continued)

While some of the regional variations in electricity emission factors can clearly be explained by generation resource mix—e.g., nuclear and hydro sources produce no airborne emissions; coal and oil contain more sulfur than does natural gas; and coal is the primary source of airborne Hg—emission factors are not simply linear functions of fossil fuel mix. Emission rates can be reduced through the use of air pollution control devices and efficient generation equipment.

Comparing emission reductions to emissions from cars and power plants

The national-average annual rates of cool roof emission reductions are 3.02 kg CO_2, 4.81 g NO_x, 12.4 g SO_2, and 61.2 μg Hg per square meter of conditioned roof area. For context, we note that the US EPA estimates that the typical passenger car is driven 12,500 miles (21,100 km) annually, emitting 5.19 t CO_2 and 17.4 kg NO_x each year (EPA 2000). The US EPA does not quantify vehicular emissions of SO_2 and Hg. Installing 1,720 m^2 of cool roofing would offset the typical car's annual emission of CO_2, while 3,610 m^2 of cool roofing would be required to offset its annual emission of NO_x. Retrofitting the entire US stock of commercial buildings with cool roofs would reduce annual emissions by 7.80 Mt CO_2 (annual CO_2 output of 1.50 million cars) and 12.4 kt NO_x (annual NO_x output of 0.71 million cars).

Since cool roofs tend to save electricity at peak demand hours (e.g., late afternoon in summer), we also compare cool roof emission reductions to the emissions of a typical gas-fired plant used to produce

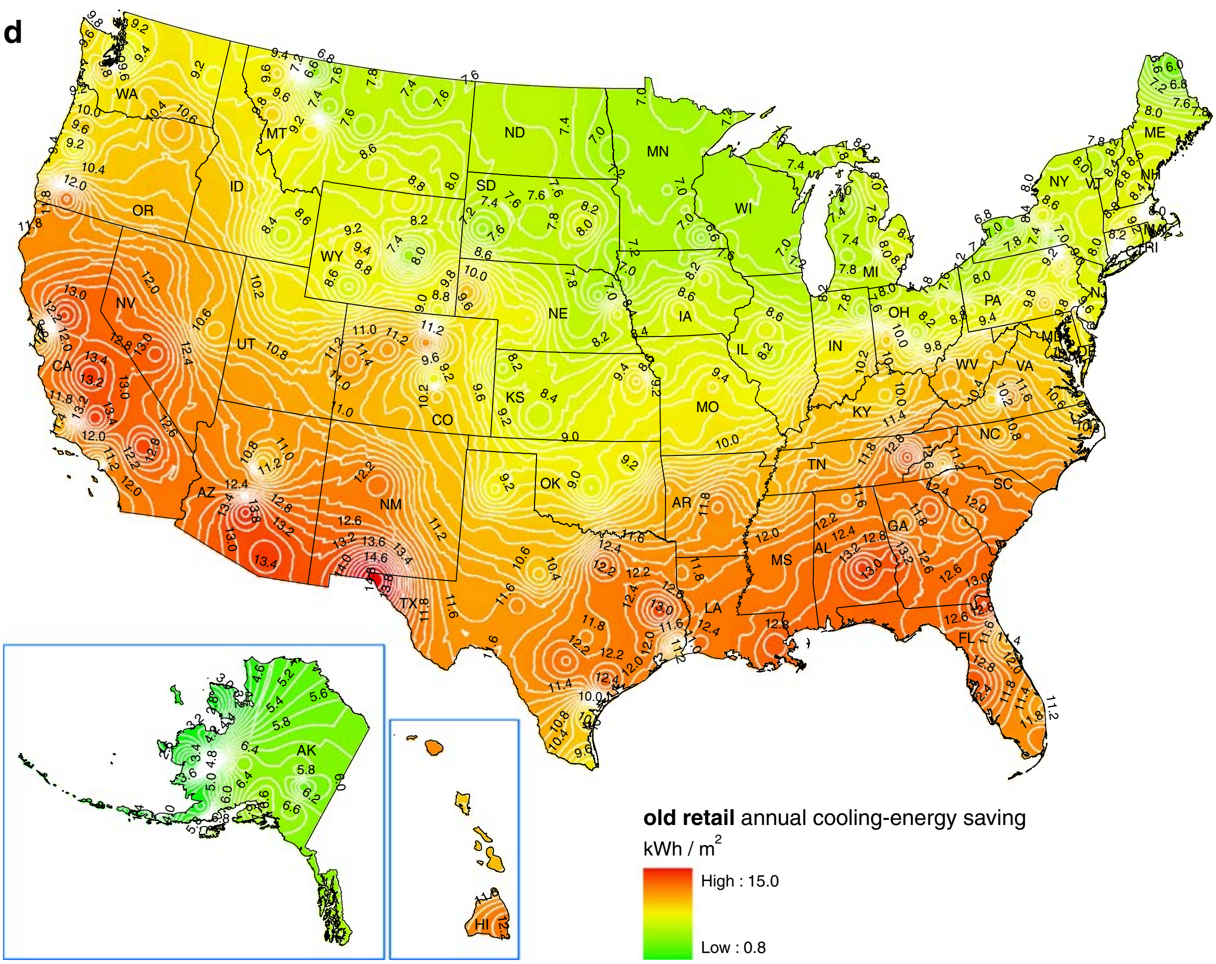


Fig. 9 (continued)

peak power. In 2004, the average annual energy output of the 1,380 US power plants that used natural gas as their primary fuel was 471 GWh. For purposes of comparison, we define a typical peak power plant as a 350-MW gas-fired plant operated at a capacity factor of 0.15 to generate 460 GWh/year, approximately equal to the average annual energy output of the aforementioned set of gas-fueled power plants. Using the average emission factors for this set of plants, the typical 350-MW peak power plant would annually emit 246 kt CO_2, 151 t NO_x, 31.4 t SO_2, and no Hg. Offsetting the peak power plant's emissions of CO_2, NO_x, or SO_2 would require the installation of 81.3 million, 31.4 million, or 2.5 million square meters of cool roofing, respectively. Retrofitting the entire US stock of commercial buildings with cool roofs would reduce annual emissions by 7.80 Mt CO_2 (annual CO_2 output of 31.8 peak power plants), 12.4 kt NO_x (annual NO_x output of 82.0 peak power plants), and 32.0 kt SO_2 (annual SO_2 output of 1,020 peak power plants).

National sums

State and national potentials for commercial building cool roof savings depend on both average per-CRA rates and the total CRA that can be made cool. For example, retrofitting 80% of the 2.58 billion square meters of commercial building CRA in the USA would yield

- an annual cooling energy saving of 10.4 TWh;
- an annual heating energy penalty of 133 million therms;

Table 5 Ratio of conditioned roof area to population ($r_{j,d}$; m^2/thousand persons) for the stock of commercial building class j in each US census division d

	New England	Middle Atlantic	East North Central	West North Central	South Atlantic	East South Central	West South Central	Mountain	Pacific
Vacant, new	0	97	33	24	54	20	217	64	61
Vacant, old	225	59	275	272	129	187	283	17	112
Office, new	433	538	834	643	674	540	859	654	597
Office, old	437	1081	755	1056	490	554	410	830	558
Laboratory, new	42	12	14	0	55	96	20	8	74
Laboratory, old	138	16	39	0	0	0	0	11	2
Non-refrigerated warehouse, new	138	567	428	517	673	532	797	403	273
Non-refrigerated warehouse, old	331	181	764	690	365	135	365	233	166
Food sales, new	124	75	178	171	159	61	313	33	50
Food sales, old	175	176	99	159	114	196	90	116	116
Public order and safety, new	9	122	50	219	110	118	170	81	18
Public order and safety, old	88	63	23	36	9	38	19	37	55
Outpatient health care, new	24	57	159	166	207	170	126	264	98
Outpatient health care, old	11	91	90	125	79	121	10	163	66
Refrigerated warehouse, new	0	0	1	7	39	34	14	0	45
Refrigerated warehouse, old	0	3	68	0	2	0	0	0	12
Religious worship, new	0	158	273	296	459	616	298	245	80
Religious worship, old	101	235	408	615	317	385	500	272	281
Public assembly, new	12	75	271	379	242	384	527	69	217
Public assembly, old	518	659	213	407	211	387	248	328	235
Education, new	36	71	554	353	1580	199	1262	852	349
Education, old	324	553	655	708	1049	844	998	976	981
Food service, new	23	53	155	129	279	122	375	73	184
Food service, old	122	66	172	389	182	286	194	40	92
Inpatient health care, new	10	14	15	38	66	174	90	69	25
Inpatient health care, old	10	68	81	105	137	46	36	49	57
Nursing, new	15	60	0	110	68	51	86	159	46
Nursing, old	50	24	119	382	126	50	8	132	51
Lodging, new	167	44	126	276	157	219	143	96	142
Lodging, old	204	114	102	459	102	324	99	311	175
Strip shopping mall, new	169	126	175	68	393	216	444	178	207
Strip shopping mall, old	267	88	200	2	146	141	195	195	87
Enclosed mall, new	338	63	0	48	187	46	52	166	179
Enclosed mall, old	20	68	42	109	0	28	123	78	5
Retail other than mall, new	178	181	231	490	566	908	409	294	486

Table 5 (continued)

	New England	Middle Atlantic	East North Central	West North Central	South Atlantic	East South Central	West South Central	Mountain	Pacific
Retail other than mall, old	333	350	399	432	379	464	473	370	392
Service, new	63	202	126	407	366	350	171	192	66
Service, old	256	272	316	495	128	523	128	456	153
Other, new	19	71	55	6	172	0	65	4	37
Other, old	4	148	62	64	0	108	33	85	10

- an annual energy cost saving of $735 million;
- an annual CO_2 reduction of 6.23 Mt, offsetting the annual CO_2 emissions of 1.20 million cars or 25.4 peak power plants;
- an annual NO_x reduction of 9.93 kt, offsetting the annual NO_x emissions of 0.57 million cars or 65.7 peak power plants;
- an annual SO_2 reduction of 25.6 kt, offsetting the annual SO_2 emissions of 815 peak power plants; and
- an annual Hg reduction of 126 kg.

We compare these values to past estimates of national savings (Konopacki et al. 1997) in Appendix, finding good agreement after accounting for improvements in building energy simulation and estimation of building stock.

Summary

This study combines city-specific building energy simulations, state energy prices, regional electricity emission factors (mass of greenhouse gas or air pollutant emitted per unit energy supplied to the grid), and county-level estimates of building density to characterize local, state-average, and US-average values of cooling energy saving, heating energy penalty, energy cost saving, and emission reduction per unit conditioned roof area.

We used a building energy model with an enhanced roof assembly heat transfer module to simulate in each of 236 US cities the annual heating and cooling energy uses of new and old office and retail building prototypes. We estimated for each combination of prototype and city the per-CRA cooling energy saving (annual cooling energy use with a conventional roof minus annual cooling-energy use with a cool roof) and per-CRA heating energy penalty (annual heating energy use with a cool roof minus annual heating energy use with a conventional roof) when roof solar reflectance is increased to 0.55 (weathered cool white roof) from 0.20 (weathered conventional gray roof).

Annual energy cost saving (economic value of cooling energy saving less economic value of heating-energy penalty) was calculated using year 2005 average commercial sector prices of electricity and natural gas in each state. Net annual reductions in airborne emissions of CO_2, NO_x, SO_2, and Hg (emission decrease from cooling energy saving minus emission increase from heating energy penalty) were computed using year 2004 regional electricity generation emission factors (adjusted for transmission losses) and non-regional gas furnace emission factors.

Weighted by conditioned roof area of the building stock, state-average annual per-CRA cooling energy saving ranged from 3.30 kWh/m^2 in Alaska to 7.69 kWh/m^2 in Arizona; the national average was 5.02 kWh/m^2. State-average annual per-CRA heating energy penalty ranged from 0.003 $therm/m^2$ in Hawaii to 0.141 $therm/m^2$ in Wyoming (national average 0.065 $therm/m^2$). A cool roof almost always reduced the cooling load more than it increased the heating load.

Annual per-CRA energy cost saving ranged from $\$0.126/m^2$ in West Virginia to $\$1.14/m^2$ in Arizona; the national average was $\$0.356/m^2$.

Annual per-CRA CO_2 reduction ranged from 1.07 kg/m^2 in Alaska to 4.97 kg/m^2 in Hawaii (national average 3.02 kg/m^2). Annual per-CRA NO_x reduction ranged from 1.70 g/m^2 in New York to 11.7 g/m^2 in Hawaii; the national average was 4.81 g/m^2. Annual per-CRA SO_2 reduction ranged

Table 6 Matrix V of ratios of annual cooling-energy savings for each of 40 building classes to those of the four prototypes

	New office	Old office	New retail	Old retail
Vacant, new				
Vacant, old				
Office, new	1			
Office, old		1		
Laboratory, new	1			
Laboratory, old		1		
Non-refrigerated warehouse, new	1			
Non-refrigerated warehouse, old		1		
Food sales, new			1	
Food sales, old				1
Public order and safety, new	1			
Public order and safety, old		1		
Outpatient health care, new	1			
Outpatient health care, old		1		
Refrigerated warehouse, new	2			
Refrigerated warehouse, old		2		
Religious worship, new	0.4			
Religious worship, old		0.4		
Public assembly, new	0.6			
Public assembly, old		0.6		
Education, new	1.1			
Education, old		0.6		
Food service, new			1	
Food service, old				1
Inpatient health care, new	5.5			
Inpatient health care, old		3.1		
Nursing, new	3.6			
Nursing, old		2		
Lodging, new	3.6			
Lodging, old		2		
Strip shopping mall, new			1	
Strip shopping mall, old				1
Enclosed mall, new			1	
Enclosed mall, old				1
Retail other than mall, new			1	
Retail other than mall, old				1
Service, new			1	
Service, old				1
Other, new				
Other, old				

Blank entries are zero

from 1.79 g/m^2 in California to 26.1 g/m^2 in Alabama (national average 12.4 g/m^2). Annual per-CRA Hg reduction (excluding that in parts of Alaska and Hawaii for which Hg electricity emission factors were unavailable) ranged from 1.08 µg/m^2 in Alaska to 105 µg/m^2 in Alabama; the national average was 61.2 µg/m^2.

We calculated from a year 2003 survey of commercial building stock the total commercial building CRA in each of the nine US census

Table 7 Matrix W of ratios of annual heating-energy penalties for each of 40 building classes to those of the four prototypes

	New office	Old office	New retail	Old retail
Vacant, new				
Vacant, old				
Office, new	1			
Office, old		1		
Laboratory, new	1			
Laboratory, old		1		
Non-refrigerated warehouse, new	1			
Non-refrigerated warehouse, old		1		
Food sales, new			1	
Food sales, old				1
Public order and safety, new	1			
Public order and safety, old		1		
Outpatient health care, new	1			
Outpatient health care, old		1		
Refrigerated warehouse, new				
Refrigerated warehouse, old				
Religious worship, new	0.4			
Religious worship, old		0.4		
Public assembly, new	0.6			
Public assembly, old		0.6		
Education, new	3.7			
Education, old		1.5		
Food service, new			1	
Food service, old				1
Inpatient health care, new	16			
Inpatient health care, old		7		
Nursing, new	1.8			
Nursing, old		0.9		
Lodging, new	1.8			
Lodging, old		0.9		
Strip shopping mall, new			1	
Strip shopping mall, old				1
Enclosed mall, new			1	
Enclosed mall, old				1
Retail other than mall, new			1	
Retail other than mall, old				1
Service, new			1	
Service, old				1
Other, new				
Other, old				

Blank entries are zero

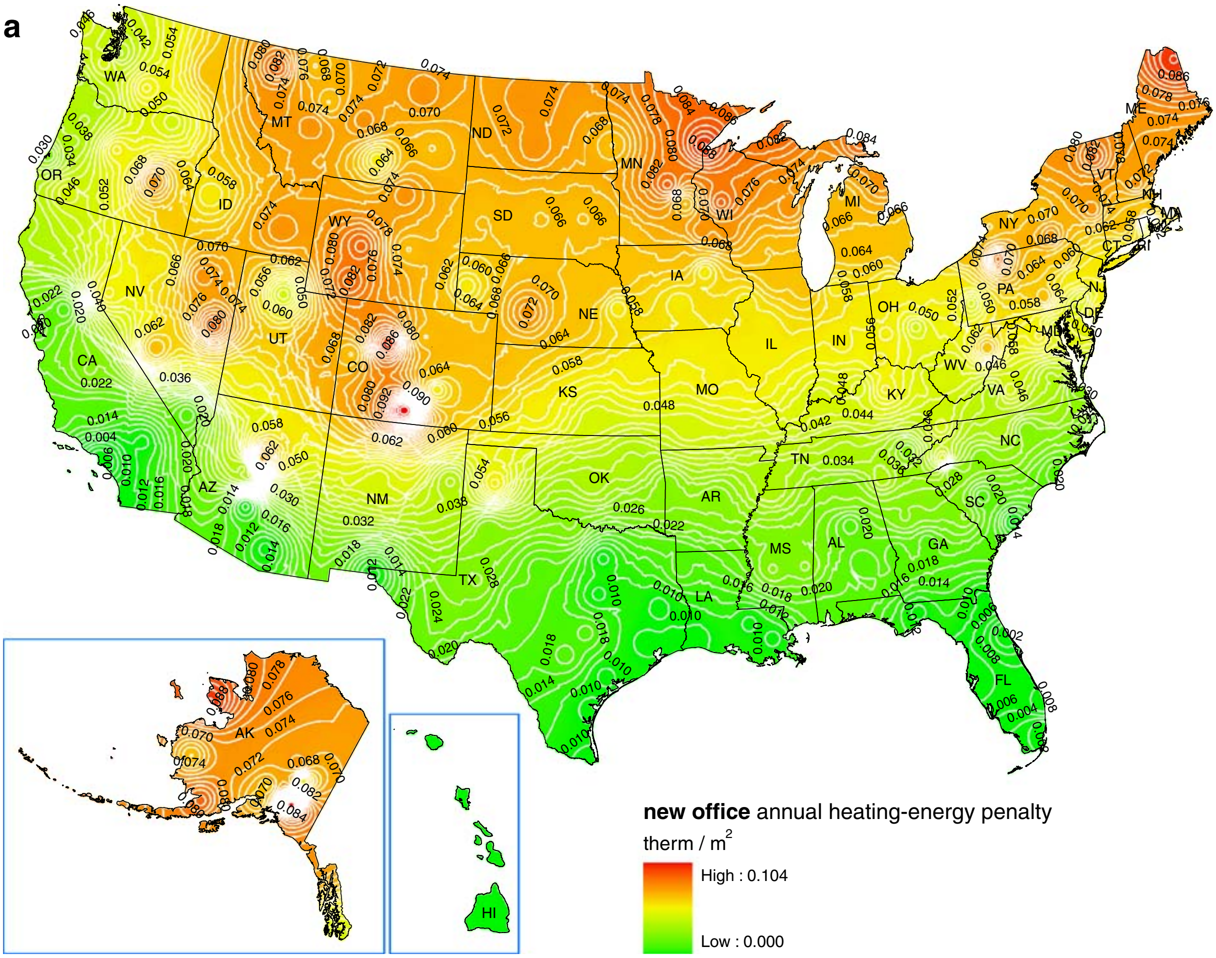


Fig. 10 Annual heating energy penalty per unit conditioned roof area $g_k(x, y)$ (therm/m^2) for each of four building prototypes k: **a** new office, **b** old office, **c** new retail, and **d** old retail

divisions. Local per-LA rates of saving, penalty, and reduction were estimated by multiplying a stock-weighted average of per-CRA rates by the local density of CRA (ratio of CRA to land area). We then calculated state-average rates as the ratio of state sums (integral of per-LA rate over state) to state CRA. National-average rates were computed in the same fashion.

We estimate that immediately retrofitting 80% of the 2.58 billion square meters of commercial building CRA in the USA would yield an annual cooling energy saving of 10.4 TWh; an annual heating energy penalty of 133 million therms; and an annual energy-cost saving of $735 million. It would also offer an annual CO_2 reduction of 6.23 Mt, offsetting the annual CO_2 emissions of 1.20 million cars or 25.4 peak power plants; an annual NO_x reduction of 9.93 kt, offsetting the annual NO_x emissions of 0.57 million cars or 65.7 peak power plants; an annual SO_2 reduction of 25.6 kt, offsetting the annual SO_2 emissions of 815 peak power plants; and an annual Hg reduction of 126 kg.

b

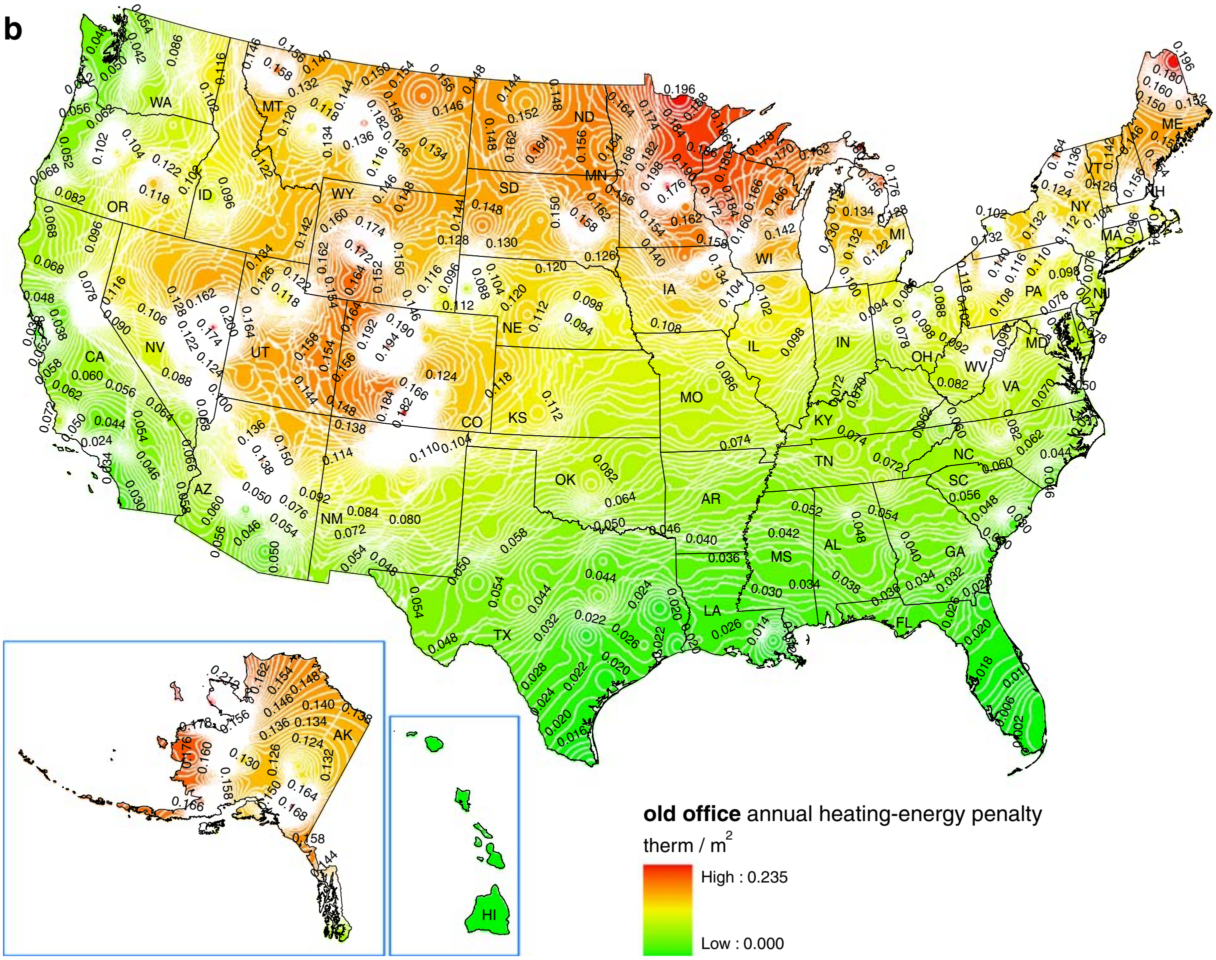


Fig. 10 (continued)

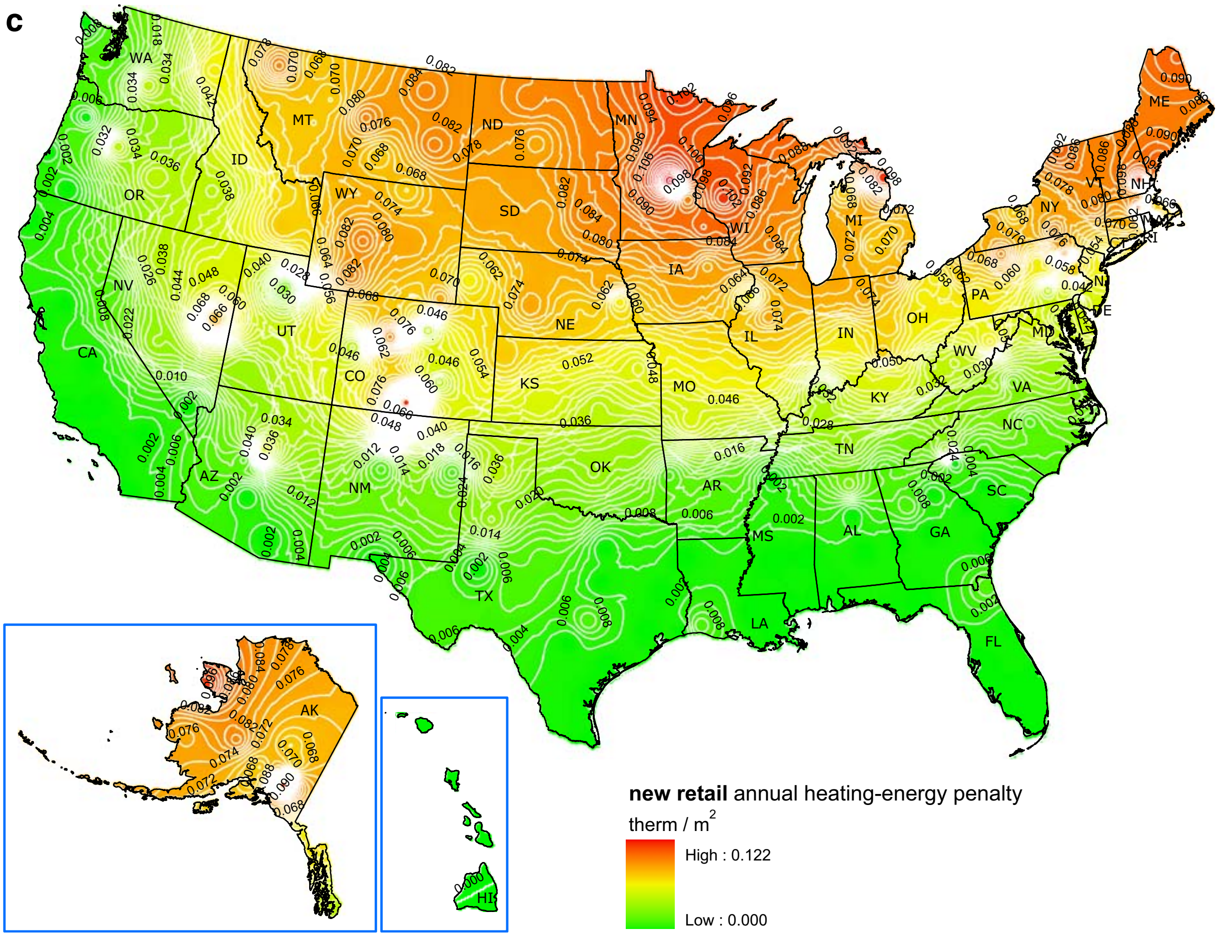


Fig. 10 (continued)

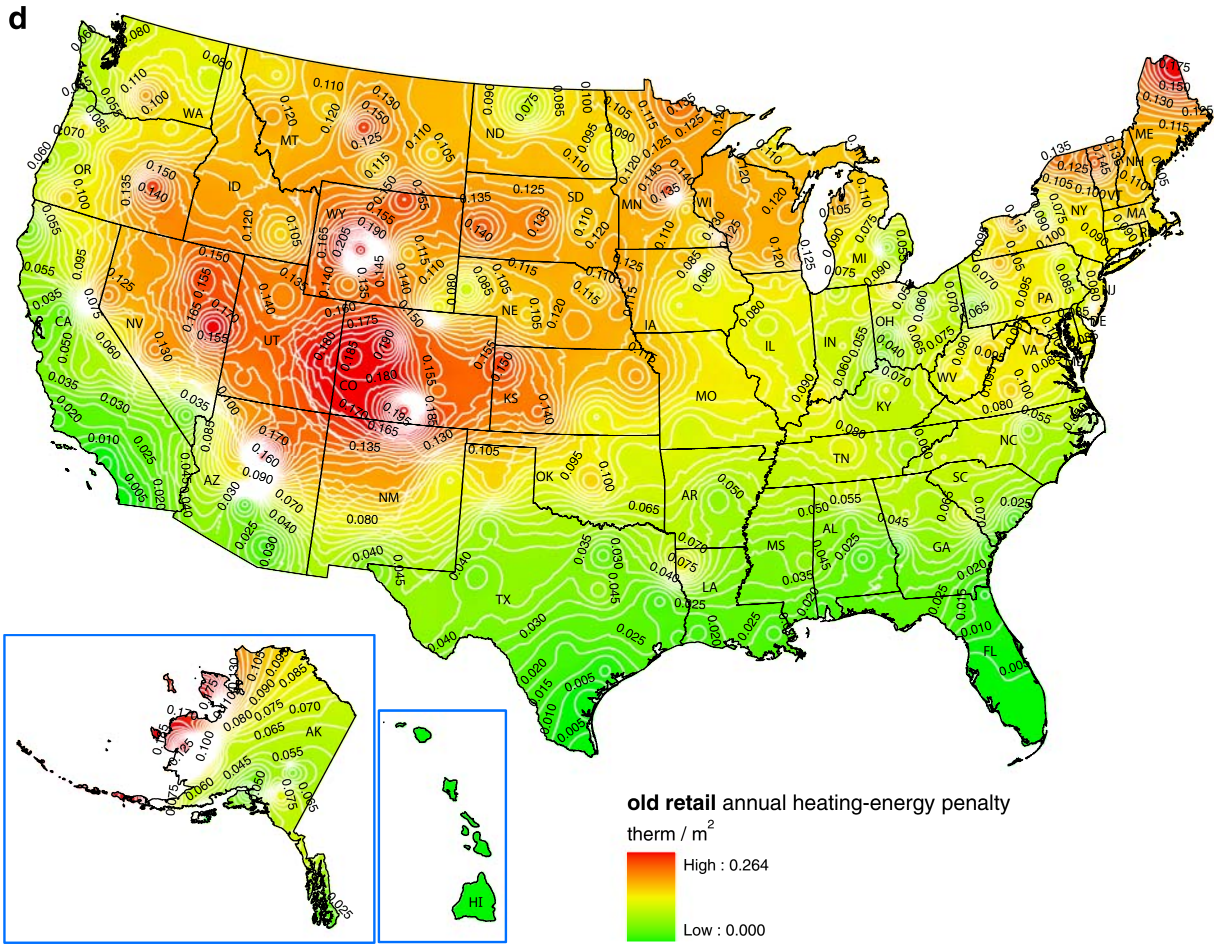


Fig. 10 (continued)

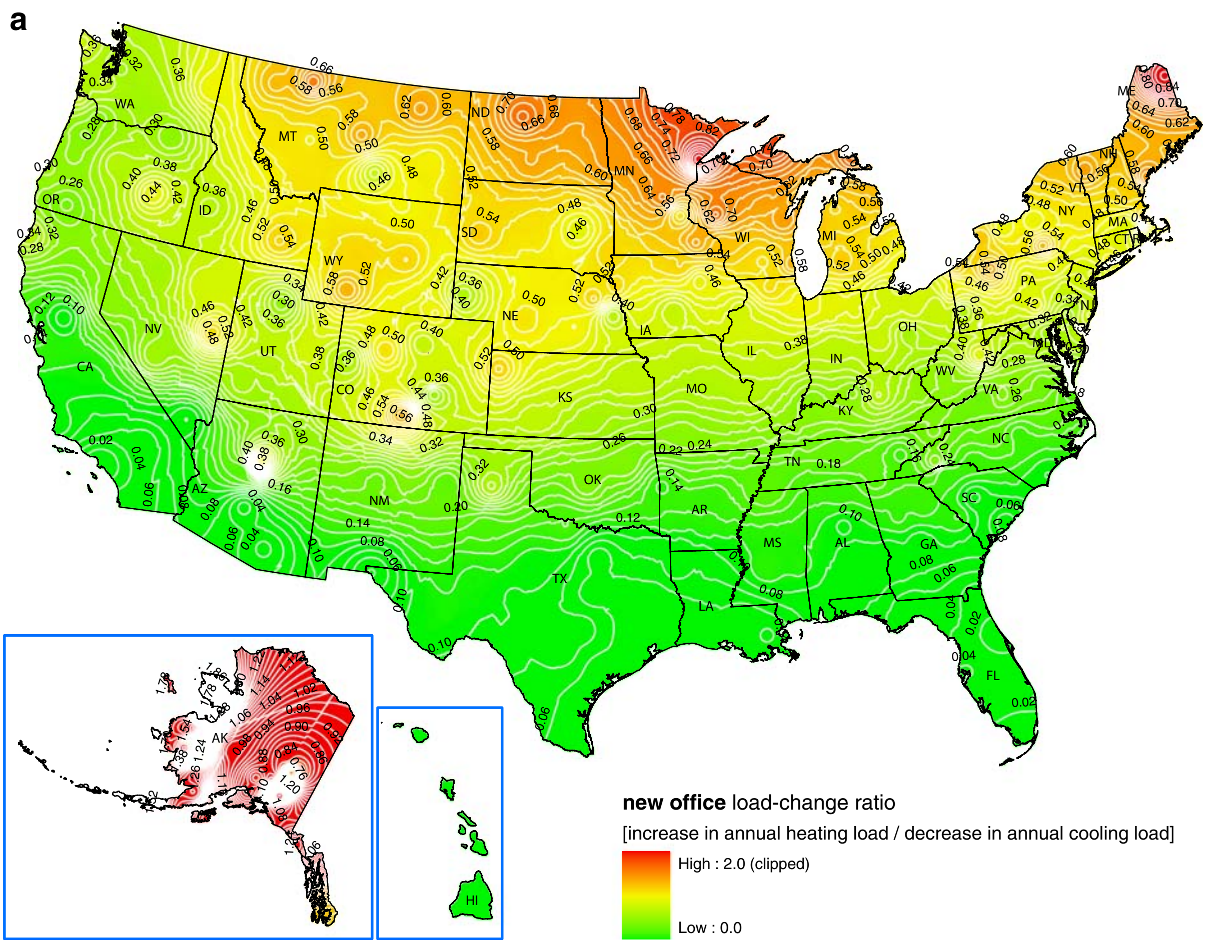


Fig. 11 Load change ratio (dimensionless ratio of increase in annual heating load to decrease in annual cooling load) $\ell_k(x, y)$ for each of four building prototypes k: **a** new office, **b** old office, **c** new retail, and **d** old retail

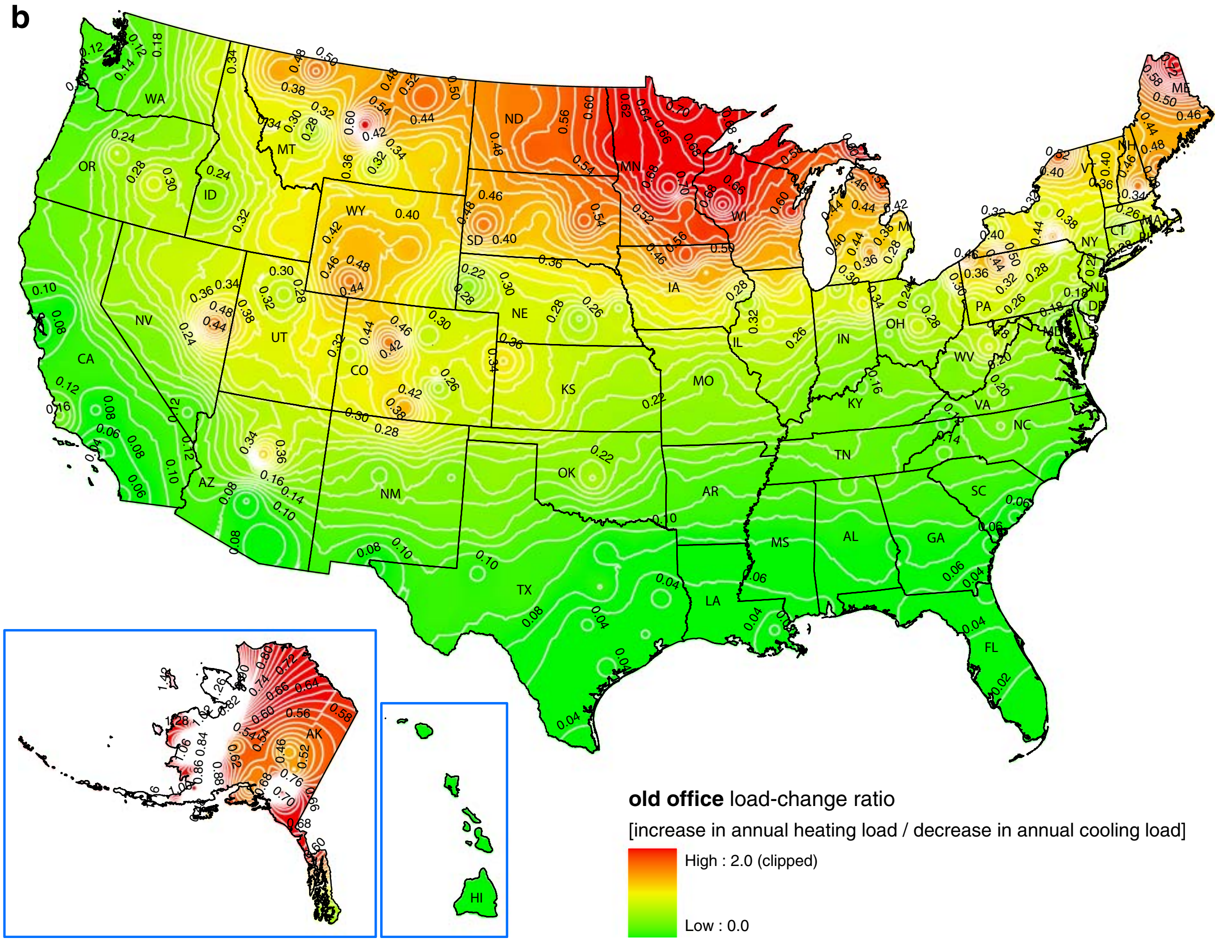


Fig. 11 (continued)

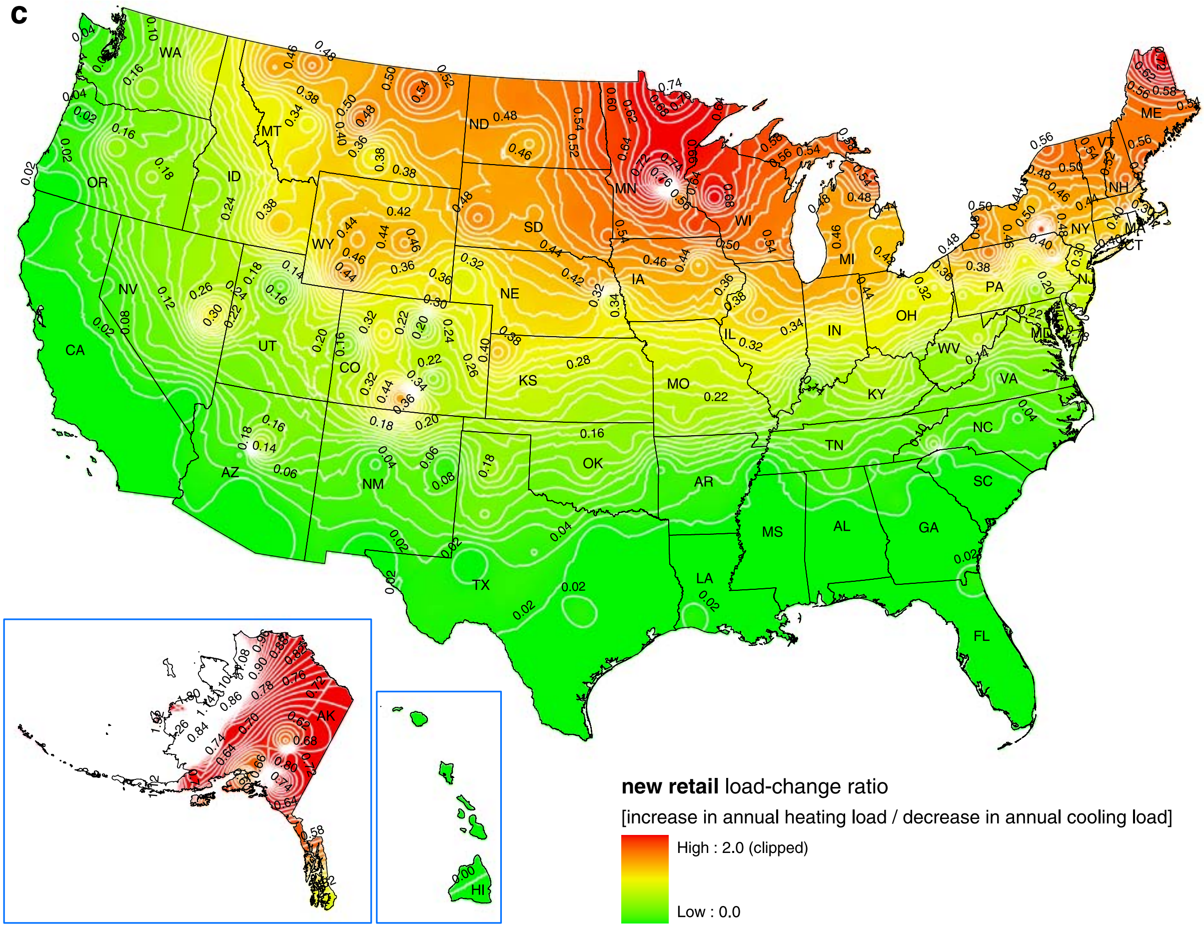
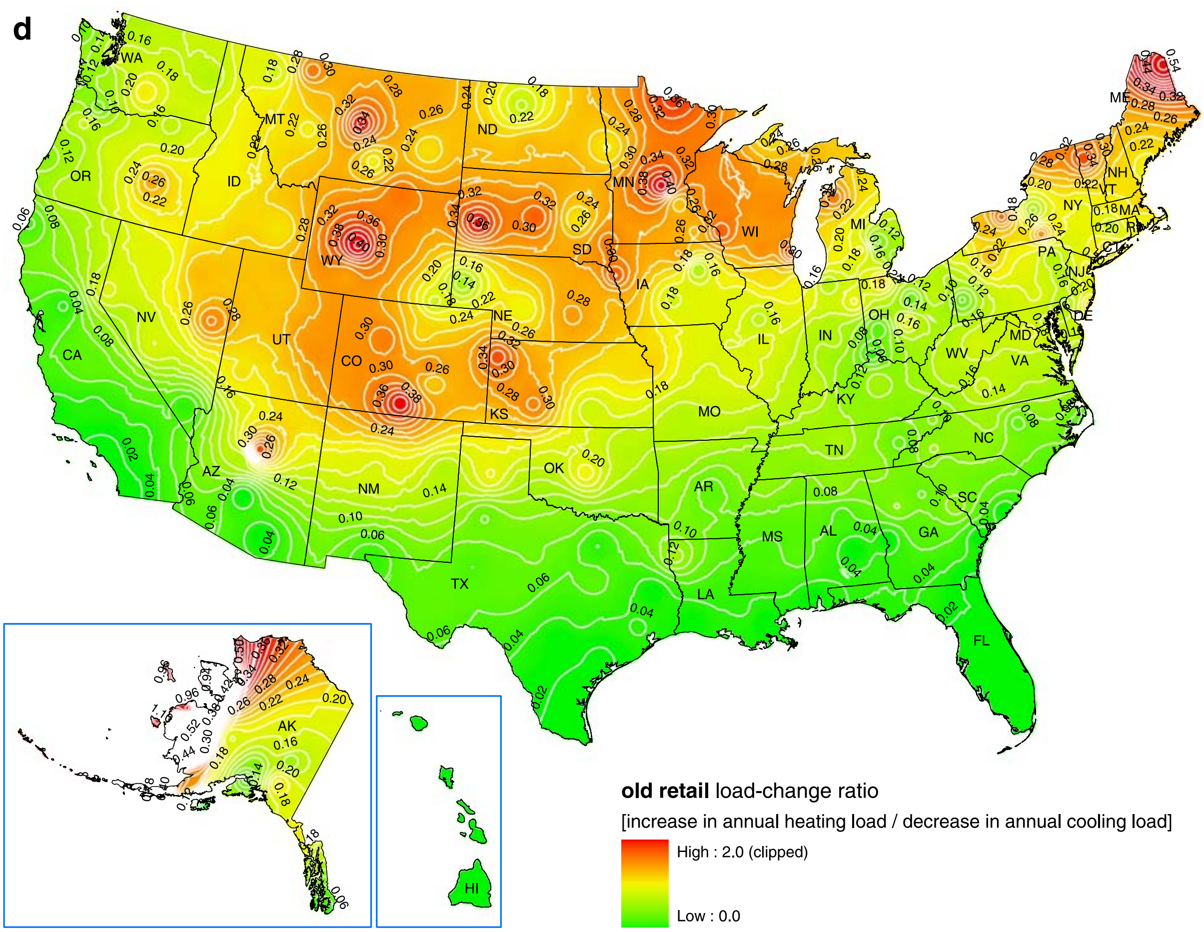


Fig. 11 (continued)



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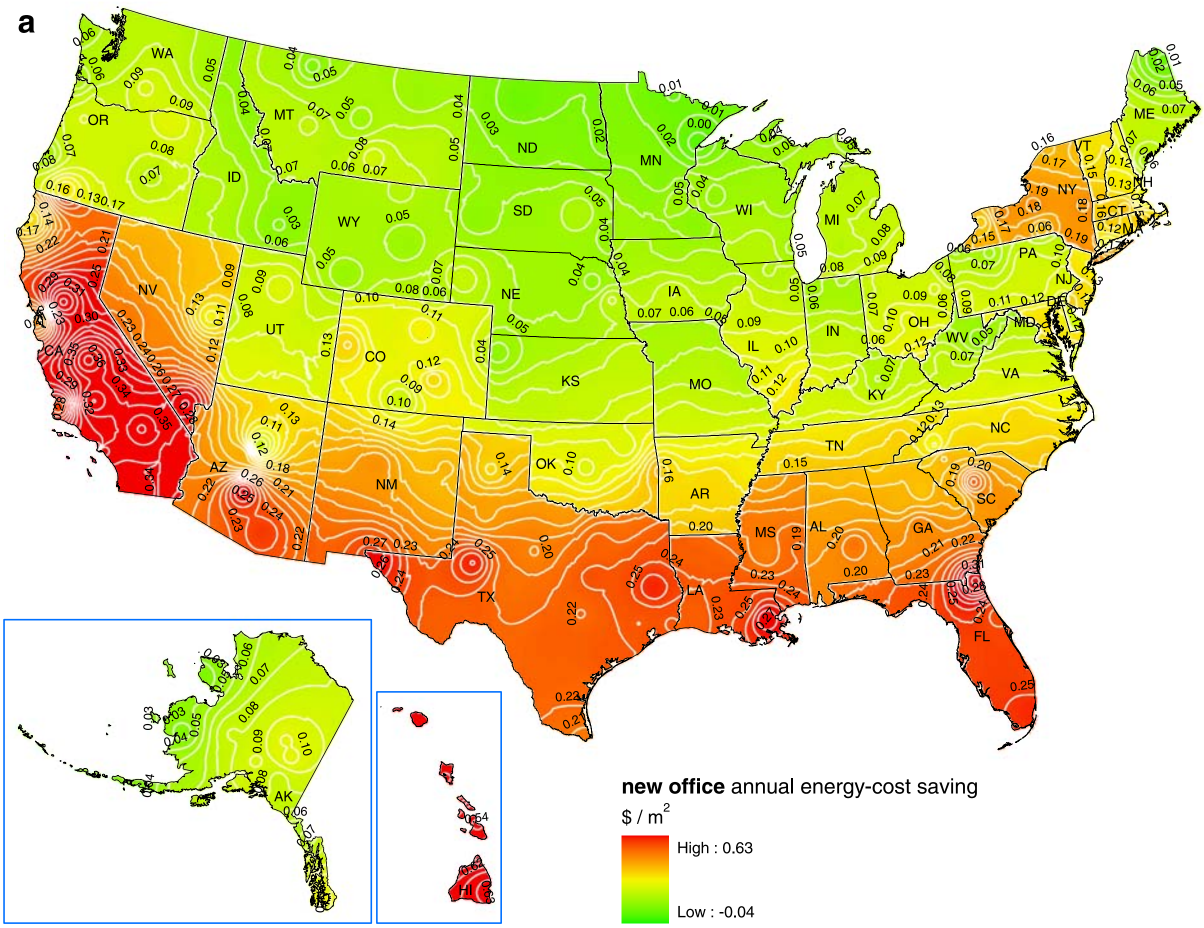


Fig. 12 Annual net energy cost saving per unit conditioned roof area $c(x, y)$ ($/m^2) for each of four building prototypes: **a** new office, **b** old office, **c** new retail, and **d** old retail

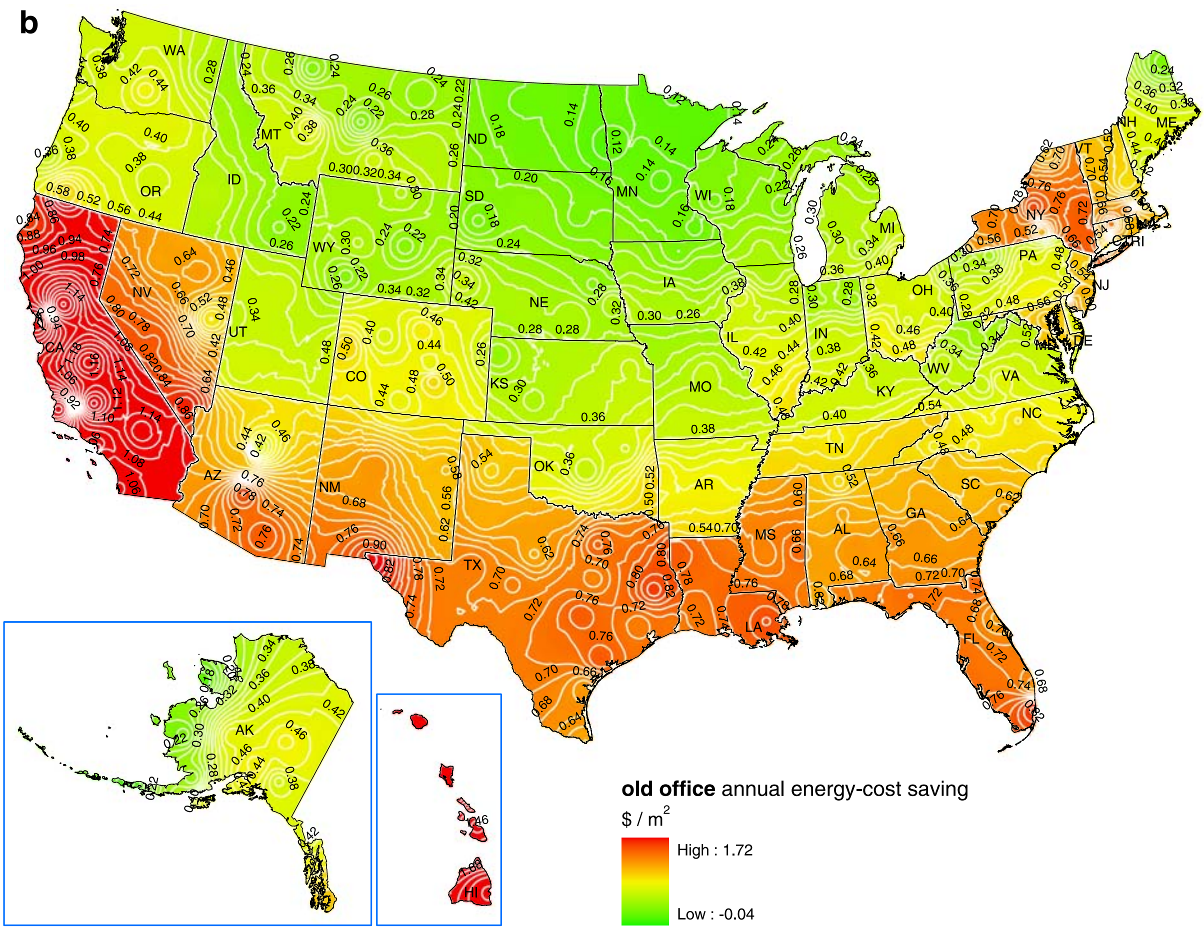
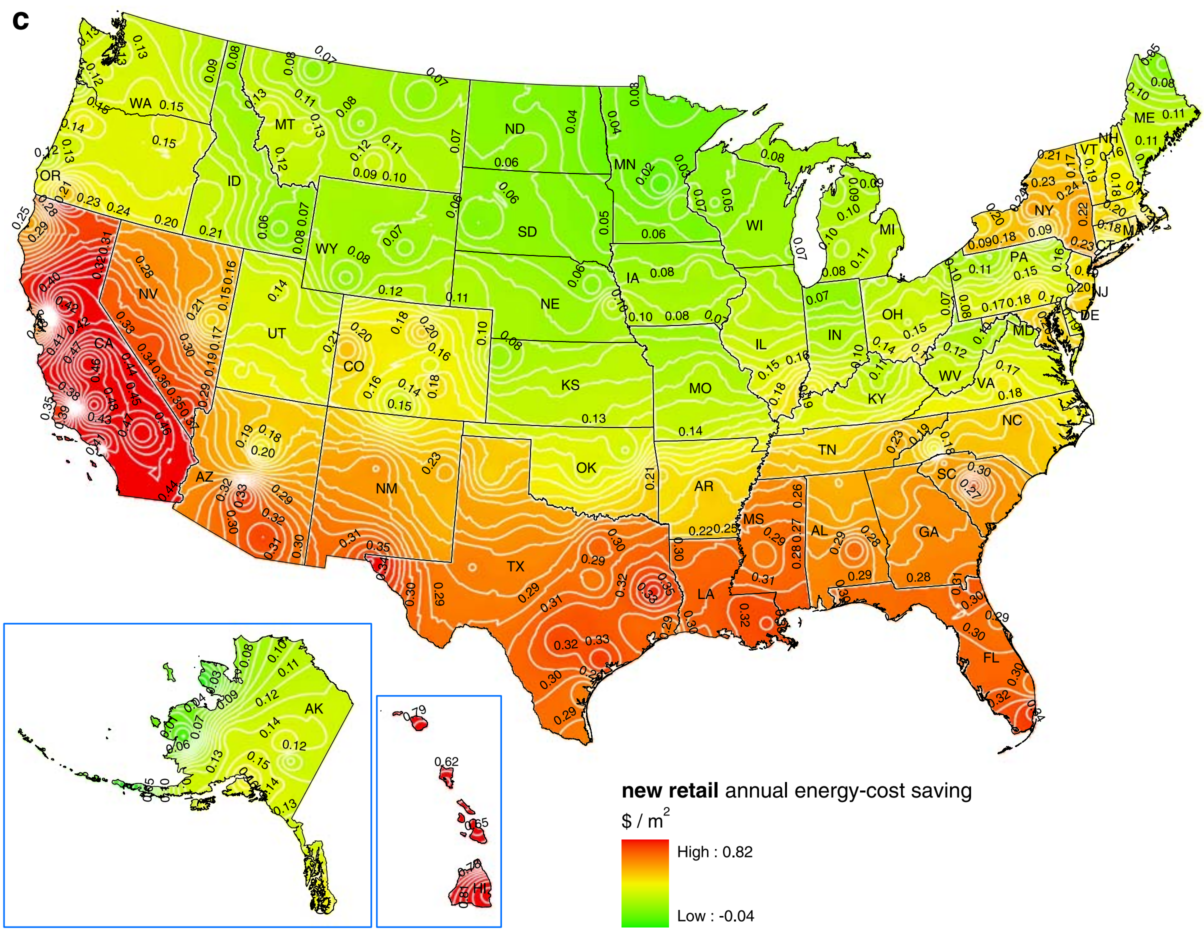


Fig. 12 (continued)



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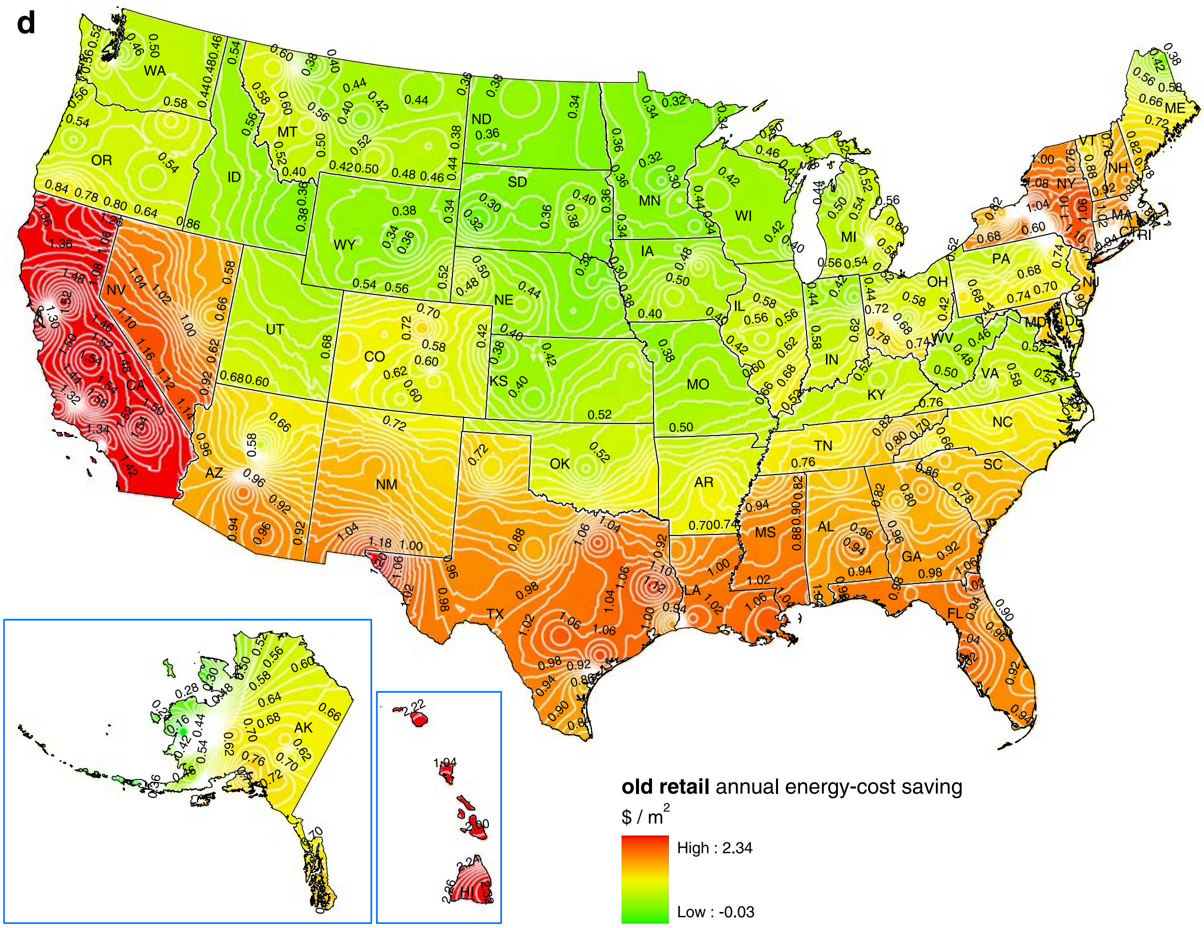

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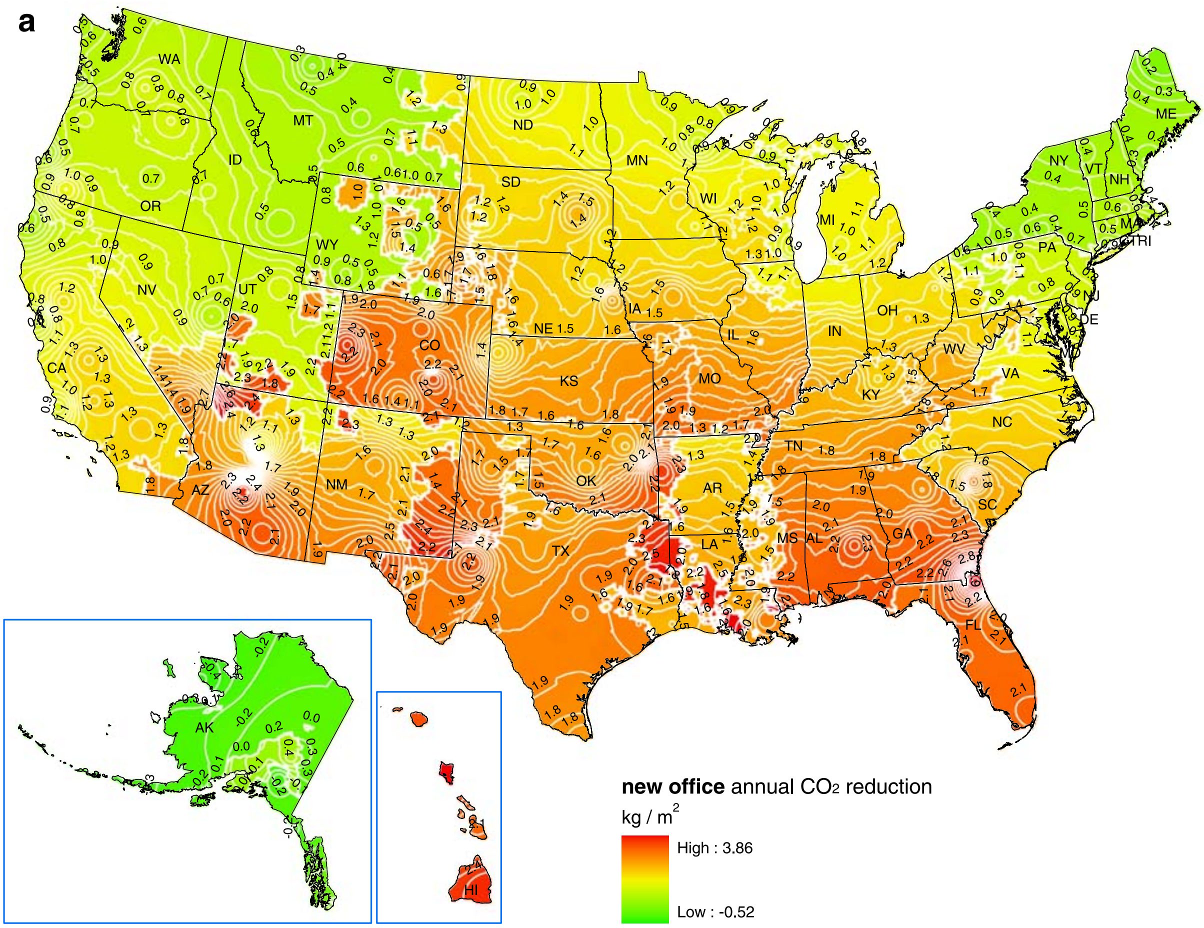


Fig. 13 Annual reduction in emission of carbon dioxide (CO_2) per unit conditioned roof area $p_{CO_2,k}(x,y)$ (kg/m^2) for each of four building prototypes k: **a** new office, **b** old office, **c** new retail, and **d** old retail

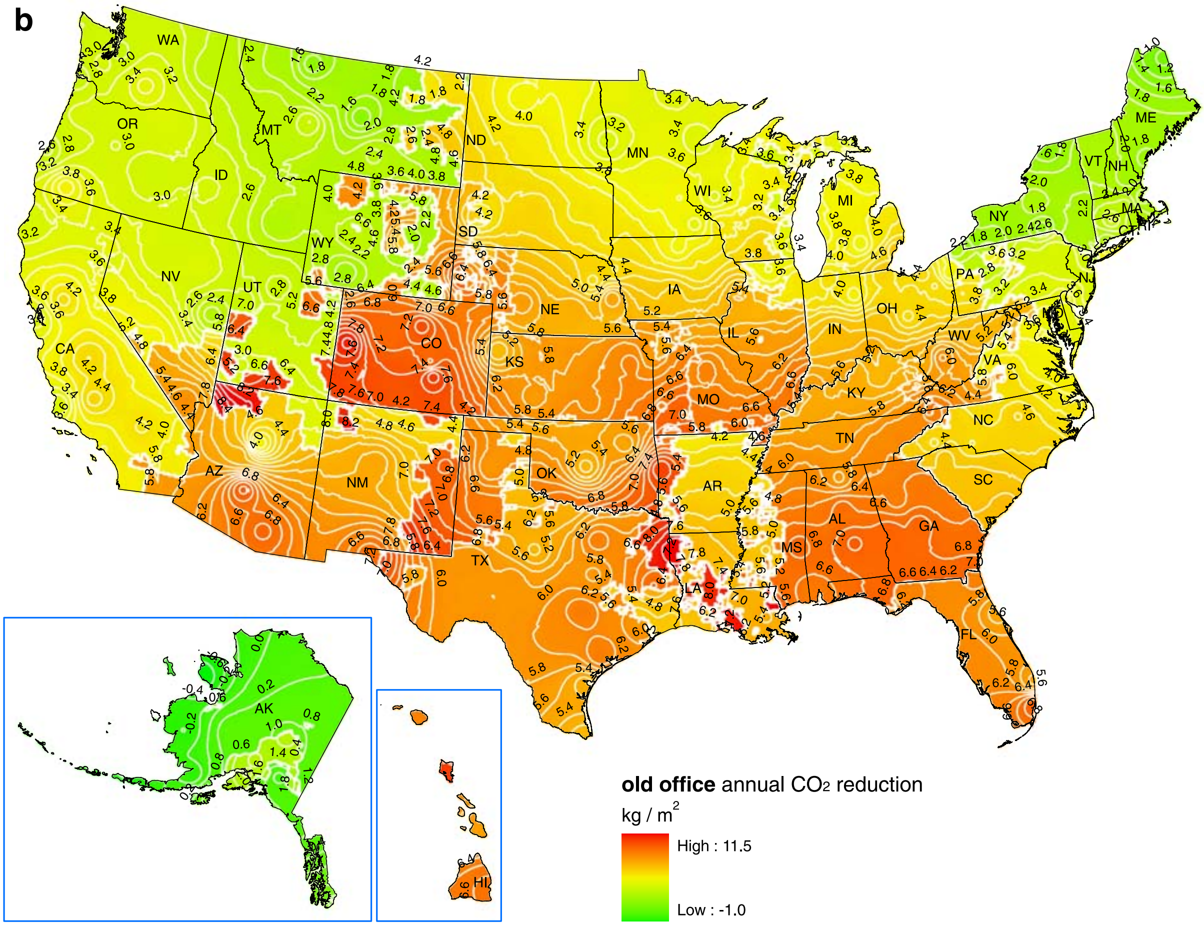


Fig. 13 (continued)

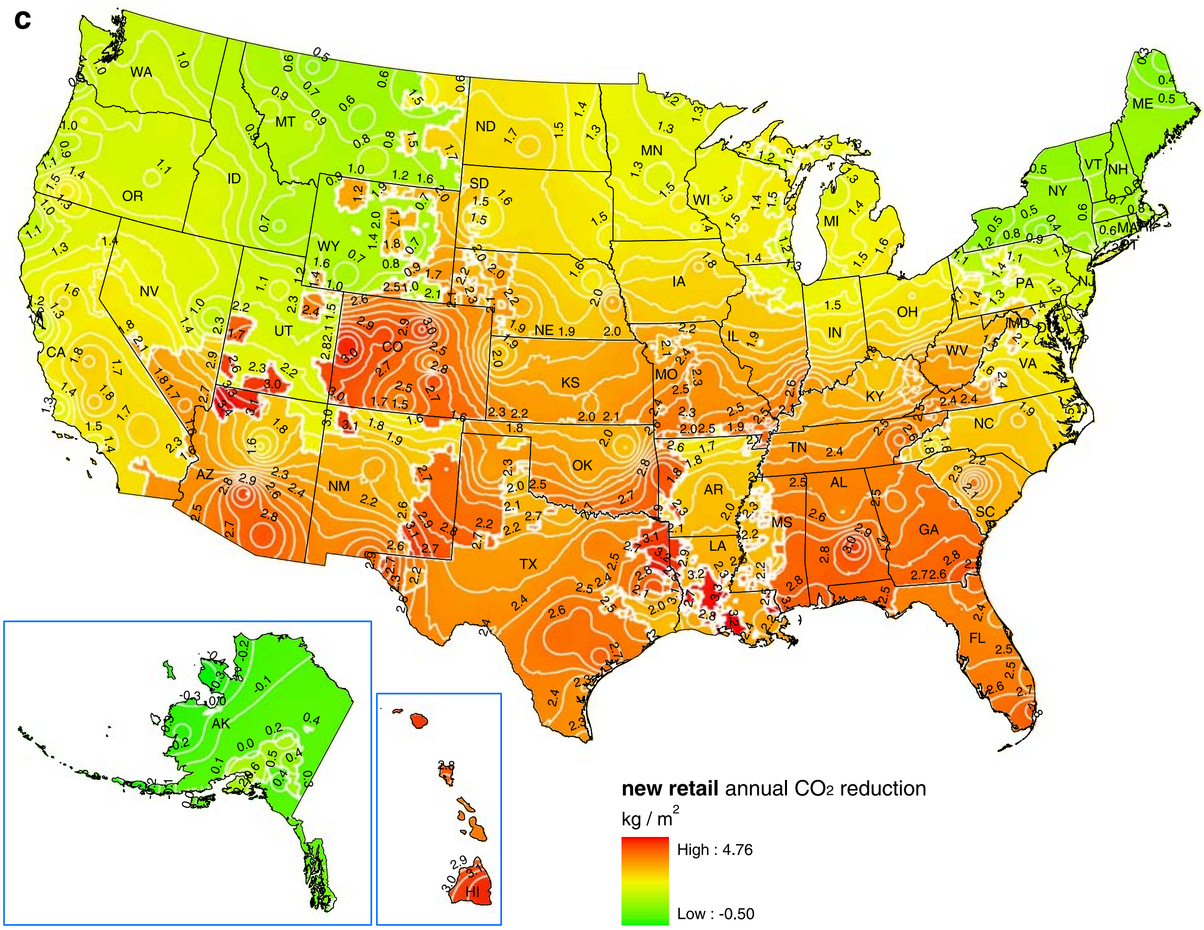
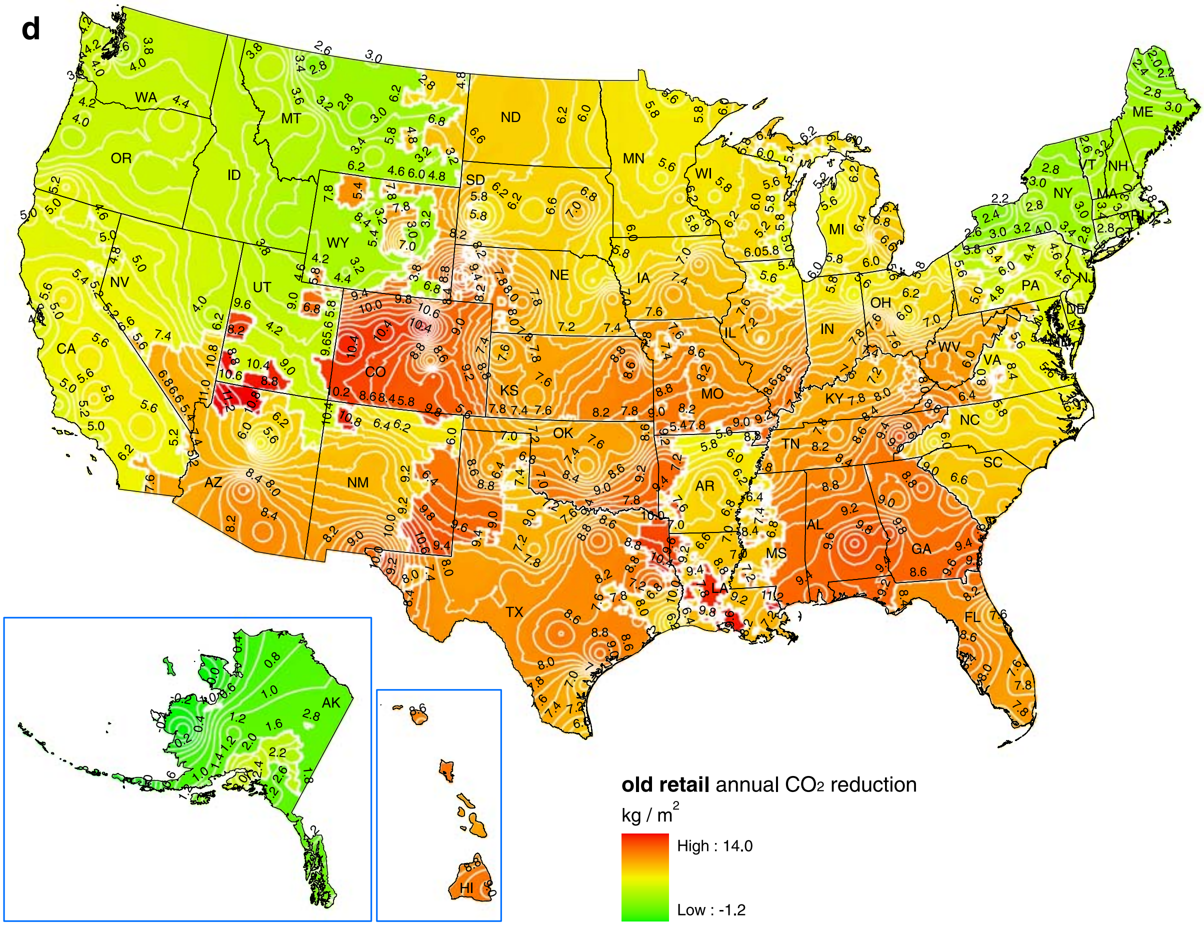


Fig. 13 (continued)



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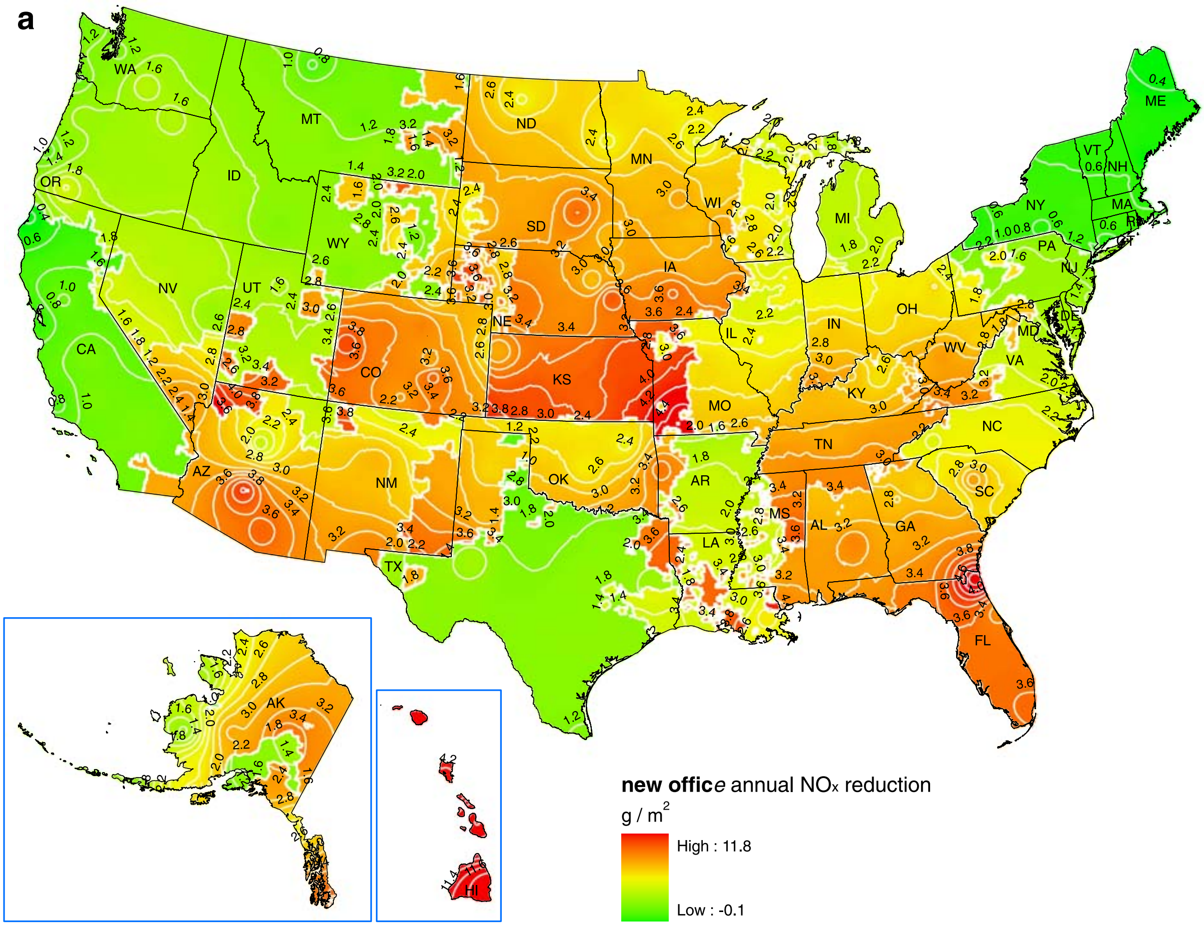


Fig. 14 Annual reduction in emission of nitrogen oxides (NO_x) per unit conditioned roof area $p_{NO_x,k}(x,y)$ (g/m^2) for each of four building prototypes k: **a** new office, **b** old office, **c** new retail, and **d** old retail

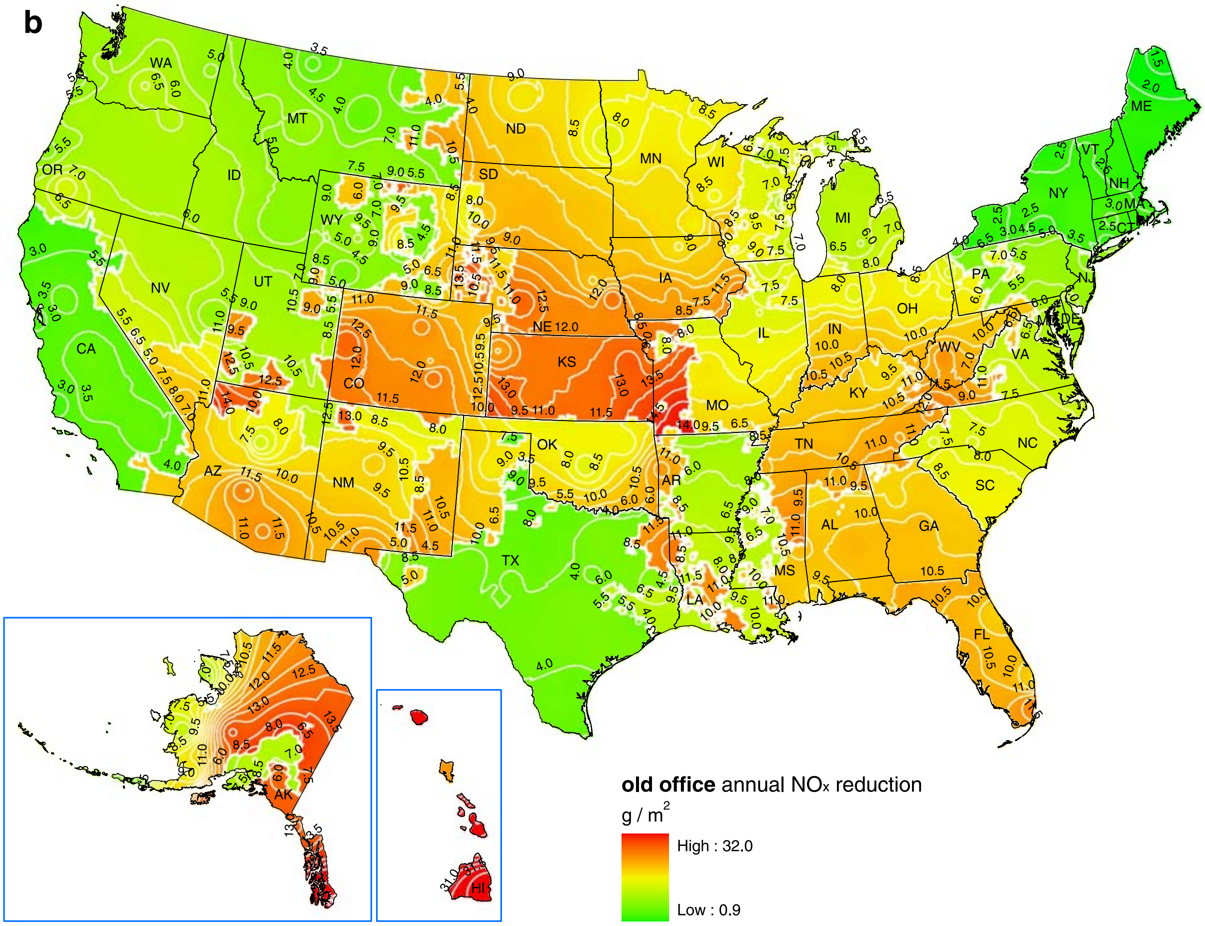
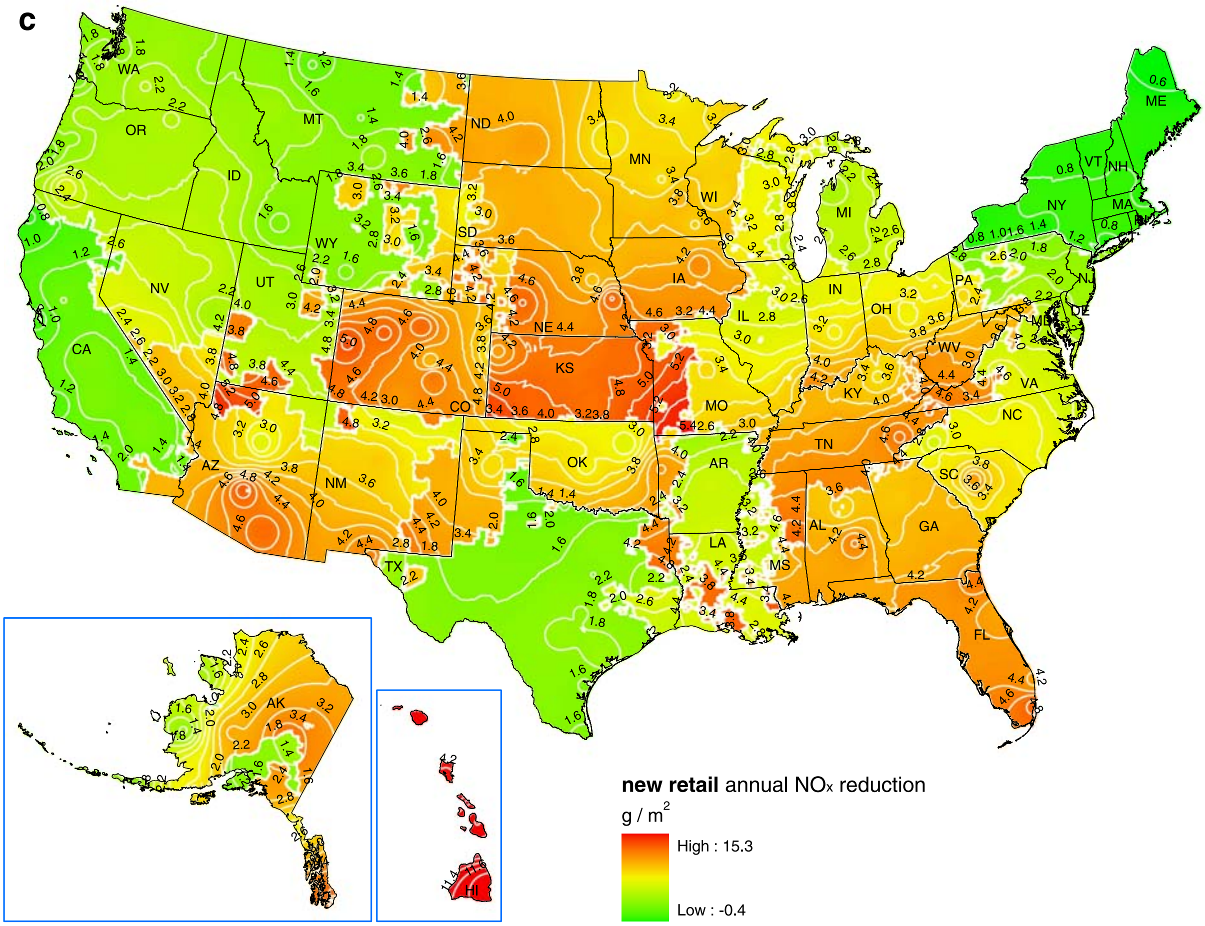


Fig. 14 (continued)



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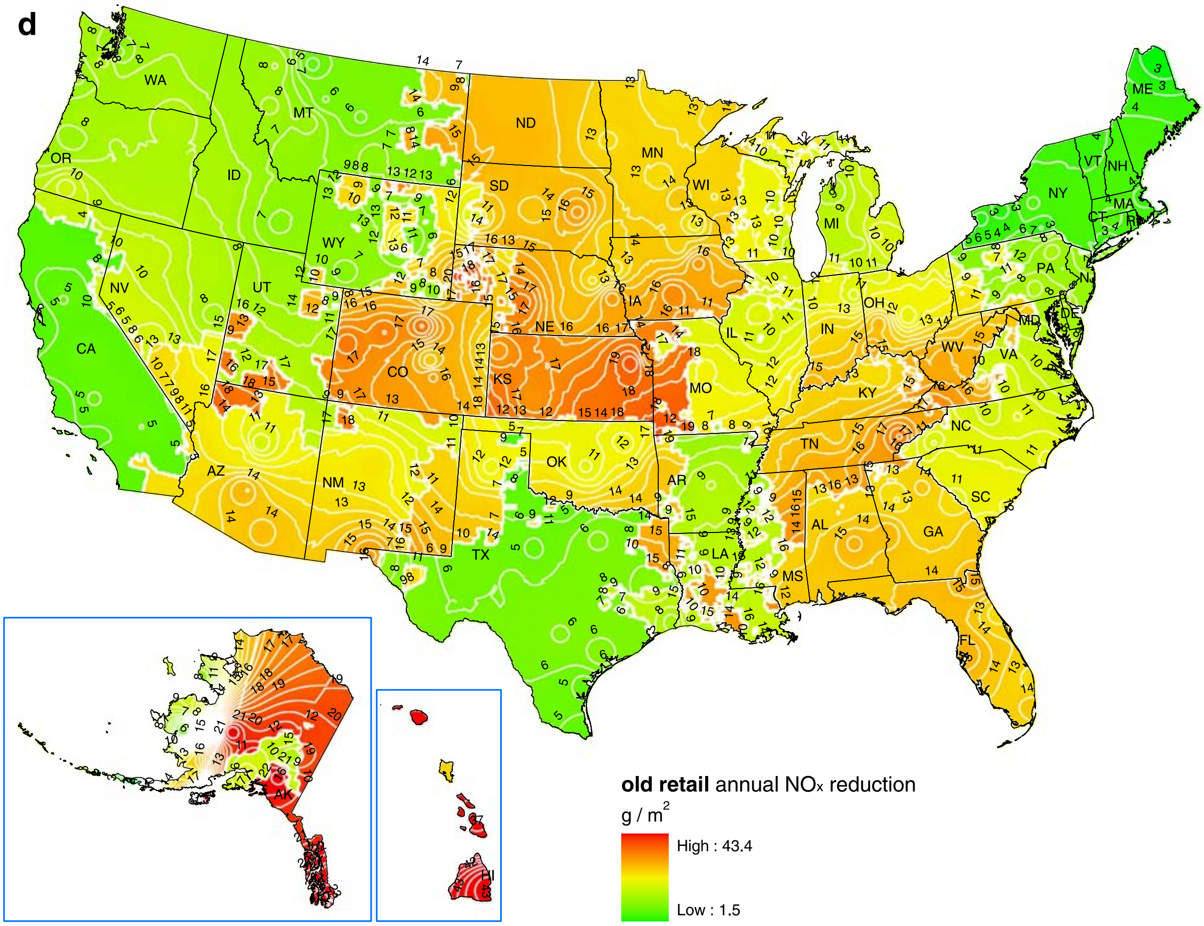

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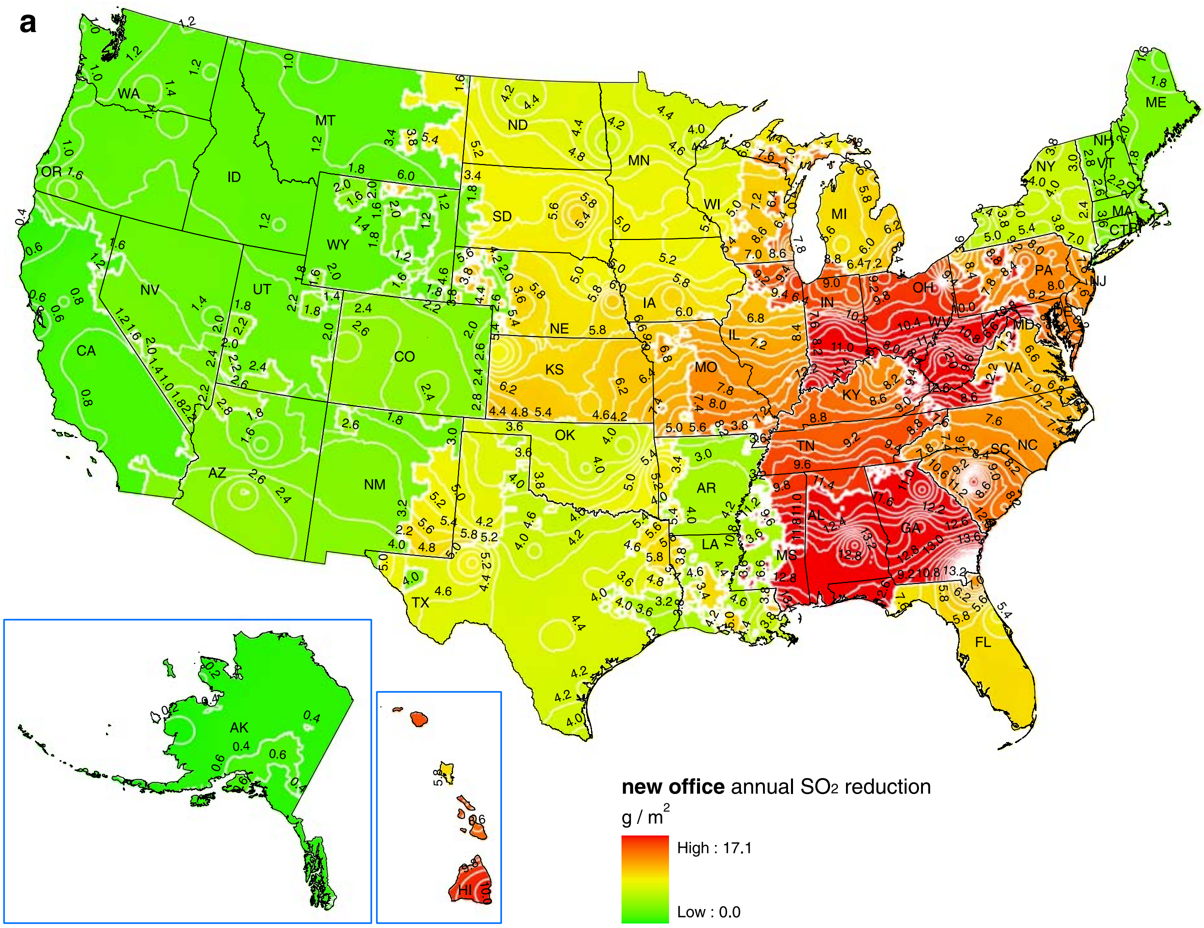


Fig. 15 Annual reduction in emission of sulfur dioxide (SO_2) per unit conditioned roof area $p_{SO_2,k}(x,y)$ (g/m^2) for each of four building prototypes k: **a** new office, **b** old office, **c** new retail, and **d** old retail

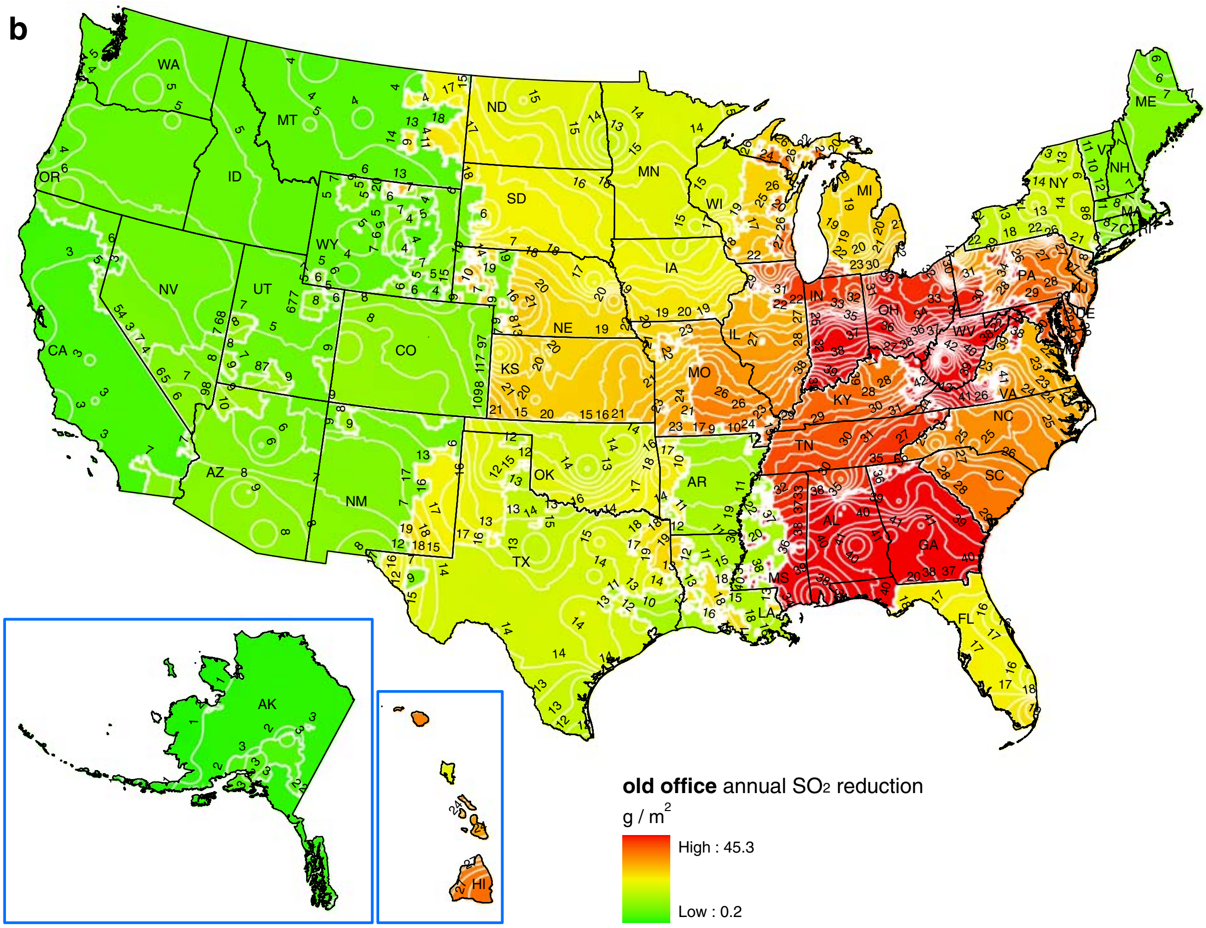


Fig. 15 (continued)

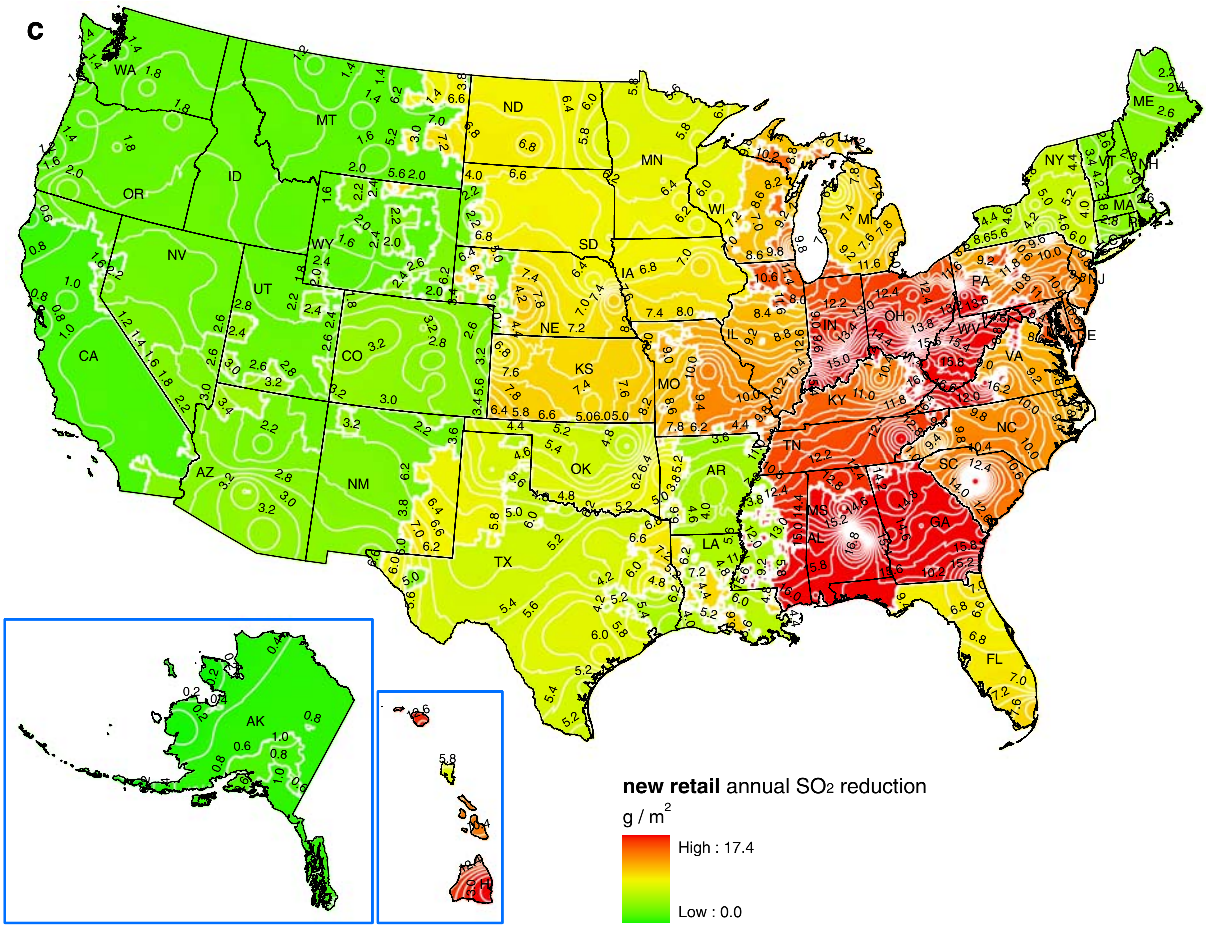


Fig. 15 (continued)

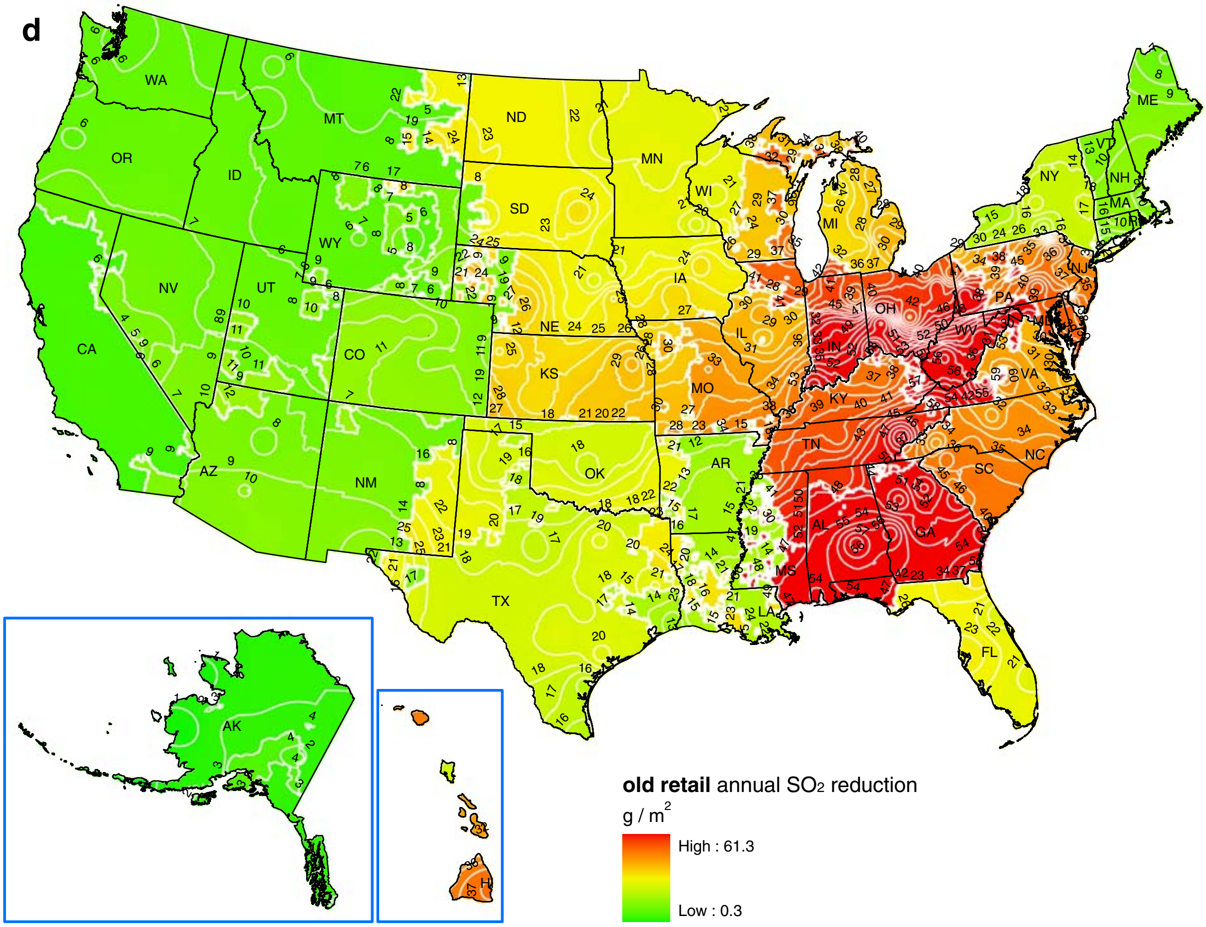


Fig. 15 (continued)

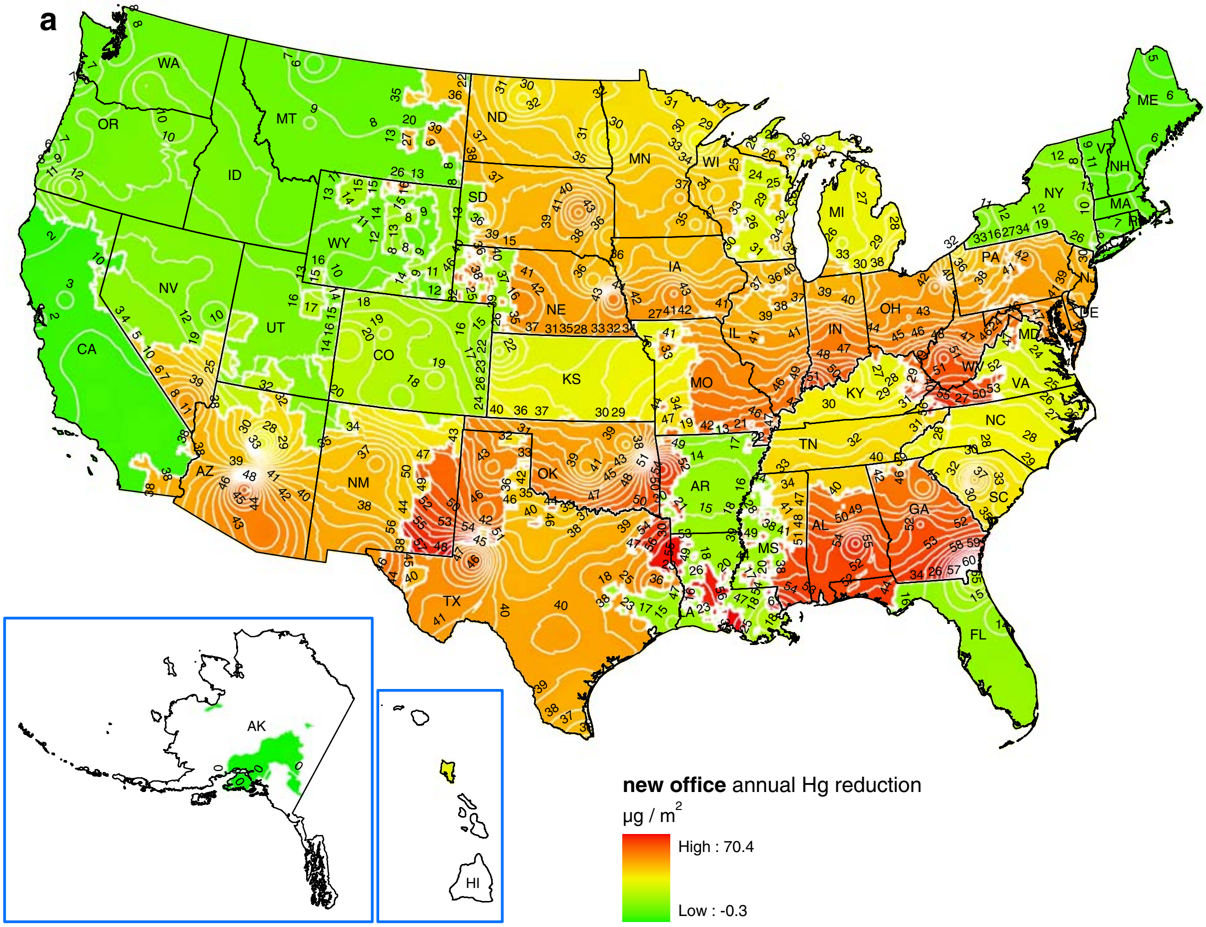


Fig. 16 Annual reduction in emission of mercury (Hg) per unit conditioned roof area $p_{\mathrm{Hg},k}(x,y)$ (μg/m^2) for each of four building prototypes k: **a** new office, **b** old office, **c** new retail, and **d** old retail

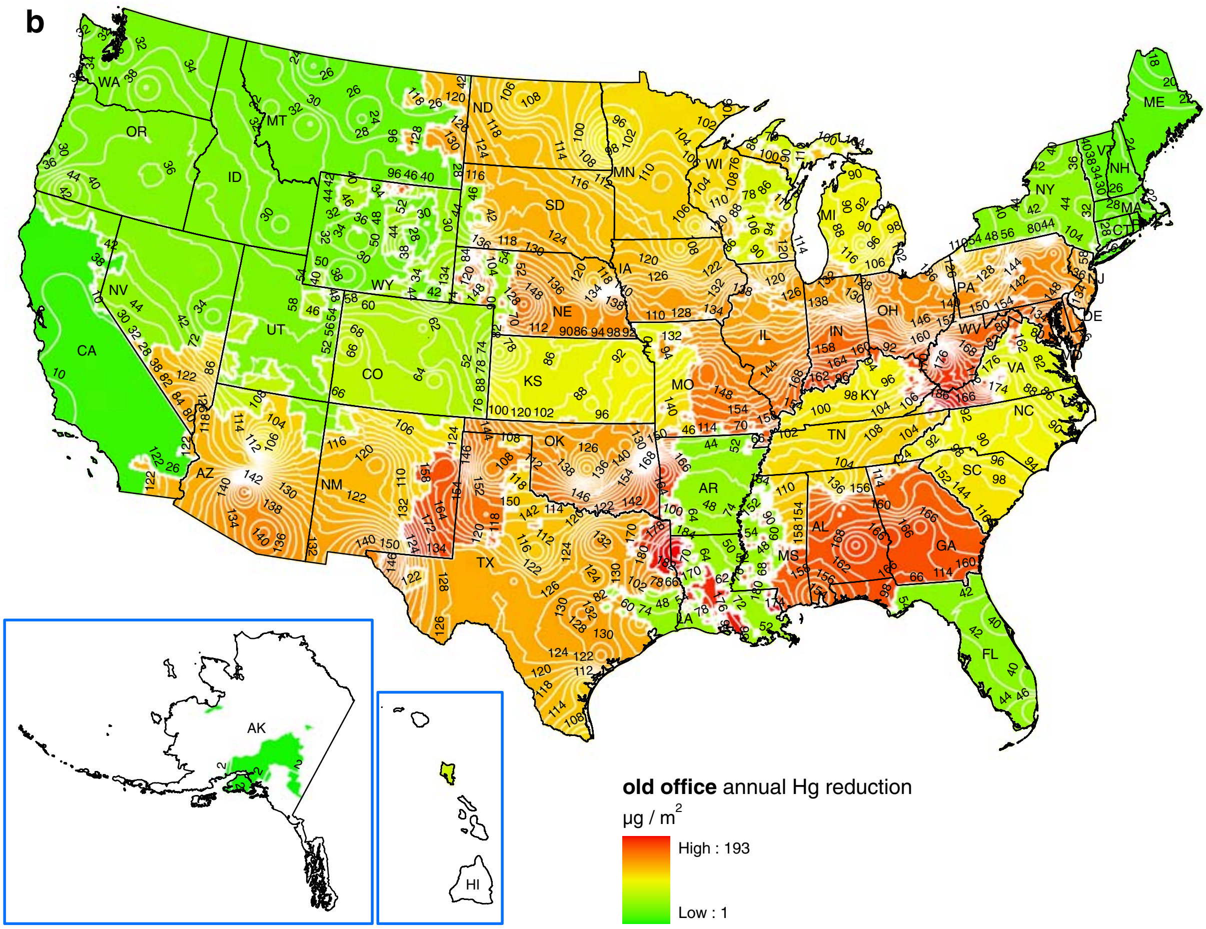
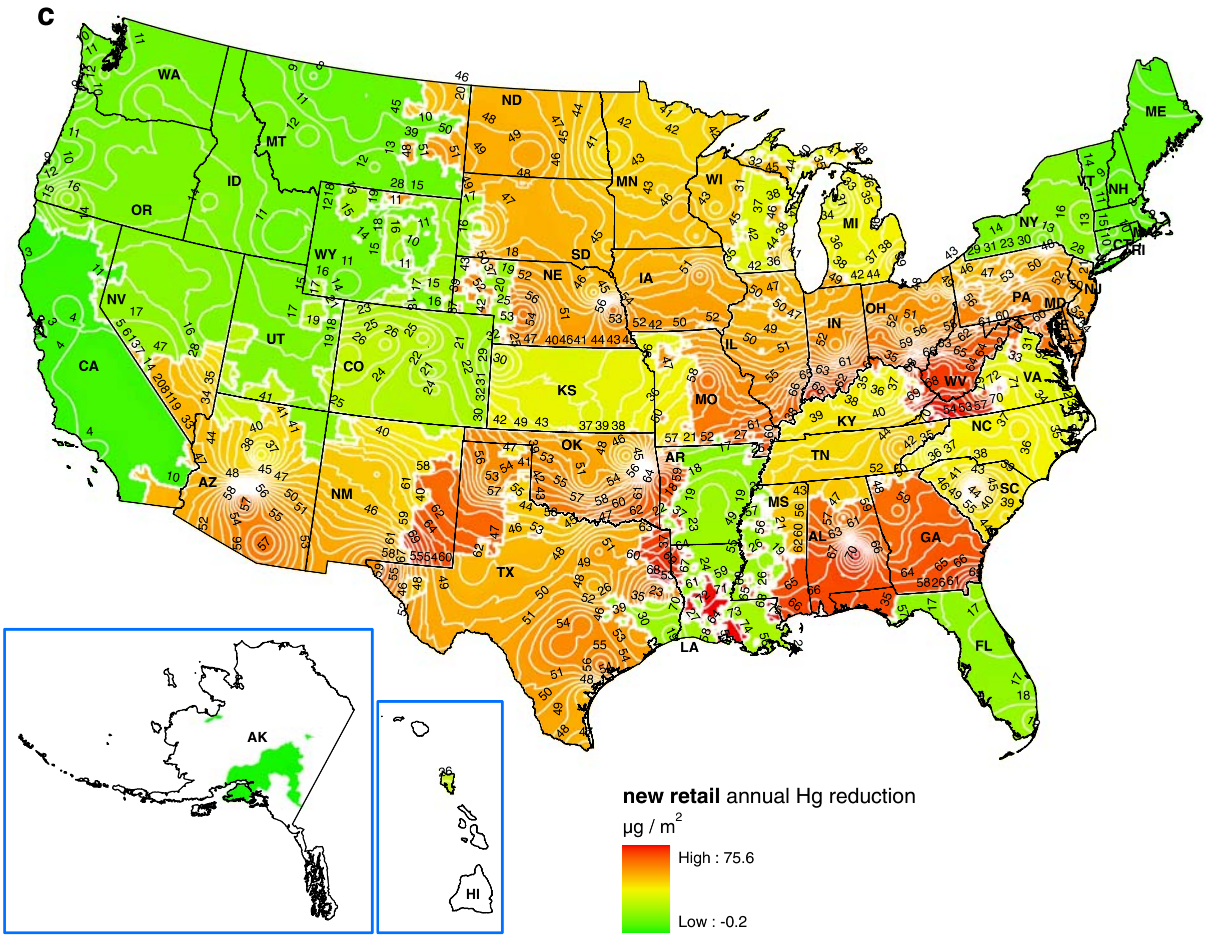


Fig. 16 (continued)



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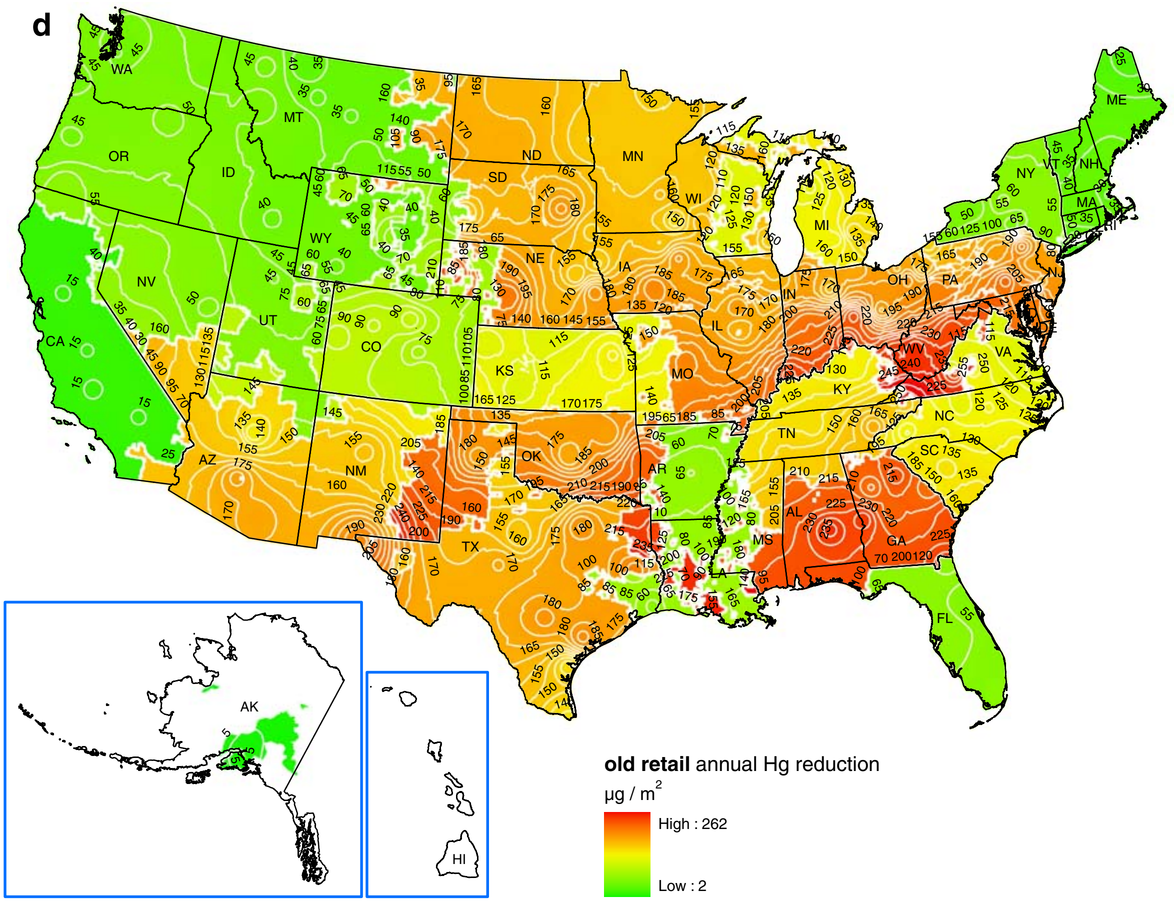

Fig. 16 (continued)

Table 8 National and state average rates of commercial-building annual cooling energy saving, heating energy penalty, energy cost saving, and emission reduction per unit conditioned roof area

Region	Population (millions)	Roof area (million m^2)	Conditioned roof area [CRA] (million m^2)	Electricity price ($/kWh)	Gas price ($/therm)	Cooling-energy saving (kWh/m^2 CRA)	Heating-energy penalty (therm/m^2 CRA)	Energy-cost saving ($/$m^2$ CRA)	CO_2 reduction (kg/m^2 CRA)	NO_x reduction (g/m^2 CRA)	SO_2 reduction (g/m^2 CRA)	Hg reduction (μg/m^2 CRA)
USA	296	3930	2580	–	–	5.02	0.0645	0.356	3.02	4.81	12.4	61.2
AK	0.666	6.66	4.56	0.116	0.48	3.30	0.128	0.319	1.07	5.94	1.91	1.08
AL	4.53	59.0	43.8	0.075	1.27	6.33	0.0372	0.421	4.56	7.04	26.1	105
AR	2.78	45.7	29.6	0.062	0.99	4.69	0.0526	0.234	2.77	3.91	6.44	40.7
AZ	5.75	73.9	49.4	0.074	0.96	7.69	0.0517	0.512	4.62	7.90	5.62	96.9
CA	35.9	359	245	0.119	1.04	6.13	0.0292	0.699	2.58	2.31	1.79	8.18
CO	4.76	61.2	40.9	0.076	0.91	5.48	0.133	0.296	4.92	8.08	5.61	43.5
CT	3.48	35.6	18.8	0.115	1.26	4.96	0.0809	0.468	1.84	2.11	5.89	20.3
DC	0.567	8.28	5.94	0.091	1.28	3.81	0.0824	0.241	1.68	2.98	14.7	72.3
DE	0.831	12.1	8.70	0.076	1.26	3.84	0.0799	0.191	1.70	2.97	15.6	79.0
FL	17.5	255	183	0.082	1.29	5.72	0.0115	0.448	3.77	6.45	11.1	29.7
GA	9.05	132	94.8	0.077	1.43	5.39	0.0482	0.341	3.79	5.72	22.9	93.7
HI	1.25	12.5	8.54	0.190	2.47	6.02	0.00304	1.14	4.97	11.7	12.8	34.2
IA	2.98	50.7	32.4	0.070	1.03	4.66	0.105	0.214	3.71	8.52	13.8	101
ID	1.39	17.9	12.0	0.054	0.96	5.20	0.118	0.168	1.79	3.77	3.31	24.1
IL	12.8	179	110	0.078	1.09	4.22	0.0994	0.217	2.97	5.48	19.6	89.9
IN	6.29	88.1	53.8	0.066	1.08	4.72	0.0849	0.215	3.25	6.41	24.3	103
KS	2.77	47.1	30.1	0.066	1.11	5.23	0.0855	0.250	4.74	10.1	15.9	71.1
KY	4.16	54.2	40.3	0.060	1.19	5.20	0.0709	0.228	3.57	6.61	20.3	74.0
LA	4.59	75.5	48.9	0.086	1.11	4.83	0.0197	0.389	3.08	4.20	6.68	45.1
MA	6.45	66.1	34.9	0.124	1.39	4.68	0.0874	0.460	1.68	1.94	5.56	19.0
MD	5.54	81.0	58.0	0.090	1.16	4.20	0.0891	0.270	1.99	3.60	17.6	86.5
ME	1.32	13.6	7.17	0.106	1.40	4.56	0.115	0.323	1.48	1.77	5.42	18.2
MI	10.2	143	87.3	0.078	0.91	4.13	0.101	0.230	2.88	4.74	14.5	68.2
MN	5.22	88.6	56.6	0.066	0.99	4.17	0.137	0.136	3.09	7.45	12.4	89.5
MO	5.78	98.2	62.7	0.059	1.13	5.50	0.0832	0.230	4.77	7.95	18.2	99.3
MS	2.92	38.0	28.2	0.085	1.17	6.28	0.0359	0.485	4.10	6.21	18.4	73.7
MT	0.918	11.8	7.90	0.074	1.04	4.74	0.135	0.211	1.58	3.56	3.50	25.2
NC	8.70	127	91.1	0.069	1.25	4.91	0.0604	0.258	2.52	4.37	14.6	53.5
ND	0.644	10.9	6.99	0.061	1.00	4.13	0.126	0.126	3.11	7.42	12.2	88.7
NE	1.77	30.0	19.2	0.060	0.92	4.79	0.0939	0.197	3.90	8.77	13.9	101
NH	1.32	13.5	7.13	0.121	1.33	5.35	0.121	0.482	1.82	2.14	6.36	21.6
NJ	8.71	101	60.1	0.106	1.27	4.72	0.0786	0.400	2.14	3.61	18.5	92.7
NM	1.92	24.6	16.5	0.078	0.90	6.92	0.0921	0.456	4.15	7.14	6.13	91.0
NV	2.37	30.5	20.4	0.095	1.01	6.86	0.0737	0.570	3.64	6.37	4.74	71.8
NY	19.3	224	133	0.144	1.25	3.80	0.0732	0.452	1.37	1.70	5.59	17.5
OH	11.5	161	98.2	0.079	1.13	4.45	0.0808	0.260	3.05	6.02	22.8	96.8
OK	3.57	58.7	38.0	0.070	1.07	3.83	0.0646	0.195	3.06	4.66	7.62	73.9
OR	3.58	35.8	24.5	0.065	1.01	4.83	0.0589	0.254	1.93	3.71	3.07	22.9
PA	12.4	144	85.8	0.085	1.27	4.69	0.0830	0.289	2.40	4.31	20.2	98.0
RI	1.07	11.0	5.80	0.117	1.29	4.61	0.0730	0.445	1.71	1.95	5.43	18.8
SC	4.23	61.7	44.3	0.074	1.33	5.38	0.0466	0.330	2.86	4.86	16.0	58.9
SD	0.785	13.3	8.51	0.062	1.00	4.47	0.122	0.155	3.49	7.92	12.3	89.6
TN	5.93	77.1	57.3	0.072	1.21	5.78	0.0588	0.339	4.04	7.31	21.1	73.5
TX	22.9	376	243	0.089	1.02	4.93	0.0253	0.408	3.39	2.72	7.72	70.7
UT	2.41	31.1	20.8	0.061	0.80	5.43	0.116	0.233	2.03	4.13	3.54	25.9
VA	7.51	110	78.6	0.061	1.15	4.35	0.0789	0.170	2.26	4.15	14.6	55.8

Table 8 (continued)

Region	Population (millions)	Roof area (million m^2)	Conditioned roof area [CRA] (million m^2)	Electricity price (\$/kWh)	Gas price (\$/therm)	Cooling-energy saving (kWh/m^2 CRA)	Heating-energy penalty (therm/m^2 CRA)	Energy-cost saving (\$/m^2 CRA)	CO_2 reduction (kg/m^2 CRA)	NO_x reduction (g/m^2 CRA)	SO_2 reduction (g/m^2 CRA)	Hg reduction (μg/m^2 CRA)
VT	0.630	6.46	3.41	0.113	0.94	4.95	0.112	0.454	1.67	1.97	5.90	20.0
WA	6.19	61.8	42.3	0.063	1.01	4.46	0.0602	0.220	1.75	3.40	2.84	21.1
WI	5.55	77.8	47.5	0.077	1.01	3.76	0.128	0.157	2.58	5.46	15.9	71.2
WV	1.82	26.6	19.1	0.055	1.19	4.33	0.0941	0.126	2.90	5.80	22.2	94.2
WY	0.502	6.46	4.32	0.062	0.89	4.86	0.141	0.171	2.65	5.00	4.17	30.9

Includes the District of Columbia (DC). Also shown are population, commercial building roof area, commercial building conditioned roof area, and commercial sector prices of electricity and natural gas. To obtain a lifetime rate of cooling energy saving, heating energy penalty, or emission reduction, multiply the corresponding annual value by the expected life of the roof. The present value of lifetime energy-cost saving is the product of the annual energy-cost saving and the present value multiplier selected from Table 1 or computed from Eq. 3

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Appendix

In a 1997 study, Konopacki et al. (1997) estimated that immediately increasing the solar reflectance of *all roofs* on a subset of US commercial buildings by 0.45 would incur an annual cooling energy saving of 2.9 TWh, an annual heating-energy penalty of 71 million therms, and an annual energy cost saving of \$210 million. To match the basic assumptions in the current study—i.e., only 80% of commercial building CRA retrofitted; roof solar reflectance increased by 0.35, rather than by 0.45—we can revise the 1997 national sums by a factor of $0.80 \times 0.35 = 0.62$. However, the national cooling energy saving, heating energy penalty, and energy cost saving predicted by the current study (10.4 TWh, 133 million therms, and \$735 million) are 6.0, 3.0, and 5.6 times greater, respectively, than revised estimates from the 1997 study (1.8 TWh, 44 million therms, and \$131 million). Several factors make the current national sums exceed those computed in 1997.

1. When computing CRA from the 1992 Commercial Buildings Energy Consumption Survey (EIA 1994b), the 1997 study included only seven classes of building (office, retail store, primary school, secondary school, hospital, nursing home, and grocery store) out of the 21 classes surveyed. We estimate from our analysis of the 2003 CBECS dataset that these seven building classes (principle building activities) comprised only 38% of the total commercial building CRA. Hence, the 1997 national sums should be multiplied by a factor of $1/0.38 = 2.6$ to account for the omitted building classes.
2. The 2003 CBECS detailed tables (EIA 2006c) report the total floor space of buildings with at least some air conditioning at 5,900 million square meters, which is 11% higher than the value of 5,300 million square meters reported by the 1992 CBECS detailed tables (EIA 1994c). Therefore, the 1997 national sums should be multiplied by factor of 1.1 to account for net new construction.
3. For equal increases in roof solar reflectance (0.35), the current study predicts greater cooling energy savings and smaller heating energy penal-

ties per unit CRA than does the 1997 study. For example, for a new office building in Atlanta, GA, the current study predicts a per-CRA cooling energy saving 88% higher and a per-CRA heating energy penalty 13% lower than the corresponding 1997 values (pre-scaled by a factor of 0.35/0.45= 0.78). We attribute most of the difference to the use in the current study of an improved roof assembly heat transfer module in DOE-2.1E. This module incorporates radiative heat transfer, an improved external convection coefficient, and temperature-dependent thermal conductance of insulation (Gartland et al. 1996). Hence, to account for improvements in simulation of roof heat transfer, the 1997 national cooling energy saving should be multiplied by a factor of 1.9, and the 1997 national heating energy penalty should be multiplied by a factor of 0.9.

4. The year 2005 US average commercial sector electricity and natural gas prices ($0.0867/kWh and $1.12/therm) are 12% and 121% higher, respectively, than the corresponding 1993 values ($0.0774/kWh and $0.506/therm; EIA 2007b, c).

Adjusting the 1997 estimate of US annual cooling energy saving by the factors listed above yields 2.9 TWh × 0.80 (roof fraction upraded) × 0.35/0.45 (smaller increase in solar reflectance) × 2.6 (more building classes) × 1.1 (construction) × 1.9 (better simulation) = 9.8 TWh, which is 6% below the current study's estimate of 10.4 TWh.

Adjusting the 1997 estimate of US annual heating energy penalty by the factors listed above yields 133 million therms × 0.80 (roof fraction upgraded) × 0.35/0.45 (smaller increase in solar reflectance) × 2.6 (more building classes) × 1.1 (construction) × 0:9 (better simulation) = 114 million therms, which is 16% below the current study's estimate of 133 million therms.

Computing US annual energy cost saving from 2005 US-average commercial sector energy prices and the adjusted values of cooling energy saving and heating energy penalty yields $9.8\text{ TWh} \times \$0.0867/\text{kWh} - 114\text{ million therms} \times \$1.12/\text{therm} = \$722\text{M}$, which is 2% lower than the current study's estimate of $735 million.

Hence, the adjusted 1997 estimates of national annual cooling energy saving, heating energy penalty, and energy cost saving agree quite well with those made in the current study.

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