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# Quantifying Carbon Mitigation Wedges in U.S. Cities: Near-Term Strategy Analysis and Critical Review

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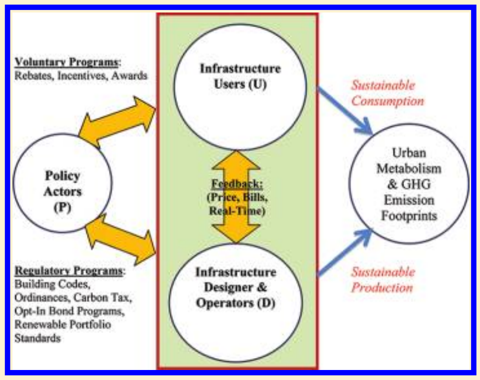
Supporting Information

**ABSTRACT:** A case study of Denver, Colorado explores the roles of three social actors—individual users, infrastructure designer-operators, and policy actors—in near-term greenhouse gas (GHG) mitigation in U.S. cities. Energy efficiency, renewable energy, urban design, price- and behavioral-feedback strategies are evaluated across buildings–facilities, transportation, and materials/waste sectors in cities, comparing voluntary versus regulatory action configurations. GHG mitigation impact depends upon strategy effectiveness per unit, as well as societal participation rates in various action-configurations. Greatest impact occurs with regulations addressing the vast existing buildings stock in cities, followed by voluntary behavior change in electricity use/purchases, technology shifts (e.g., to teleconferencing), and green-energy purchases among individual users. A portfolio mix of voluntary and regulatory actions can yield a best-case maximum of ~1% GHG mitigation annually in buildings and transportation sectors, combined. Relying solely on voluntary actions reduces mitigation rates more than five-fold. A portfolio analysis of climate action plans in 55 U.S. cities reveals predominance of voluntary outreach programs that have low societal participation rates and hence low GHG impact, while innovative higher-impact behavioral, technological, and policy/regulatory strategies are under-utilized. Less than half the cities capitalize on cross-scale linkages with higher-impact state-scale policies. Interdisciplinary field research can help address the mis-match in plans, actions, and outcomes.




## 1. INTRODUCTION

Cities can play a significant role in global Greenhouse Gas (GHG) mitigation given more than one thousand cities worldwide are engaged in climate action planning,[1] more than 80% of the population in developed countries with high per capita carbon emissions, such as the United States, lives in cities,[2] and the population of the 40 largest cities of the world[3] exceeds that of many nations, making a strong case for carbon mitigation actions initiated at the city-scale. However, while long-term GHG stabilization wedges have been articulated at the national scale,[4] little systematic quantitative information is available about the various strategies for GHG mitigation that are typically undertaken at the city scale. This paper, inspired by the wedges concept, asks the question—what is the rate and extent of GHG mitigation that can be achieved by cities in the *near-term* of about five years, with existing technologies, and with current energy prices, state and national policies, and physical infrastructure?

Several organizations have reviewed city-scale climate actions qualitatively (e.g., 5, 6); others have quantified GHG mitigation of various strategies on a per unit basis, i.e., per weatherized home or per appliance installed.[7−10] However the *rate* of GHG mitigation depends not only upon the strategy effectiveness per unit, but also on the rate at which social actors adopt these strategies, i.e., the percentage of homes or businesses adopting these strategies over a certain time period. Societal participation rates allow the dynamic (temporal aspect) of GHG mitigation to be visualized, but such participation rates have not been explored to-date at the city scale.

A few city-scale studies have computed GHG mitigation futures with high assumed participation rates—e.g., 95% of homes implementing cavity wall insulation[11]—but do not address how the assumed (extraordinarily high) 95% participation would be achieved by cities. At the national scale, Dietz et al.[12] have computed the maximum technical potential for energy savings, i.e., the maximum percentage of homes wherein penetration of a certain technology can occur, subsequently scaled-down by plasticity, i.e., the percentage of those homes that can actually be induced to act. The best-case (maximum) plasticity observed across several U.S. communities in field trials was applied nationwide to quantify energy-savings achievable from voluntary household actions if all communities in the U.S. achieved the best-case plasticity; it is posited that these reductions could be achieved in a span of 10 years.[12]

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A single best-case participation percentage applied nationally, however, does not provide cities with finer detail on local-scale variations, for example, differences in action configurations (i.e., voluntary, mandatory, or opt-in program designs) or in local context (local economy, urban form, etc.) that shape *annual participation rates* in GHG mitigation programs. Such annual rates are important to compare policies against each other, and against the continuous annual increases in energy/electricity use (e.g., Table 1) that they counter. Furthermore, the national study focused on household actions, but does not address city actions that can include spatial smart-growth planning, zoning, and innovative time-of-sale (ToS) energy efficiency ordinances, the efficacy of which depend on local physical context, e.g., population density, spatial and demographic opportunities for smart growth, and the number of homes sold annually, respectively.

**Table 1. Population and Demographic Trends in Denver, CO from 2000 to 2005 for Estimating Business-As-Usual (BAU) Trends**

| demographic trends | annual % change | per capita energy use | annual % change local | annual % change national |
|---|---|---|---|---|
| population[a] | +0.95% | electricity | +0.91%[c] | +0.82%[d] |
| new home stock[b] | +1.26% | natural gas | −1.36%[c] | −2.63%[d] |
| new commercial area, net[b] | +0.19% | motor gasoline | −0.70%[e,f] | −0.04%[d] |
| | | diesel | +1.22%[e,f] | +1.08%[d] |

Baseline Year 2005 Demographics: population = 579,744 people; number of households (HH) = 256,524 (36% rental); commercial sq ft = 229 million

Baseline Year 2005 Energy Use Data (from Hillman and Ramaswami[16]):

-Average household electricity use (HHE) = 545 kWh/HH/mo (17% of buildings sector overall)

-Average household natural gas use (HHNG) = 45 therms/HH/mo (11% of buildings sector overall)

-Residential energy use intensity (REUI) = 4499 kBTU/HH/mo

-Average commercial energy use intensity (CEUI) = 122 kBTU/sf/yr

-Average per person VMT = 23.1 miles/person/day

-Average commute distance = 17.4 miles/commuter/workday

-Average automobile fuel economy = 19 mpg

-Jet fuel use per enplaned passenger = 19.5 gal/enplaned passenger

Emissions Factors:

electricity 2005 = 0.793 kg-$CO_2$e/kWh[c], and projected to be about 0.72 kg-$CO_2$e/kWh in 2012

natural gas = 5.4 kg-$CO_2$e/therm[c]; gasoline PTW= 9.3 kg-$CO_2$e/gal[g]; diesel PTW = 9.5 kg-$CO_2$e/gallon[g]

[a]U.S. Census. [b]City and County of Denver (CCD) Assessors Database. [c]Xcel Energy. [d]Energy Information Administration (EIA) – National Energy Database. [e]Energy Information Administration (EIA) – Colorado State Energy Database. [f]Colorado Department of Revenue (DOR). [g]Argonne GREET: Pump-To-Wheels (PTW) combustion emissions factor.

An important contribution of this paper is that it conducts *bottom-up analysis* to help cities explore how different action-configurations, along with local conditions, shape rates of GHG mitigation. For example, the same *strategy*, i.e., low-cost energy efficiency retrofits in homes, can have different participation rates in voluntary—versus regulatory (mandatory)— action-configurations such as the ToS mandate, annual participation rates in which would depend upon local economic context such as annual home sales. Cities seek such context-specific field data both on participation rates and energy savings per unit home or per commuter-trip to configure their climate actions. Furthermore, cities seek to understand how rates of GHG mitigation from city-scale actions connect and compare with those expected from other subnational policies, e.g., with regional- or state-scale policies.[13]

To address these needs, the specific objectives of this paper are to (1) conduct a first-order analysis of the rate and extent of GHG mitigation that can be accomplished by city-scale actions with currently available technologies and a range of social actor participation rates in voluntary and policy/regulatory actions; (2) quantitatively demonstrate cross-scale policy linkage between city-scale and other subnational (state or regional) climate actions; and (3) develop insights about the relative roles of the three social actor groups in GHG mitigation:[14]

- infrastructure users (U), i.e., home-dwellers, businesses, and industries in a city;
- infrastructure designer-operators (D) who shape the design and operations of buildings, electric power-plants, water treatment plants, landfills, etc.;
- policy actors (P), including government officials, non-governmental organizations (NGOs), media, and interest groups operating within and across city-scale.

The broad strategies by which the three actors influence each other and the GHG emission footprints of cities are shown in Figure 1. GHG mitigation strategies are categorized as those *primarily* accomplished by each actor category and supported by other actors, e.g., voluntary efforts include purely behavioral changes toward energy conservation undertaken by users (U), along with financial incentives for energy retrofits provided by policy actors (in which case, denoted as (U,P)). Voluntary adoption of green design is primarily undertaken by infrastructure designer-operators (D), while zoning codes, local ordinances, bond programs, and other voter-approved measures are results of the action of policy actors (P). Policy actions (P) are defined as those that need passage of city-council resolutions and/or voter approval; voluntary programs (U or D) do not require such policy processes. Note that city-scale policy actions (P) do not refer exclusively to regulations (i.e., mandates), but can also include opt-in bond programs that institutionalize the provision of financial incentives for voluntary energy efficiency investments, or decisions to change utility provisioning from privately to municipally owned utilities. All these city-scale policy actions require voter approval and result in formal changes in a city's operating rules.

Thus rather than classifying actions as "purely voluntary" or "purely regulatory" we distinguish actions according to the primary agency of the actors (U, D, or P, or a combination thereof) who take the strategies and implement them into action.

Categorizing climate actions in this manner helps assess the relative role of the three social actor categories, quantify differences between voluntary and regulatory/policy actions, and identify those actions with greatest GHG mitigation impact. Social science research exploring underlying social, cultural, political, and institutional factors that influence the actors may then be applied to facilitate translation of the highest-impact climate actions across cities.

## 2. OVERALL METHODOLOGY

**Baseline Carbon Emissions Footprint and Infrastructure Sectors.** GHG mitigation is described for the City and County of Denver, for which a baseline GHG emissions footprint has been estimated in previous ES&T papers[15,16]

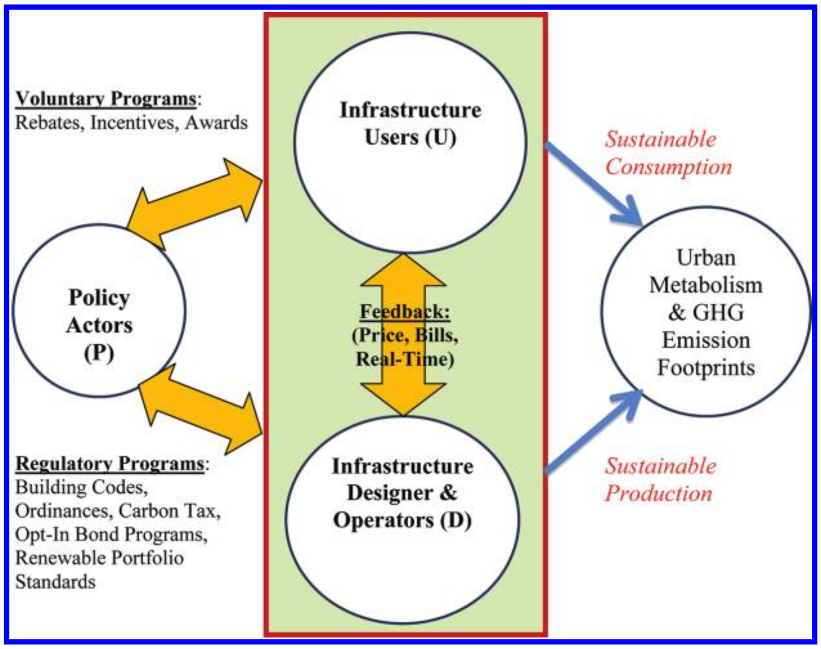


**Figure 1.** Available action options and interactions among the three social actors—individual users (U), infrastructure designer-operators (U), and policy actors (P)—that shape the urban metabolism and GHG mitigation footprints of cities. (This Figure zooms in on the SEIS framework described in ref 1 to detail the actor actions and interactions).

**Table 2. GHG Mitigation in the Buildings and Facilities Sector for Denver, CO, Organized by Strategy and by Program Design for Each Strategy**

| strategy/nudge [participating unit] | energy or carbon savings per unit | participation rate of units in various [program designs] | overall range of GHG impact from action (eq 1) |
|---|---|---|---|
| Free giveaways of two compact fluorescent lamps (CFLs) [home] | ~1.5% HHE[24] | 50% [mail-in program[24]] | 0.75% HHE[a] |
| | | 8−10% [door-to-door[22]] | 0.12−0.15% HHE[a] |
| Door-to-door weatherization outreach [home] | 5% HHNG[20] | 2−4% [door-to-door;[22] DSM Rebate] | 0.1−0.2% HHNG[a] |
| Basic energy efficiency upgrades [whole home] | 2.8% HHE[20] 13.6% HHNG | 0.4% [E$P; free to qualifying homes; budget-limit[20]] | 0.01% HHE[a] 0.05% HHNG[a] |
| | | 20−35% [[d]ToS[44]/date certain[44]] | 0.56−0.98% HHE[a] 2.7−4.7% HHNG[a] |
| Higher cost home energy upgrades [home] | 1.7 mt-$CO_2$e/HH (diverse upgrades: windows, solar heaters, attic fans, geothermal[45]) | ≪0.1% [[d]low-interest loan[23]] | 0.018% HHE[a], HHNG[a] |
| | | 2.6% [[d]opt-in bond[45]] | 0.47% HHE[a], HHNG[a] |
| New "green" buildings [square feet, sf] | 20−30% energy savings per square foot | 5% of new sf/year [voluntary green commercial const.[41]] | 0.01−0.015% CRE[b]; CRNG[b] |
| | | 76% of new sf/yr [[d]mandate green const. >20,000 sf[42]] | 0.15−0.23% CRE[b]; CRNG[b] |
| Commercial−industrial DSM | 2% electricity sales over 8 years[21] | scaled to 1.5% over 5 y | 1.5% CRIE[c] |
| Green electricity purchase [utility MWh] | windsource 0 mt-$CO_2$e/kWh | 1−5% MWh[37,38] (voluntary) | 2−15% CRIE[c] |
| | | 15% MWh (RPS 2012[48]) | |
| Behavioral feedback [home] | 2−4% HHE/home (bills[32,33]) | 100% (all homes - mandate) | 2−4% HHE[a] |
| | 6−12% HHE/home (real-time displays[12]) | 4% (outreach to[22]) to (100% (all homes - mandate) | 0.24−0.48% HHE[a] 6−12% HHE[a] |
| Price feedback | 0.15−0.35% per unit % price increase[47] | 1.6% weighted avg.[46] carbon tax[d] (all homes) | 0.4% CRIE[c] |
| Worst case impact of city-scale actions on buildings−facilities from BAU−2012 = −1.2% | | | |
| Best case impact of city-scale actions on buildings−facilities from BAU−2012 = −8.5% | | | |
| Buildings−facilities GHG BAU trend (2007−2012) = +5.9% | | | |

[a]Household electricity (HHE) and household natural gas (HHNG) contribute 17% and 11% to overall buildings−facilities GHG. [b]Commercial−residential electricity use (CRE) contributes 61%; Commercial−residential natural gas use (CRNG) contributes 29%. [c]Commercial−residential−industrial electricity use (CRIE) contributes 71%; Commercial−residential−industrial natural gas use (CRING) contributes 29%. [d]Represents programs implemented in other cities, mapped to Denver, CO.

employing a hybrid life cycle-based methodology (see Supporting Information; 15). The GHG emissions footprint integrates human activities occurring in buildings, transportation, and materials/waste sectors within city boundaries, with important trans-boundary infrastructures such as electricity generation, fuel production, regional and long-distance transportation, and regional water and waste infrastructures. Denver's GHG emissions footprint has been found to be similar to that of other metro-cities and to U.S. per capita GHG emissions of ∼25 mt-$CO_2$e/capita,[16] where mt-$CO_2$e represents the global warming potential of all six GHGs expressed in metric tonnes of $CO_2$-equivalents. Given the similarity of Denver's GHG footprint with the U.S. average and other U.S. cities, GHG mitigation actions analyzed here for Denver are likely to broadly represent those of typical large US cities when local homes, industry, and businesses, along with key trans-boundary infrastructures are engaged in climate action.

It should be noted that the infrastructure supply chain footprint method described above, akin to geographic-based inventories, considers a city's homes, businesses, and industry together, unlike consumption-based inventories that primarily trace household consumption fully upstream, incorporating international trade.[17] Thus strategies that attempt to shape the trade of goods between cities and various regions of the world are not addressed in this paper.

**Characterizing the Business-As-Usual (BAU) Case.** Denver seeks a 10% per capita reduction in GHG emissions over 5 years (2007−2012), from the 2005 baseline of ∼25 mt-$CO_2$e/capita.[15,18] We analyzed 2000−2007 data to estimate the business-as-usual (BAU) GHG trend, using population, built area, and per capita trends shown in Table 1. Table 1 shows that Denver's BAU trends are in-line with larger national-scale economic or technological trends,[19] superimposed upon which we evaluate the impacts of new GHG mitigation actions actually implemented by Denver, or considered for implementation, from 2007 to 2012. Because this paper seeks to illustrate the relative impacts of various GHG mitigation strategies undertaken by the three different social actor groups, the effects of brief periods of high and low oil prices and the present recession are not included in the analysis.

**Strategies by Sector, Classification of Actions, and Quantification of Impact.** Broad strategies are identified for GHG mitigation for each of buildings, transportation, and materials/waste sectors. For each strategy, various action-configurations are classified according to actor involvement, U, D, P or a combination thereof. The GHG Mitigation Impact of each action is then computed as follows:

$$\text{GHG Mitigation Impact\%} = \left(\frac{\text{E\%}}{\text{U}}\right) \times (\text{P\%}) \qquad (1)$$

where (E%/U) represents average strategy effectiveness per unit of analysis (i.e., percent energy or GHG savings per home weatherized), which is independent of how many homes use the strategy. P% represents the participation rate over the target 5-year period (i.e., the percentage of homes in a community implementing weatherization in 5 years), unique to each action-configuration and dependent on local context.

The computations in this paper apply eq 1 using both performance and participation rates drawn from real-world field studies/surveys conducted in Denver over the past 3 years, and/or mapped to Denver based on field data from other cities. The strategy effectiveness (performance) and participation rate data are shown for each action in Columns 2 and 3 in Tables 2 and 3. Their product is shown in column 4, and represents impact as the percentage GHG mitigated; this is also presented in the results (Figure 3). Detailed calculations and assumptions are provided as Supporting Information. The combination of measured strategy effectiveness with measured societal participation rates in different action-configurations, using local contextual data in eq 1, makes this a unique and valuable study that provides "bottom-up" analysis for cities.

**Table 3. GHG Mitigation in the Transportation Sector for Denver, CO, Organized by Strategy Set for Addressing Surface Vehicle Miles Traveled (VMT) and Airline Travel. Pump-to-Wheels Analysis Is Applied. All Elasticity Reflects Reductions in VMT (Negative Sign Not Shown).**

| strategy or nudge | strategy effectiveness per unit: VMT or person | %VMT, %trips or %people impacted | overall GHG impact |
|---|---|---|---|
| Fleet EE upgrades | 25% fuel saved per fleet VMT | 1.2%[15] of Denver VMT[a] | −0.2% |
| Employer-based commuter programs (long trips) | 0.5 mt-$CO_2$e/employee[50−52] | 60,000 employees in ride-arranger programs, commuting into Denver[60] [20% commuters] | −0.6% |
| Bike mode shift (short trips) | Bike VMT displaces 30−60% automobile VMT[58] | 2 million bike miles [ <0.04% of Denver's motorized VMT] | <−0.02% |
| Individual travel marketing/behavior change | 2−12% reduction in commuter VMT [9% median][59] | 11,000 commuters (10% of Denver residents who work outside Denver) | −0.1% |
| Urban planning smart growth: travel demand elasticity wrt land-use variables | VMT elasticity: best case synergy[65] of 25% is applied [individual elasticity[61,62] density: 5−12%; diversity: 5%; design: 3%; accessibility to jobs: 20%] | 75% of new 2007−2012 population (3.4% Denver's population overall) | −0.6% |
| | mass transit only:[61] 0.5% | applies to remaining 96% people | −0.4% |
| Telepresence for air travelers | accessibility to jobs[b] | 3.3% airline travelers[b] | −0.7% |

[a] Unless otherwise stated, VMT refers to annual community-wide surface travel VMT in Denver which contributes 81% of transport sector GHG. Commuter travel at 17 miles/worker-workday (5 days per week), while total VMT per capita is 23.5 miles/person-day. [b] Air travel GHG contributes the remainder (19%) of transport sector GHG.

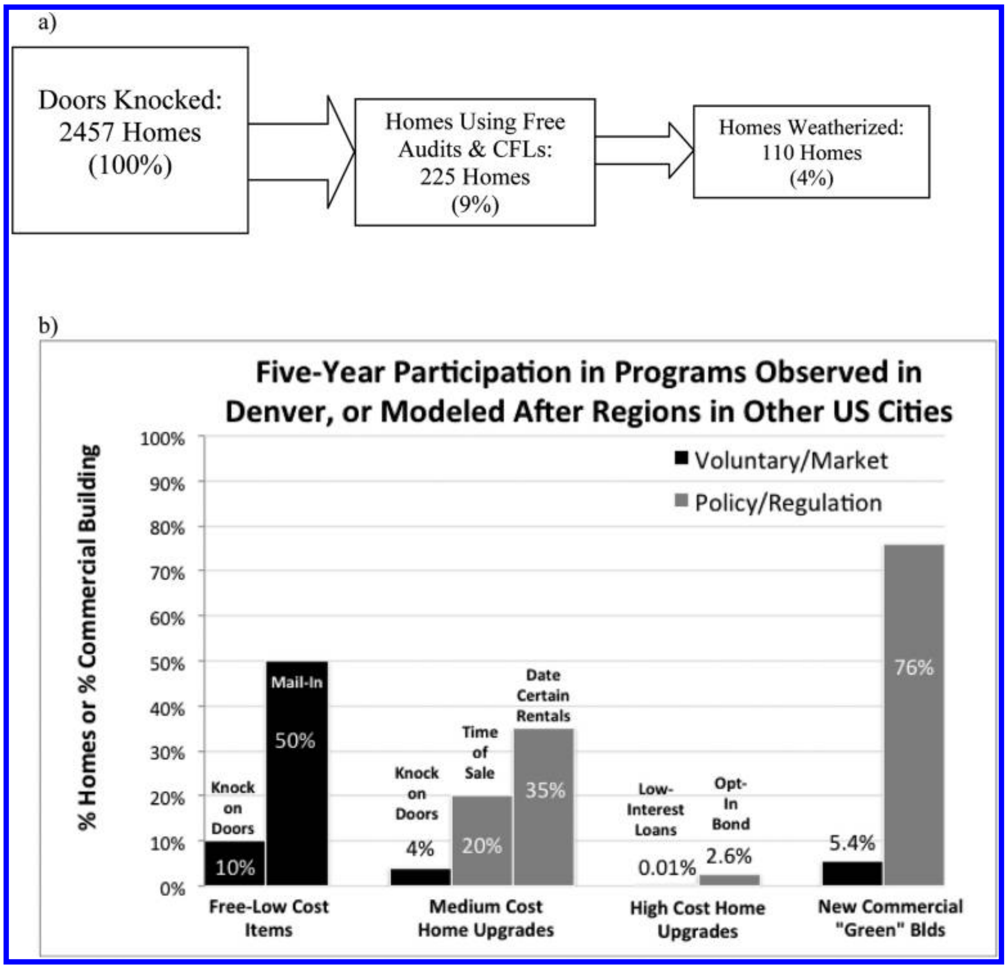


**Figure 2.** (a) Typical participation pipeline in Denver Neighborhood Outreach Programs. Sunnyside Neighborhood is shown here. Three different neighborhoods showed participation ranging from 8 to 10% in using free audits with other giveaways, and 2–4% in following up with weatherization/insulation. (b) Community-wide participation rates in building sector programs of varying costs and in varying program configurations computed over five years. Free giveaways and knock-on-door outreach are implemented only once per neighborhood, and estimated to reach all neighborhoods in about 5 years, thus the rates seen in Figure 2a are assumed to apply community-wide over 5 years. Date-certain would require all 35% homes in Denver that are rental properties to comply in 5 years, while time-of-sale impacts 5% Denver homes that go on sale annually, yielding 20–25% participation over 5 years.

In contrast, national top-down analyses compute total technical potential for GHG savings nationwide (assuming maximum adoption), scaled-down by plasticity, i.e., the best-case percentage of nonadopters who can be induced to adopt a particular program; such adoption assumed to occur in a 10-year time frame.[12]

## 3. BUILDINGS AND FACILITIES ENERGY USE

**Voluntary Change Among Users (U,P)—Efficiency Upgrades.** Most cities offer different types of voluntary programs that might include: (a) *Free giveaways* of low-cost items such as compact fluorescent lamps (CFLs), low-flow showerheads and aerators, free to the users; (b) *Door-to-door weatherization* outreach programs offering energy audits, weatherization, and insulation subsidies, at moderate net costs to home-dwellers (<\$1000 to \$2000), often in conjunction with utility demand side management (DSM) programs; (c) *Whole-home basic energy efficiency upgrades* coordinated with state low-income energy assistance programs that provide attic, wall, or floor insulation and furnace/refrigerator upgrades (where needed), at no cost to the home-dweller (average Colorado program costs are \$2850/home;[20]); (d) *Loans* for higher-cost whole-home upgrades including windows, solar thermal and solar photovoltaic upgrades (cost >\$10,000/home to home-owner); (e) *Rebates for commercial and industrial energy efficiency upgrades* focused on lighting, motors, blowers, etc., as part of utility DSM. In Colorado, the rebates reflect a 75%/25% cost split between users (U) and the utility; over eight years, the electricity DSM targets about 2% utility-wide electricity sales.[21]

Cities often tap into neighborhood associations and NGOs to implement the voluntary programs enumerated above. Few cities have their own funding for rebates and subsidies, and typically coordinate with state or federal block grants, if available. Exceptions include cities with municipally owned electric utilities and those that have implemented carbon taxes (discussed in the policy action). To model GHG impact from the voluntary programs in Denver, CO, field data on strategy effectiveness were obtained from measured energy savings in 1500 Colorado homes retrofitted with various energy efficiency upgrades from 2002 to 2005.[20] Field data on participation rates are from three different neighborhood outreach programs in Denver, CO,[22] from a low-interest loan program offered in Fort Collins, CO[23] and from Xcel Energy's DSM Program


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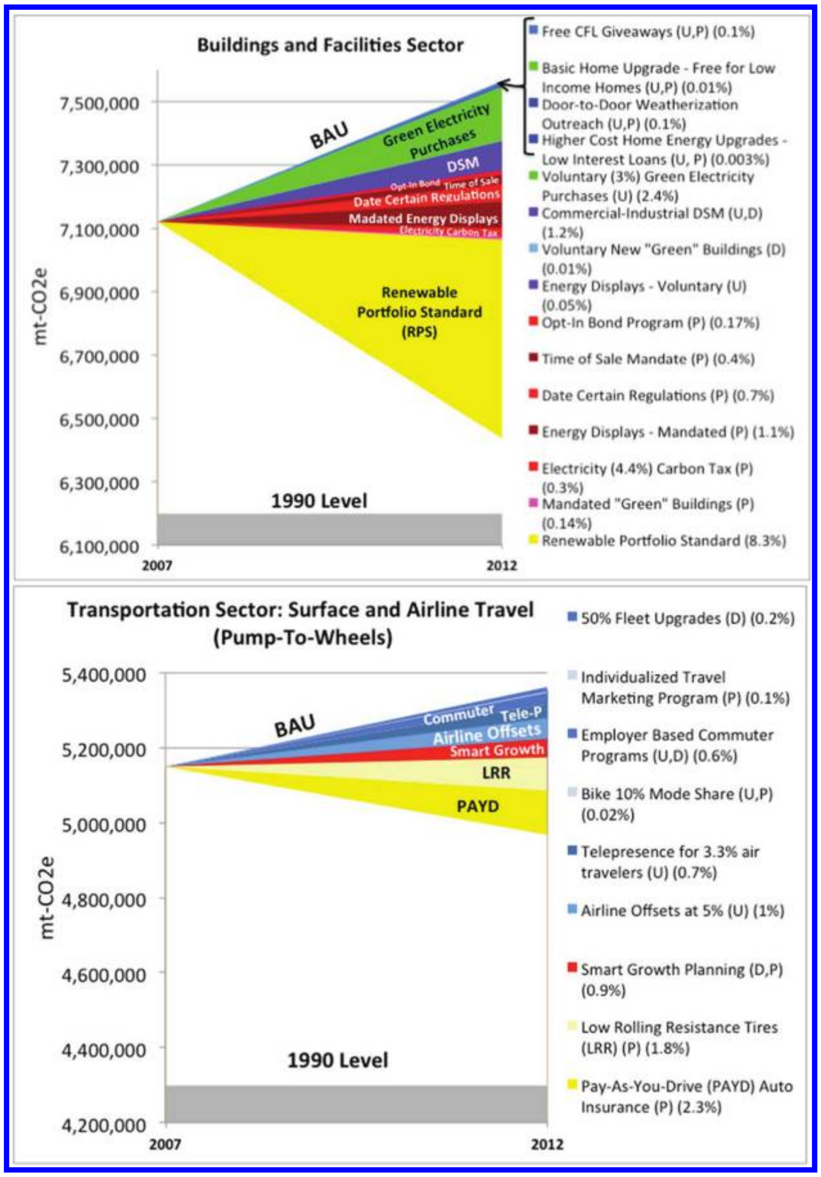


**Figure 3.** GHG mitigation wedges showing impacts of actual and hypothetical programs by actor category. Voluntary actions primarily initiated by individual users (U) and infrastructure designer-operators (D) are shown in blue−green. Policy actions (P) at the city-scale are in red−orange, and those at the state- or regional-scale are in yellow. (a) Buildings and facilities sector; (b) transportation sector including surface and airline well-to-wheels GHG emissions. Many individual actions are not apparent due to their very small impact (<1%) on % GHG mitigation, as reported in the legend alongside each action (%) and also computed in Table 1. These smaller impact actions appear grouped together while the higher impact actions appear individually distinct.

Reports.[21] The strategy effectiveness and participations rates in different action configurations are summarized in Table 2.

A typical participation pipeline in Denver's neighborhood outreach programs, illustrated in Figure 2a, shows that about 8−10% of Denver homes respond to door-to-door campaigns and accept free items like CFLs or energy audits; however, only 2−4% follow-on with actions like weatherization and attic insulation.[22] Best-case voluntary participation rates of up to 50% have been reported in free CFL-giveaway using mail-in rebates in Seattle,[24] thus cities are likely to use the mail-in approach in the future for small self-installed items like CFLs. For home weatherization and attic insulation, participation rates decline to about 2−4% in neighborhood knock-on-door outreach programs conducted in three Denver neighborhoods in 2009 (Figure 2a); similar rates are assumed Denver-wide, with the city planning such outreach to all its remaining neighborhoods in the subsequent 5−6 years. Participation rates are even lower (<1%) for voluntary adoption of loans for higher cost whole home upgrades (such as energy efficient windows, solar panels, solar water heaters, etc.), based on data from Fort Collins' Zilch Loan program.[23] See Figure 2b. These observed participation rates are in line with those reported in national-level reviews of outreach and loan programs.[25−29] For example, USEPA's toolkit[29] considers weatherization outreach to 3.5% households in 3 years to be an aggressive goal.

When whole-home upgrades for basic energy efficiency are offered entirely free to low-income homes as in Colorado's Energy $avings Partnership (E$P) program, demand outstrips the available funding, so that participation rates in the E$P Program become funding-limited reaching only 0.4% of the housing stock over a 5-year period (personal communication; Arapahoe County E$P Office). Obtaining consistent funding to offer financial incentives for energy retrofit programs is a challenge for most cities. Funding staff to run such outreach programs can also be a challenge in smaller cities.

Consequentially, the observed low participation rates in energy efficiency programs lead to relatively small impacts for these programs, together, yielding <0.25% GHG mitigation over 5 years (see Figure 3a).

**Voluntary Change Among Users (U)—Conservation Behaviors.** Many cities are applying community-based social marketing to promote energy conservation in homes.[30] The role of behavioral feedback in energy conservation, explored since the 1970s, is also seeing renewed interest. (a) *Behavioral feedback* can be provided monthly on home energy bills, and instantaneously using real-time energy displays. Feedback on monthly bills coupled with social norming[31] has shown measured average electricity savings of 3−4% community-wide, in a few U.S. cities.[32,33] Real-time in-home energy displays that provide users instantaneous feedback on their electricity use report electricity savings from 6% to 12%, in large-scale pilot studies of more than 500 homes.[34,35] The higher reported range of energy use reductions may be due to self-selection in the pilot studies; long-term persistence in savings over time is also being tracked in ongoing research. Hybrid programs that combine behavioral feedback with subsidies for retrofits can yield greater energy savings per home;[36] however cities must find ways to fund such subsidies. Because technical know-how is needed to install these low-cost energy displays in homes, we expect voluntary community-wide adoption of displays to be similar to that of the audit-install programs (Figure 2a) at about 2−4%.[22] We applied these participation rates, along with midpoint electricity savings of 9% per participating home to compute the impact of voluntary adoption of real-time feedback devices in Table 2 and Figure 3a. Given small participation rates (2−4%) and about 9% reductions in electricity use in participating homes, the impact of these voluntary energy conservation programs is also relatively low at 0.05% GHG mitigated over 5 years.

(b) *Voluntary Green Electricity Purchases* (U): A second broad strategy for changing consumer behavior lies in shifting energy purchases toward renewables, a fast-growth area for public participation. In Denver, participation increased by ∼64% from 2005 to 2007 among both residential and commercial customers, with certified green-energy purchases representing 1% of Denver's electricity use in 2007.[37] Based on these local trends, green-e certified electricity purchases are estimated to reach 3% of the total MWh (mega Watt-hours) use in Denver over a 5-year period, as shown in Table 2. Similar increasing trends in participation are reported in national studies of green energy purchases across 750 U.S. utilities, with the maximum observed at 17% of customers purchasing green energy equivalent to 5% MWh of utility electricity sales.[38] Given the larger participation rates with both commercial and residential sectors involved, and with a high strategy effectiveness that yields zero $CO_2e$/kWh, GHG mitigated is also greater at 0.5%.

**Voluntary Change in Infrastructure Provision in Cities (D).** Commercial and residential buildings, streetlights, and traffic signals are the infrastructures that are consistently provisioned within a city's boundary. (a) *Voluntary "Green" Buildings*: Real-time performance studies of LEED[39] and Energy-Star buildings[40] report observed average energy savings ranging from 20% to 33% per square foot compared to current average stock. Energy end-use information on new buildings construction obtained from the Denver County Assessor's database (Table 1), along with data on voluntary market penetration of green buildings in Denver, are used to model the impact of voluntary adoption of green buildings standards. Nationwide studies indicate voluntary market penetration of green buildings in new stock ranging from <1% to a maximum of 7.6% (Boston), with Denver at 5.4%,[41] as shown in Figure 2b. However, with new construction accounting for only 0.2% of total commercial area in Denver annually (Table 1), voluntary penetration of green buildings at 5.4% in Denver impacts only 5.4% of about 1% of the total commercial stock over a 5-year period, yielding a small GHG impact <0.1% as seen in Table 2 and Figure 3a. This does not imply new green buildings are ineffectual; rather, it is important that they diffuse faster given their impact lasts for 30−50 years into the future.

**City-Scale Policies (P).** Many of the voluntary strategies listed above can be institutionalized via city-scale policies that enable more widespread and rapid diffusion of these strategies in society. For many U.S. cities, the building stock is relatively old, and only a small percent (∼1% homes and 0.2% commercial space; Table 1) is built new each year. In Denver, more than 85% of homes were constructed prior to the 1990s (Supporting Information), before attic insulation was codified for new homes. City policies are therefore designed at three leverage points: the time of construction (for new buildings), during remodel or during sale of properties (for the vast existing stock), and unique strategies to address rental properties, as listed below.

(a) *Mandated New "Green" Buildings*: As an example, San Francisco is requiring LEED certification for all new commercial construction larger than 20,000 square feet.[42] (b) *Time-of-sale (ToS) mandates*: the cities of Berkeley and San Francisco have instituted residential and commercial energy conservation ordinances requiring all buildings be upgraded to very basic energy efficiency standards (e.g., attic insulation, insulated pipes, etc.) at ToS.[43] (c) *Date Certain Regulations*: Boulder's Smart Regulations require all rental property (∼50% of their building stock) to have basic energy efficiency upgrades within a 5-year time frame.[44] (d) *Opt-in Bond Program with Special Property Assessment*: Boulder, CO, has also implemented an innovative voter-approved bond program wherein property-owners may opt-in for large loans for high-end energy efficiency investments (e.g., windows, solar thermal, solar panels, etc.), financed and paid for over time via special property taxes that remain associated with the home, even if the home is later sold.[45] This addresses a major barrier for investing in high-cost energy upgrades—the risk that homeowners may relocate and not recoup the savings from their investment add drawbacks.

Not surprisingly, participation rates fostered by the above policies (addressing new construction, time-of-sale, rentals, and high-end remodels) are many-fold greater than those observed in corresponding voluntary energy efficiency programs, as seen in Figure 2b. Participation rates if Denver were to implement a ToS ordinance were computed from data on home sales that show about 5% homes sold each year; thus ∼20% are estimated to participate cumulatively over 5 years, assuming 10% of sold homes would not comply (based on compliance data from Berkeley's ToS; personal communication) and that some homes may be sold twice in 5 years. A date-certain rule requiring all rental properties be upgraded to basic standards in 5 years would impact all 35% of Denver homes that are listed as rental property per the Assessor's Office—a market segment that has little incentive to otherwise engage in energy efficiency. Study of new commercial construction over the past 5 years from Denver's Assessor's database indicated 76% (on average) to be larger than 20,000 sq ft and hence would participate in a (hypothetical) new green construction mandate modeled after San Francisco. It is important to note that because only 0.2% of commercial space is built new each year, even the 76% adoption among these would only address 0.76% of total commercial stock over 5 years, illustrating the immense inertia in the system. Participation rates in the opt-in bond program were based upon public reports of 2.6% households participating in Boulder over a 5-year period during which the bonds were issued twice; subsequent financing has proved difficult although the program was "sold-out" within weeks of each offering to the public. The above 5-year participation rates in Policy actions are shown in Figure 2b and Table 2. The larger participation rates in the ToS, date-certain, and opt-in bond programs (compared to voluntary counterparts), together yield a 1.5% reduction in GHG over 5 years—a 6-fold increase over their corresponding voluntary program designs which together yielded ∼0.25% GHG mitigation.

(e) Electricity Carbon Tax: A few pioneering cities have also independently instituted a carbon tax on electricity consumption separate from utility-derived taxes or fees (e.g., Boulder, CO levied 2.2%, 0.4%, and 0.2% tax increments on residential, commercial, and industrial electricity use, respectively[46]). Knowledge of electricity demand elasticity with respect to price (−0.15 to −0.35 for the Rocky Mountain region;[47]) can help estimate the direct impact of such taxes on electricity. The computations in Table 2 and Figure 3a are based upon a local electricity tax rate double that previously passed in Boulder, CO, (effectively a weighted average tax of 0.16% on overall electricity use) with a midpoint elasticity of −0.25 for the Rocky Mountain Region,[47] yielding 0.3% GHG mitigated in the building sector (Figure 3a). Tax revenues are often used to finance a city's energy outreach programs; such indirect additional benefits were not computed to avoid double-counting with earlier strategies.

In many parts of the U.S., e.g., California, utilities employ time-of-use pricing; while this achieves peak-shaving of electricity demand, overall energy-use impacts are mixed.[35] More detailed dynamic electricity dispatch models would be needed to identify GHG mitigation at specific times of day. The emerging smart grid offers such opportunities, but is considered a long-term option beyond the 2007−2012 time frame of this study. In the near-term, following the lead of Europe, several cities are considering installing real-time feedback devices in all homes. In citywide application, these real-time feedback devices are expected to yield greater electricity use reduction than monthly feedback in electricity bills (>4%;[30]), although less than the maximum observed in pilot studies (as high as 12%[13]). A lower-end 6% electricity savings per home seen in pilot studies of real-time feedback devices was applied to all 100% Denver homes to compute the impact, yielding 0.4% GHG mitigated (see Figure 3a and Table 2) from a *hypothetical mandate* that requires all homes to install these devices, similar to carbon-monoxide detectors required by many Colorado cities.

**State-Scale Synergistic Policies (P).** Specific state-level policies that regulate electric utilities and/or shape appliance standards can be synergistic with the city-scale policies and programs described above. Specifically relevant to the buildings sector in Denver is the Colorado Renewable Portfolio Standard (RPS) that requires electric utilities to incorporate 30% renewable energy into the grid mix by 2020,[48] projected to reduce Denver's electricity GHG emissions factor from 0.8 to 0.72 kg-$CO_2$e/kWh from 2007 to 2012, a 10% reduction. The impact of this emission factor was applied to the electricity-use remaining in Denver after all other energy efficiency and conservation strategies (described above) had been applied, and is shown in Figure 3a. Because the electricity EF is applied to all (residential, commercial, and industrial) electricity use, its impact is high with 8.3% GHG mitigated as shown in Figure 3a. Note, the reduction in electricity EF (of 10%) does not yield a corresponding 10% reduction in the building sector GHG, because it does not influence natural gas which is also used in this sector.

The impacts of all three actor-categories and state-level policies on GHG mitigation in the buildings sector are shown together in Figure 3a, and detailed in Supporting Information.

## 4. TRANSPORTATION SECTOR

A smaller menu of GHG mitigation strategies is available in the transportation sector compared to the building sector. Assuming large-scale trends in vehicle fleet fuel economy in the general population are reflected in the BAU trend, specific local actions include more rapid efficiency upgrades for local fleets (school buses, trash trucks, taxis) and efforts to promote mode shifts from personal automobile trips toward alternative modes.

**Voluntary Changes among Infrastructure Providers (D) and Users (U).** *Fleet Upgrades (D).* School buses, transit buses, and government fleets contribute only 1.2% of VMT in the Denver region.[18] Hence, even with an aggressive program that retrofits 50% of the fleets achieving 25% fuel savings,[49] the impacts are small with only 0.2% GHG mitigated over 5 years, as shown in Figure 3b.

Promoting mode shifts can be achieved by employer-based programs targeting long-distance work trips, by facilitating bike/pedestrian travel for shorter trips, and, by offering individualized travel marketing to residents who may not otherwise have access to employer-based programs.

*Employer-Based Commuter Programs (U).* The impact of employer-based incentives has been quantified in many U.S. metro area case studies, with reported annual average 0.5 mt-$CO_2$e saved per employee participating in the National Best Workplace for Commuters Program.[50] A similar range of GHG mitigation (0.5 to 1 mt-$CO_2$e/commuter) emerges in detailed studies of the Denver Regional Council of Governments (DRCOG) Ride Arranger Program in which 1429 employers offered carpool, vanpool, transit, and telecommuting during the 2009 program launch year.[51] More than half the automobile-displacement occurred from telecommuting by 11% of workers at the surveyed corporations,[51] each displacing a net average 36 automobile miles per week including induced nonwork travel.[52] Additional system-wide induced impacts, e.g., increased home energy use on telework days[53] are unclear since half the employers reported also reducing office space due to teleworking. Employee surveys[54] indicated good potential for doubling the number of employees participating in employer-based programs by 2012, yielding 60,000 additional participants over 5 years, which was applied in the computations shown in Figure 3b, each participant associated with 0.5 mt-$CO_2$e savings per year. This yields 0.6% GHG mitigated in 2012.

*Bike Mode Shift.* Likewise, with Denver's newly instituted Bike-Share Program (B-Cycle;[55]), the bicycle mode share in Denver is targeted to increase from 2% in 2009 to 10% in 2018, near the potential maximum observed in U.S. cities.[56] The new

B-Cycle Program has logged 100,000 trips and about 200,000 bicycle-miles over 6 months as measured by on-bike GPS units,[57] consistent with national data reporting average bicycle trip distances of about 2 miles.[58] Surveys conducted along three different transects in Denver revealed 22–66% of bicycle trips displaced automobile trips,[58] enabling realistic estimation of automobile GHG displacement from mode shifts to bicycle. Even if we assume these bicycle trips multiply 5-fold to meet the 10% mode-share target, automobile displacement is computed to be very small at ∼1 million VMT annually, compared to total motorized VMT exceeding 5 *billion*/year in Denver,[15] yielding a small (0.02%) GHG mitigated by 2012 (Figure 3b).

*Individualized Travel Marketing (ITM).* Additional mode shifts toward nonautomobile travel (e.g., transit) may be promoted through ITM programs that provide personalized information about existing mass transit routes and safe bike paths to promote switching to these alternatives modes. Results from such travel behavior change interventions are often in the gray literature, and must be verified in the future. A recent review reports 2–12% VMT reductions in ITM programs across U.S. cities, and confirmed the persistence in behavior change over two years in Portland, OR.[59] The theory of planned behavior was introduced to explain variations in behavior change reported in different Portland communities, dependent upon ready availability of alternate travel models. Given that transit options are widely available in the Denver region, but reported to be severely under-utilized by those working near transit outside downtown Denver,[54] we modeled travel marketing for 110,000 Denver residents who work outside Denver,[60] avoiding double-counting with previous strategies. Based on Figure 2a, about 10% of these workers are assumed to respond to the door-to-door outreach needed for ITM, each reducing their work commute VMT (currently 17.4 miles/worker/workday; Table 1) by the median 9% reported in 59, with the combination yielding 0.1% GHG mitigated. These computations are shown in Table 2 and Figure 3a.

**City-Scale Policies (P).** (a) Smart Growth Urban Planning strategies that reduce the demand for motorized travel include promoting population density (compact growth), diversity of mixed residential–commercial use, street design to support multiple travel modes, and, regional accessibility to jobs and to transit, also referred to as the 5-D's.[61,62] A recent National Research Council (NRC) study comprehensively reviewed the impact of the above variables on motorized travel, evaluated confounding factors, and identified small (but statistically significant) travel demand elasticity with respect to these land-use variables (see Table 3). Because Denver has a voter-approved mass transit program[63] and a local land use plan[64] that includes mixed-use, higher-density urban neighborhoods with access to transit, it is reasonable to represent Denver after the NRC's best-case scenario, wherein 75% of all new population growth in the city from 2007 to 2012 (0.95% per annum, Table 1) is channeled to transit-oriented neighborhoods (TODs). This subset of the population (∼3.4% of Denver's 2012 population) would experience the synergistic impacts of density, diversity, design, and transit, and they are estimated to experience a 25% reduction in VMT/capita[65] from the current 23.5 VMT/person/day.[15,16] These computations yield 0.9% GHG mitigated in the transport sector, as illustrated in Figure 3b. Additional beneficial induced effects of compact growth on buildings energy- and materials-use (e.g., 66) were noted but *not* modeled due to variability in these estimates and numerous confounding factors.

**Policies at the State-Regional Level (P).** Several cities are attempting to utilize price signals to reduce motorized transport—e.g., congestion pricing in London and Singapore,[67] and diesel taxes in Delhi.[68] In the short term, we do not expect U.S. cities to levy taxes on gasoline or on vehicles. Recently, however, VMT/user-based transportation taxes have been proposed to raise revenues for infrastructure maintenance.[69] Thus, VMT-based pay-as-you drive (PAYD) automobile insurance may be politically feasible in the near future, being listed on the climate action plans of more than 13 States in the U.S., including Colorado.[70] PAYD has been pilot-tested in Oregon and Texas. PAYD charges for auto insurance according to miles driven and is reportedly equivalent to a 40% increase in gas prices;[71] gasoline demand-price elasticity (72; Table 3) can be applied to estimate short-run and long-run behavior change triggered by PAYD. Several states have also proposed renewable fuels standards[73] and clean car feebate programs;[74] national policies have since followed in both areas,[75] although the clean cars program does not go into effect until 2014. More near-term regional policies have also been proposed for Colorado, such as mandating sale of low rolling-resistance tires that can achieve 1–2% fuel economy gains without compromising safety.[76]

## 5. MATERIALS, WASTE, AND OTHER TRANS-BOUNDARY INFRASTRUCTURES

**Airline Travel and Purchased Travel Offsets.** Airline travel is one of the trans-boundary infrastructures serving cities made visible in Denver's trans-boundary GHG accounting method.[15,16] Air travel contributes 2% GHG nationally,[77] and about 6% for Denver, with an average of 19 gallons jet fuel used per enplaned passenger at Denver's airport.[15] Passenger surveys conducted at two major U.S. airports reveal about 33% of outbound passenger trips are for nonconference business travel.[78] The Denver region's transportation planning organization (DRCOG) already provides telework assistance to many of the large employers (firms) in the region and finds about 10% employees telework.[51,52] It is assumed similar participation rates would emerge if the region were to offer telepresence/teleconference facilities, avoiding 10% of work-related air travel after a 5-year time frame, i.e., impacting 3.3% of air travelers as shown in Figure 3b, yielding 0.7% reductions in overall transport sector GHG over 5 years from increasing use of telepresence. Studies computing the net benefit of teleconferencing/telepresence, including induced effects of increased energy use in the buildings sector, find airline fuel savings dominate the benefits.[79]

The purchase of travel offsets can also be an option for mitigating GHG arising from airline travel, cited in the Climate Action plans of cities such as Denver[80] and San Francisco.[81] Airline survey reports in the UK indicate about 6% of all airline passengers purchased such offsets.[82] If similar participation of 5% of air travelers is seen in U.S. cities over the next 5 years, ∼1% GHG mitigation of overall transport sector emissions result (Figure 3b).

The impact of transportation sector strategies on in-boundary and trans-boundary GHG emissions are shown in Figure 3b, detailed calculations are shown in Supporting Information.

**Materials Substitution, Conservation, and Recycling.** Other trans-boundary strategies explored by cities include the


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use of green concrete; initiating water conservation efforts that would reduce both water supply and treatment energy-use; and promoting reduce, reuse, and recycle of waste materials through policies such as "pay-as-you-throw" (PAYT[83]). In 2007, Denver became the first city to require 15% fly ash in all new flatwork concrete construction, and is documenting annual tons of fly ash substitutions in green concrete.[84] The materials data along with the life cycle GHG savings of green concrete[85] enable computing the mitigation impact of this strategy. Water conservation results in small savings of 0.5−1 W-hour per gallon of water saved, considering water and wastewater treatment energy at the respective treatment plants;[86,87] trans-boundary energy needs to pump water into Denver are very small.[86] Waste-reduction impacts under the PAYT scenario were estimated using EPA's national average of 0.32 mt$CO_2$e saved per participant.[88] Other waste sector strategies include landfill energy recovery. A 5-MW landfill gas to electricity powerplant is now operational at Denver's landfill, but is owned by the electric utility as part of its renewable portfolio, and hence is not counted again. Direct food-waste to electricity projects are presently being piloted in Denver at the Convention Center (see also 89). The combined impacts of these material sector strategies are estimated at 190,000 mt$CO_2$e (~1% of Denver's total projected GHG emissions) if PAYT is mandated for the entire community. Deeper reductions require industrial symbiosis-based strategies, ranging from combined heat and power to greater levels of local−regional material−energy symbioses incorporating industrial and municipal wastes.[90] Supportive urban design and zoning codes are needed to facilitate symbiosis across industrial−commercial−residential sectors in a city.

Food is an important trans-boundary material flow that contributes significantly to city GHG emission footprints (Figure S1). Strategies promoting healthy diets that reduce red-meat consumption among residents[91] are estimated to save as much as 0.6 mt-$CO_2$e/capita, annually;[92] however program outcomes are difficult to track community-wide. More data on such campaigns are needed to determine the extent of GHG mitigation that occurs, and how it can be reported and attributed to cities.

## 6. CASE STUDY RESULTS AND REVIEW OF CLIMATE ACTION PLANS IN U.S. CITIES

This case study of Denver, CO, has evaluated diverse strategies that can be applied to reduce GHG emissions associated with human activities in cities, covering technology, building design, urban planning, smart growth, and policy strategies including regulation and market-based approaches, as well as behavior change strategies. We believe this is a first study to quantify the order-of-magnitude impacts of such diverse strategies across multiple infrastructure sectors—buildings, facilities, transportation, and materials/waste sectors—in cities, exploring the role of the different social actors in the configuration of climate actions.

For the same strategy, climate actions configured upon voluntary participation among individual users (U) and infrastructure designer-operators (D) tend to have a much slower rate of penetration compared with stronger policy/regulatory actions (P), as seen in Figures 2b and 3a, b. For each strategy, while technology effectiveness can vary by 50%, societal participation rates can vary by several factors and even orders of magnitude (>1000%) depending upon the action-configuration. Consequently, overall action-impacts vary widely as in Table 2. In the worst case, the low range of technology effectiveness combined with low societal participation rates yields almost no change (−1%) from the 2012-BAU over 5 years, while the best-case technology effectiveness with highest participation rates achieves reductions exceeding 1% annually (−5% over 5 years). These results suggest that cities must employ a portfolio approach carefully selecting those voluntary programs proven to attract high societal participation, combined with at least a few high-impact regulatory policies.

A strategy portfolio analysis was conducted of 55 U.S. cities' climate action plans. These cities represent all those among 900+ U.S. cities that have pledged GHG mitigation and had reached the milestone of developing communitywide plans as of November 2010.[93] Figure 4 shows ~95% of cities engaging

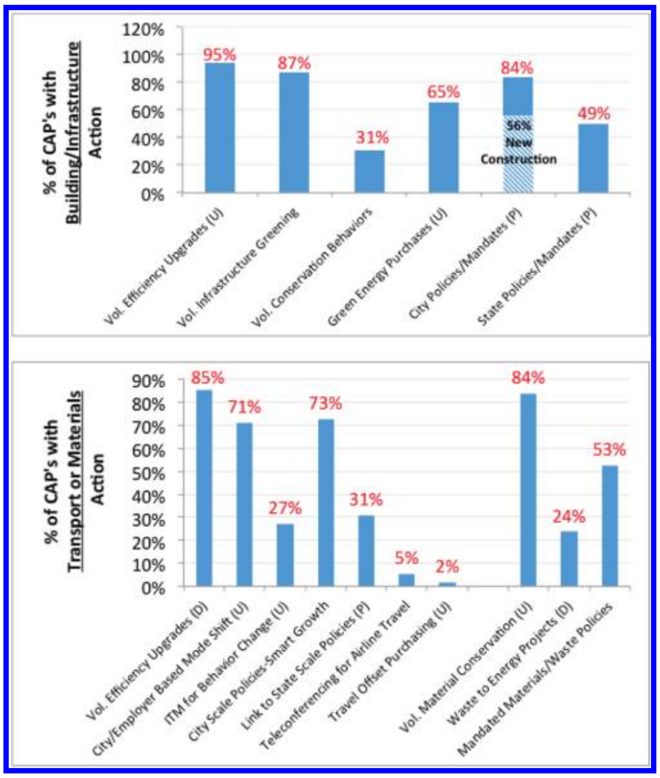


**Figure 4.** Portfolio analysis of Climate Action Plans (CAPs) launched by 55 U.S. cities: (a) buildings−facilities sector; (b) transportation sector.

in typical voluntary energy-efficiency programs, while more innovative voluntary strategies such as green energy purchasing (65%), feedback-based behavioral strategies (31%), and technology−telecommuting strategies (5%) are being under-utilized in comparison. Among city-scale policies, smart growth planning and energy-efficient building codes for new construction are widespread. However, only about a quarter (28%) are exploring regulations addressing existing building stock or rental property that would achieve more rapid GHG mitigation. Few cities (<50%) are establishing links with state-scale policies.

Comparing the portfolio review of U.S. cities (Figure 4a and b) with the Denver-area case study results (Figure 3a and b) yields interesting insights. In the buildings sector, green energy purchasing and feedback-based behavior change interventions appear promising for voluntary program design (Figure 3a), but are currently being underutilized in our meta-review of city


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plans (Figure 4a). U.S. cities are emphasizing a variety of voluntary energy efficiency interventions—however, many of these typical interventions (e.g., items 1−4; Figure 3a), together, barely make a dent in the BAU trend in our case study. The same efficiency interventions have greater impact when implemented via city policies that address the older stock of buildings in cities, e.g., time-of-sale or date-certain ordinances. However, less than 30% of U.S. cities are pursuing such policies (Figure 4a). If several of these policies are implemented together −as they are in cities such as Berkeley, CA, San Francisco, CA, and Boulder, CO−deep reductions in building-sector GHG emissions are possible in the near term. .

In conjunction with statewide polices such as RPS for electricity, reductions to 1990 levels are possible in the buildings sector over the short span of 10 years—with no new technologies. This can be seen in Figure 3a, where 2012 GHG approach 1990 levels, covering almost 85% of the difference in 5 years of climate action in the buildings sector, assuming all actions shown are adopted. Greater GHG reduction to reach 1990 levels is expected as the state of Colorado's RPS reaches it stated goal of 30% penetration of renewables in the grid-mix by 2020, and the subsequent Clean Air Clean Jobs Act that phases out coal-fired powerplants with natural gas (HB 10-1365) comes into effect

In contrast, the transportation sector is more challenging. With all the strategies discussed here enacted from 2007 to 2012, year 2012 transportation sector GHG levels are reduced to a much smaller extent, covering only 10% of the GHG mitigation necessary to reach 1990 levels (Figure 3b). Popular programs such as biking, even with higher mode share, have little impact; strategies like car-share require densities exceeding 5−10 dwelling units/acre,[94] uncommon in most U.S. cities.[16] Even with best-case projected smart growth benefits of mass transit, compact infill development, multimodal street design, and mixed use development, VMT and GHG mitigation are modest in the near-term, although long-term reductions will be high.[61] These results show the tremendous inertia and path-dependency in the transportation sector, given geography and past development patterns. In the near-term, technology strategies such as telecommuting and teleconferencing/tele-presence appear favorable; both strategies are presently underutilized by cities (Figure 4b). Smart growth and transit-oriented development—already significant in the short term as much as any of the other transportation sector strategies—will show continued impact in the medium- and long-term. Some of the state-scale policies such as PAYD insurance or LRR are significant, but still relatively modest (Figure 3b). Long-term vehicle-fuel transformations supported by appropriate State- and national-scale policies are essential for deep GHG mitigation in the transportation sector to approach 1990 levels.

More research is also urgently needed on cross-sector strategies that have potential to reduce GHG emissions significantly in U.S. cities, but that have not been quantified in this paper due to lack of widespread field data. These include a good understanding of the induced effects that smart growth development can potentially have not only on transportation energy use, but also on buildings energy due to smaller homes with common walls, and reduced infrastructure needs, as well as on the potential for urban municipal and industrial symbiosis.[66,90] Little is known about optimum housing density in mixed use developments that can support symbiosis, facilitating combined heat and power, food-waste to energy, energy exchanges among the water, buildings, and power sectors, or even further, urban industrial symbiosis. The interplay among ICT technologies, transportation energy use, and buildings energy use can also be confounding,[53] and must be unraveled to develop innovative emerging pathways for GHG mitigation.

## 7. DISCUSSION

What do these results mean for cities and for researchers of sustainable city-systems? If rapid GHG mitigation is the goal, case study results in this paper indicate that cities must capitalize on innovative technology−strategies at the interface of information technologies and human behavior, find ways to enhance societal participation in voluntary programs, or address the political challenges of introducing and implementing regulatory programs. Recognizing that cities do not have unlimited resources to implement all the strategies shown in Figure 3a, b, choosing the optimal action-categories at the city-scale for further linkage across spatial scale—with regional and state actors—is important. Although economic costs are important in program design,[95,96] diffusion of innovations in society, careful field measurements of energy and carbon reductions, reporting of voluntary participation rates in different program designs, and the political feasibility of regulatory actions are equally important considerations.

The data in this paper show that societal participation rate is a key parameter that shapes GHG mitigation outcomes in cities. To-date, cities do not systematically record such data in either their voluntary or their mandatory programs. We know little about how such participation rates relate to variables such as culture, values, beliefs, norms, community network ties, and policy capacity in different communities. When participation rates in voluntary programs are low, significant administrative resources are dissipated. Hence, low-participation programs must be reassessed or redesigned to enhance participation. Cities are experimenting with programs such as Portland's Climate Masters Program that empower community leaders to enhance adoption of sustainability practices. Pairing such field experiments with research on social networks and diffusion of innovation[97,98] can yield important insights essential to translate successful outreach programs to other cities through better understanding of energy opinion leaders, social networks, and associated participation rates in voluntary programs.

Among regulatory policies, examples in this paper suggest that even challenging and complex regulations may become widely accepted when economic benefits, job creation, and health benefits are integrated into sustainable energy policy development, and, when there exists sufficient policy capacity to bring together seemingly divergent advocacy groups to common ground. Anecdotally, these factors have been cited as important in developing regulations such as the Renewable Portfolio Standard and the Clean Air Clean Jobs Act in Colorado, and the Time-of-Sale ordinances in California. Theories and frameworks drawn from public affairs, such as the advocacy coalition framework[99] can help uncover these relationships further. The Institutional Analysis and Development Framework[100] can be applied to examine collective action situations where people interact directly, such as committees that develop climate action plans in cites, analyzing the rules of participation, negotiation and sanctions, and their nested linkages with state and national plans. Improved understanding of policy processes, social actors, coalitions, and networks is essential to facilitate the translation of high-impact GHG policies across cities. In the absence of applied theoretical research, examples of individual city and state successes will abound, but with few insights to translate them to other communities.

Improved system-wide analytical tools are also needed to fully evaluate some of the cross-sector strategies highlighted in this paper, e.g., induced effects on the buildings sector from transportation sector strategies such as telecommuting, telepresence, and compact growth. Over the longer term, industrial symbiosis in cities may hold the key to deeper GHG mitigation. Interdisciplinary frameworks[101] linking industrial ecology, engineering, urban planning, public affairs, and behavioral science are essential to evaluate these interactions across infrastructure sectors and between infrastructure systems and social actors, addressing both sustainable production pathways (e.g., clean energy as specified by renewable portfolio standards) and sustainable consumption pathways (e.g., reducing electricity use in home via feedback). This paper illustrates the potential for such broadly integrative field research, conducted in partnership with communities, to advance GHG mitigation in cities.

## ■ ASSOCIATED CONTENT

### Supporting Information

This information is available free of charge via the Internet at http://pubs.acs.org/

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### Notes

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