Quantifying Carbon Footprint Reduction Opportunities for U.S. Households and Communities

Supporting Materials

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A. Detailed Methods of Benchmark Carbon Footprint Model

1. Motor Vehicles

Emissions from motor vehicles include: 1) direct tailpipe emissions from fuel combustion in vehicles, 2) indirect "well-to-pump" emissions from the pre-consumer life cycle of fuels, 3) vehicle manufacturing, and 4) vehicle maintenance and repairs (including parts and services). Government-related indirect emissions from road construction and maintenance, policing, and other activities are currently not included in the model.

1.1. Direct tailpipe emissions

The average U.S. household drove 21,200 vehicle miles in 2001 (*1*), the latest year national average household vehicles miles traveled are available at the time of model construction. The weighted fuel economy of the U.S. vehicle fleet is about 20 miles per gallon (*2*). Combustion of a gallon of gasoline produces 8,874 gCO_2 and diesel produces 10,153 gCO_2 (*3*). For benchmarking purposes, all vehicles are initially assumed to be gasoline since diesel vehicles account for only a small fraction of the U.S. vehicle fleet, although users of the online tool[3] can further specify gasoline or diesel fuel type. Other vehicle fuels (e.g., biofuels and electricity) are currently not included in the model. Direct emissions for the average U.S. household (with 2.5 persons) are calculated as: 21,200 miles / 20 mpg * 8,874 gCO_2/gallon = 11.9 mtCO2e/yr.

The calculator populates default values for the average number of vehicles and average miles per vehicle for each household type (using equation 2 in the main paper). The default number of vehicles

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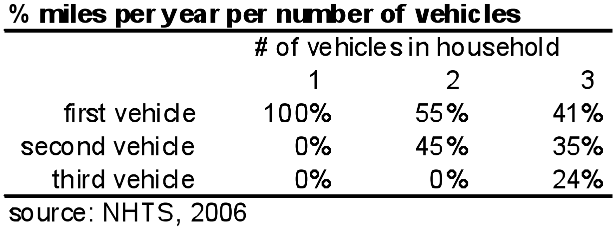
[3] Results of this study have been made available in an open access online carbon management tool for U.S. households, available at http://coolclimate.berkeley.edu and http://coolcalifornia.org/calculator.

per household is given by the Consumer Expenditures Survey (*4*) and is rounded to the nearest whole number. Vehicle miles traveled are distributed per vehicle using the National Household Travel Survey (*5*):

Table 1. Allocation of vehicle miles per number of vehicles owned by households



% miles per year per number of vehicles

	# of vehicles in household		
	1	2	3
first vehicle	100%	55%	41%
second vehicle	0%	45%	35%
third vehicle	0%	0%	24%

source: NHTS, 2006

1.2. Indirect "well-to-pump" emissions

Estimating emissions from the full life cycle of transportation fuels (from "well-to-wheels") has become increasingly important aspect of transportation policy. In order to compare emissions from disparate transportation energy sources, such as biofuels, natural gas and electricity, a life cycle assessment (LCA) approach is required. California's "Low Carbon Fuel Standard" (LCFS) mandates life cycle accounting in an effort to increase the use low carbon transportation fuels in the State. The LCFS policy analysis report of 2007 (*6*) identifies 20% as a typical value of well-to-pump emissions for gasoline, citing the GREET (*7*) model in its technical report (*8*). Well-to-pump (WTP) gasoline emissions in GREET are 26% of tailpipe emissions (or roughly 20% of well-to-wheel emissions), while diesel WTP emissions are 23% of direct emissions. Delucci's (*9*) estimate of 20,778 gCO_2e/106 btu for pre-combustion gasoline emissions equates to 29% of direct emissions. EIO-LCA (*10*) produces a more conservative estimate of about 14% (*11*) and other studies have previously assumed a value closer to this lower estimate (*12*,*13*). The LCFS program in California is currently developing default well-to-wheels emission factors for transportation fuels, and a similar effort has been proposed at the national level. Until standard default values are determined by state or national policy directives, we have chosen the GREET model as the most representative emission factors for well-to-pump emissions.

1.3. Vehicle manufacturing

EIO-LCA is used to approximate emissions from motor vehicle manufacturing. The average retail price of a domestic automobile was $17,907 (*14*) in 1997. The average producer price was 80% of the retail price (*15*), or $14,326. Applying the 1997 EIO-LCA emission factor of 628 gCO_2e/$ for the "Automobile and light truck manufacturing sector" in EIO-LCA results in 9.0 $mtCO_2e$ per vehicle. This estimate is consistent with process-based LCA studies, which include the most significant emissions from vehicle manufacturing, but exclude economy-wide impacts further up the supply chain. Published studies include estimates of 4.4 $mtCO_2e$ for a Volkswagen Golf (*16*), 8-9 $mtCO_2e$ for Ford Galaxy and S-Max models (*17*), 9-10 $mtCO_2e$ for Mercedes S Class models (*18*) and 6.8 $mtCO_2e$ from vehicle components and assembly over the lifetime of a typical vehicle in the GREET (*19*) model.

Allocating emissions from motor vehicles, as with other consumer goods with long life spans, presents challenges to carbon footprint calculator designers. Should upstream emissions from the production of vehicles be allocated at the time of purchase, or over the lifetime of the vehicle? When a vehicle is sold, what portion of manufacturing emissions should be allocated to the new owner? Allocating emissions at the time of purchase produces a disincentive to purchase new, and potentially more fuel efficient vehicles. If, on the other hand, emissions are allocated over the lifetime of vehicles on a per-mile-basis, there is no incentive to reduce the very significant emissions from vehicle manufacturing.

Table 2 provides an example of the effect of different assumptions for embodied motor vehicle emissions. Increasing fuel efficiency from 25 to 40 mpg for a vehicle driven 10,000/yr reduces well-to-wheel GHG emissions by ~1.6 mtCO_2e/yr (1.3 direct plus 0.3 well-to-pump) or 16 mtCO_2e over 10 years. If 9 mtCO_2e of manufacturing emissions are allocated at the time new vehicles are purchased, then it would take nearly 6 years for this action to result net GHG savings. Purchasing a new fuel efficient vehicle every 3 years would result in net negative savings (additional emissions) of 11 mtCO_2e over 10 years with no manufacturing emissions passed on to the future owners of these vehicles. If, on the other hand, embodied emissions are allocated on a per mile basis, then driving a 40 mpg vehicle would result in lifecycle savings of 10 mtCO_2e over 10 years, regardless of how many new or used vehicles are purchased over this period. Thus, from one perspective regularly purchasing new fuel efficient vehicles reduces net GHG emissions, while from the other perspective net emissions are increased.

Table 2. Allocating vehicle manufacturing emissions at time of purchase or on a per mile basis

Effect of purchasing more efficient vehicle under different embodied GHG emissions assumptions (switching from a 25 mpg to 40 mpg vehicle, driving 100,000 miles in 10 years)

Allocation of manufacturing GHG emissions	Frequency new or used vehicles purchased	mtCO2e saved in fuel consumption	mtCO2e from vehicle manufacturing	Net CO2e saved
Allocated upfront	New every 3 yrs	16	27	-11
Allocated upfront	New every 5 yrs	16	18	-2
Allocated upfront	New every 10 yrs	16	9	7
Allocated upfront	Used every 3 yrs	16	0	16
Allocated upfront	Used every 5 yrs	16	0	16
Allocated upfront	Used every 10 yrs	16	0	16
Allocated per mile	New every 3 yrs	16	6	10
Allocated per mile	New every 5 yrs	16	6	10
Allocated per mile	New every 10 yrs	16	6	10
Allocated per mile	Used every 3 yrs	16	6	10
Allocated per mile	Used every 5 yrs	16	6	10
Allocated per mile	Used every 10 yrs	16	6	10

Assumptions:
Direct emissions = 8874 gCO2/gallon
Well-to-pump emissions = 20% of direct emissions
Manufacturing emissions = 9 mtCO2e/vehicle
Vehicle lifetime = 160,000 miles

Another, seemingly more reasonable, approach would be to allocate emissions based on depreciation of vehicles on an annual basis. This would allocate most of the emissions to the early years of a vehicle's lifetime and fewer emissions toward the end; however, such an allocation process is difficult to accomplish in practice and has not been included in the current model.

For the current calculator we chose to allocate emissions from vehicle manufacturing on a per mile basis for the following reasons: 1) the preferred method of allocation based on vehicle deprecation was not feasible, 2) allocating emissions on a per mile basis sends a signal to reduce vehicle miles traveled, which is arguably more important than limiting production of motor vehicles, and, 3) encouraging the purchase of more fuel efficient vehicles stimulates innovation, which can lead to future emission reductions.

Emissions per vehicle mile are calculated as:

$$\frac{9tCO2e}{vehicle} * \frac{vehicle}{160{,}000 miles} = \frac{56kgCO2e}{mile}$$

where 160,000 miles is the average expected lifetime of motor vehicles (*20*)

1.4. Vehicle maintenance and repairs

EIO-LCA is used to approximate emissions from motor vehicle maintenance and repairs. See Food, Goods and Services discussion below.

2. Public Transportation

The expense “Public transportation” in the Consumer Expenditures Survey aggregates air travel, bus, rail, and other into a single expenditures category, complicating the use of CES for benchmarking purposes for different transport modes. Emissions from public transport were determined by 1) converting dollars to passenger miles using a top-down approach, 2) allocating miles to different transport modes, 3) multiplying passenger miles by GHG emission factors for each mode, 4) scaling emissions based on income, 5) accounting for the higher fraction of air travel miles for households at higher incomes.

The Transportation Energy Data Book (*21*) provides total U.S. passenger miles per transport mode (Table 1.3). The vast majority of passenger miles for non-highway vehicles are for air transportation (93%), followed by 3% from Bus, 3% from transit and commuter rail, and 1% for long distance rail (Amtrak).

Table 1.3 Passenger miles per public transportation mode (2004)

Mode	Total US (millions)	Per capita	%
Air*	752,341	2,566	93%
Bus	21,262	73	3%
Transit (light&heavy)	15,930	54	2%
Communter rail	9,719	33	1%
Amtrak	5,511	19	1%
Total		2,745	100%

Source: Transportation Energy Data Book, 2007

* includes domestic and international flights

According to the Transportation Energy Data Book (*21*) thirty-one percent of all long-distance trips are for business (*22*). These emissions are theoretically embodied in goods and services so are not included under here. Total average public transportation miles (including air travel) are defined as:

$$\frac{2745 miles *}{person} * 69\% * \frac{2.5 persons}{household} = \frac{4735 miles}{household}$$

The average US household spent $505 per year on public transportation in 2006, or 9.4 miles per dollar. We multiply consumer expenditures by 9.4 and scale total passenger miles for each income level and household size.

To calculate benchmark transportation miles for each household type we then calculated the fraction of total passenger miles by each major mode of transport using the Transportation Energy Data Book, 2007 (*22*). Air travel accounted for 93% of total passenger miles for all major public transport modes in 2004. Air travel is a normal good; as income goes up, so do expenditures on air travel, i.e., showing a positive income elasticity of demand. Other public transport modes are inferior goods, with lower demand as income increases over middle incomes. Households earning less than $25k per year take more trips by bus than by air, while household earning more than $75k per year take nearly 10 times the number of long distance trips by air than by bus.

Table 1.4 Percent of long distance trips by mode and income

	Less than $25K		$25K-$49K		$50-$74K		$75K+	
Mode	**%**	**$**	**%**	**$**	**%**	**$**	**%**	**$**
Air	38%	$ 77	58%	$ 161	63%	$ 347	85%	$ 846
Bus	49%	$ 97	32%	$ 89	24%	$ 131	9%	$ 93
Train	9%	$ 18	9%	$ 25	10%	$ 52	5%	$ 49
Other	4%	$ 8	2%	$ 4	4%	$ 20	1%	$ 12
Total	100%	$ 200	100%	$ 280	100%	$ 550	100%	$ 1,000

% source: BTS, 2006. Americans on the go. Table 13.
Total $ source: Consumer Expenditures Survey, 2006
$ per mode is interpolated

The final calculation for public transportation is:

$$\frac{\$}{year} * \frac{9.4 miles}{\$} * \frac{miles_{\text{mod}\,e}}{miles_{total}} * \frac{CO2e}{mile_{\text{mod}\,e}}$$

Emission factors for public transit modes are from the Greenhouse Gas Protocol (*23*) which incorporates studies by EPA and other sources (Table 1.5). These estimates assume average occupancy of public transit modes.

Table 1.5. Emission factors for public transit

Mode	gCO2e/mile
bus	300
commuter rail (light & heavy)	165
transit rail (subway, tram)	160
Amtrak	191

Source: Greenhouse Gas Protocol (WRI-WBCSD)

Indirect well-to-pump emissions from transportation fuels are assumed to be 26% of direct emissions, as indicated by the GREET model (*24*)

3. Air Travel

Air travel results in 1) direct CO_2 emissions from fuel combustion, 2) indirect life cycle ("well-to-pump") GHG emissions from fuel processing and other indirect emissions from the airline industry, and 3) non-CO_2 atmospheric effects on global and local temperatures and weather patterns.

GHG emissions from consumption have been shown to vary substantially depending on aircraft type, flight distance, number of stops, seat occupancy rate and seat class.(*25*) Few online calculators, however, present this level of customization, presumably due to the additional modeling efforts required and the preference to build simple, user-friendly interfaces that require less time to complete. DEFRA, 2007 (*26*) is commonly cited as a reference for GHG emission factors. This report considers typical flights within the U.K., within the E.U. and transatlantic flights. Trip length and emission factors, converted to miles and gCO_2 per passenger mile, are:

Trip length	gCO2/passenger-mile
288 miles	254
688 miles	210
4027 miles	170

Shorter flights have higher emission factors due to relatively higher emissions at takeoff and landing per passenger-mile. Extrapolating these numbers using a logarithmic curve, and assuming typical trip length of ~1200 miles (*27*), yields the following emissions estimates per given trip length.

Trip length	gCO2/passenger-mile
Number of short flights (<400 mi)	254
Number of medium flights (400-1500)	204
Number of long flights (1500-3000)	181
Number of extended flights (>3000)	172
Typical flight (1200)	200

Indirect “well-to-pump” emissions are assumed to be 20% of direct emissions, following the GREET model (*28*). Other indirect emissions, e.g., from the airline industry, are excluded from this analysis.

Airplanes traveling at high altitude have large, varied and relatively uncertain effects on surface temperature. These impacts include warming from 0_3, H_20, soot, contrails and cirrus clouds, and cooling effects from breakdown of CH_4 and emissions of sulfates and aerosols. The average net result on global radiative forcing -not including the large but uncertain effects from cirrus clouds- is reported to be roughly equivalent to the warming effect of direct CO_2 emissions from fuel consumption.(*29*) However, simply multiplying CO_2 emissions by a factor to account for radiative forcing can lead to false conclusions.(*30*) The climate impact of individual flights varies considerably, ranging from net cooling in some cases to flights with several times the impact of typical flights. The particular contribution of warming and cooling factors depends on altitude, temperature, humidity, the chemical composition of air, geographic region, time of day, season and other factors. Impacts also occur over vastly different time scales, ranging from hours to centuries, thus complicating the selection of global warming potential of a single pulse of emissions. Furthermore, net radiative forcing models assume that warming in one location cancels cooling in another, rather than producing separate distinguishable impacts on local climates.

Despite the limitations of using radiative forcing, carbon calculator modelers need some way to express climate impacts from air travel without relying on highly complex models with detailed and time-consuming user interfaces. In the absence of standards, carbon footprint calculator modelers have typically chosen to either ignore non-CO_2 impacts, or include a factor to account for radiative forcing. In the current version of the calculator we use the radiative forcing multiplier of 1.9 as proposed by Sausen et al. (29) to account for non-CO_2 impacts. While this factor is not specific to individual flights is it is a reasonable representation of average climate impacts from air travel. This approach is consistent with the assumption of typical impacts from consumption in the rest of the calculator. The total indirect emission factor for non-CO_2 atmospheric effects and well-to-pump emissions (1.9 + 0.2) is rounded to 2. This is very likely a conservative number considering we have not included the large but uncertain global warming impact of cirrus cloud formation or emission from airports.

4. Household Energy

Household consumption of electricity, natural gas and other fuels is provided in dollars by the CES for each household type by income and size. However, CES does not disaggregate electricity, natural gas and other fuels for metropolitan statistical areas. Regional energy consumption varies considerably due to different energy prices, weather, heating fuels, housing size and construction and other factors (*31*). Another possible source of data, the American Housing Survey (AHS) (*32*), provides average expenditures on electricity, natural gas and other fuels for each city; however, the AHS only includes a sample of cities every two years and inter-annual variation of energy consumption would confound comparisons. A modeling approach may be best suited to account for both regional variation and the influence of household types on energy consumption; however, such an approach is outside the scope of the current study.

Given the data limitations mentioned above, we have approximated benchmark electricity and natural gas consumption for each household type (location, household size and income) as follows:

$$I = D_h * P_s * E_s$$

where,

I = impact, expressed in gCO_2e/year

D = dollars spent per year on electricity or natural gas for each household type (h) of income and household size in the CES

P = price of energy per US State (s) in dollars per physical unit of fuel

E = emission factor for each US State (s) in gCO_2e per physical unit of fuel

This formula effectively scales state-level consumption of electricity, natural gas and other fuels by household type (size and income) for the default values in the calculator. As in all other section of the calculator, users can overwrite the default values with their own consumption levels (in dollars or physical units). A discussion of emission factors used in the analysis follows.

Direct emissions from household energy

Households contribute direct GHG emissions from the burning of fossil fuels in homes. Natural gas is typically the largest single contributor to direct household emissions for U.S. households. Natural gas is assumed to produce 117 lbs CO_2/Mbtu (33). The CES category "fuel oil and other fuels" includes expenditures on fuel oil, coal, wood, bottled gas and other fuels, accounting for 8% of total household energy expenditures for the average U.S. household, and 0.3% of total household expenditures. Published CES tables do not disaggregate consumption by individual fuels, making approximation difficult. Considering the relatively small contribution to total household GHG emissions from other fuels for most households, we use a single emission factors of 682 gCO_2e/$ provided by the EIO-LCA (*11*) model. This approximation can be expected to contribute only a very small fraction of the total uncertainty in carbon footprint estimates for most households, although in northeastern United States, where heating oil is more predominant, the total uncertainty can be expected to be substantially higher. Further work will be required to refine this calculation in future versions of the calculator, which may provide more reasonable estimates based on fuel consumption of different fuel types in physical units.

Other direct emissions from wood burning, fertilizers, and chemical processes are assumed to be relatively small in comparison to other categories of emissions and are excluded from the current analysis.

Indirect emissions from electricity production

Greenhouse gas emission factors (EF) for electricity are from eGRID (*34*). This database aggregates air emissions for each generator at thousands of electricity power plants in the United States. Aggregation is available at the level of U.S. states and 25 grid sub-regions. The eGRID data provided at the level of U.S. states account for generated electricity only, excluding imports and exports of electricity, and are therefore are not appropriate for the development of carbon footprint calculators. EPA recommends the use of eGRID sub-regions for accounting purposes; however, sub-regions do not always correspond well with U.S. states, which is currently the only geographic information asked by users in our online model. As a partial solution to this problem, we map the boundaries of U.S. states to individual eGRID subregions, with the exception of New York, which is assumed to be the average of three subregions.4 In the case of California, users can select electric utility provider, with GHG emission factors for the year 2006 provided by the California Air Resources Board (*35*), as reported to the California Climate Action Registry.

Indirect emissions from electricity and natural gas life cycles

Electricity consumption also indirectly results in GHG emissions during the production, processing, transmission and storage of fuel, as well as during the construction and maintenance of power plants. Pacca and Horvath (*36*) first approximated pre-combustion and construction life cycle emissions from

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[4] We are currently conducting research to offer more geographically-specific electricity emission factors in future versions of the calculator, but this work was not completed at the time of this writing.

coal, natural gas, wind, hydro and solar power plants in the Upper Colorado River Basin. Total life cycle emissions were 9% higher than emissions from combustion alone for a coal-fired power plant and 14% higher for a natural gas plant. Using a different methodology, Jaramillo et al (*37*) produced roughly the same results for these fuel sources. We developed pre-combustion indirect electricity emission factors for each eGRID subregion by multiplying the fuel mix in each region by emission factors (tCO2e/MWh) provided by Pacca and Horvath. When state boundaries include more than one eGRID subregion we used the average fuel mix for those regions. The results are shown in the table below. For the average U.S. fuel mix, pre-combustion emissions are 9% of combustion emissions. With the exception of Alaska, which is dominated by hydro power, indirect emissions are between 8%-12% of direct emissions. Considering the margin of error in this analysis is likely greater than the difference between indirect emission factors for U.S. states, the current online model applies the U.S. average indirect factor for all U.S. states. Future online versions of the calculator may incorporate the state-specific factors.

We assume indirect emissions from natural gas (including extraction, processing and piping natural gas to homes) add 14% to direct emissions per Jaramillo et al. (*37*).

tCO2e per 5.55 MWh/yr capacity of electricity generation per U.S. state and eGRID subregion

		Direct*			Indirect**						Indirect
State (eGRID subregion)	%***	Coal	Gas	Total	Coal	Gas	Wind	Hydro	Solar	Total	/ Direct
USA	78%	37.85	8.92	46.77	3.11	1.23	0.02	0.03	-	4	9%
Alabama (SRSO)	0.79	50.51	4.53	55.04	4.15	0.62	-	0.02	-	5	9%
Alaska (AKMS)	0.70	-	1.53	1.53	-	0.21	0.00	0.34	-	1	36%
Arizona (AZNM)	0.81	35.70	13.06	48.76	2.93	1.80	0.00	0.02	0.00	5	10%
Arkansas (SRMV)	0.68	16.54	18.66	35.20	1.36	2.58	-	0.01	-	4	11%
California (CAMX)	0.74	9.29	17.46	26.75	0.76	2.41	0.02	0.09	0.03	3	12%
Colorado (RMPA)	1.00	55.94	8.04	63.98	4.59	1.11	0.01	0.04	-	6	9%
Connecticut (NEWE)	0.58	11.82	15.14	26.96	0.97	2.09	0.00	0.03	-	3	11%
Delaware (RFCE)	0.56	35.19	3.98	39.17	2.89	0.55	0.00	0.00	-	3	9%
District of Columbia (SRVC)	0.57	39.38	2.04	41.42	3.23	0.28	-	0.01	-	4	9%
Florida (FRCC)	0.65	20.48	16.12	36.60	1.68	2.23	-	0.00	-	4	11%
Georgia (SRSO)	0.79	50.51	4.53	55.04	4.15	0.62	-	0.02	-	5	9%
Hawaii (HIMS)	0.05	1.15	-	1.15	0.09	-	0.00	0.02	-	0	10%
Idaho (NWPP)	0.95	26.81	4.48	31.29	2.20	0.62	0.01	0.25	-	3	10%
Illinois (RFCW)	0.76	56.83	1.13	57.96	4.67	0.16	0.00	0.00	-	5	8%
Indiana (RFCW)	0.76	56.83	1.13	57.96	4.67	0.16	0.00	0.00	-	5	8%
Iowa (MROW)	0.84	57.37	1.67	59.04	4.71	0.23	0.02	0.02	-	5	8%
Kansas (SPNO)	0.85	61.07	2.45	63.52	5.02	0.34	0.01	0.00	-	5	8%
Kentucky (SRTV)	0.78	52.08	1.48	53.56	4.28	0.20	-	0.04	-	5	8%
Louisiana (SRMV)	0.88	64.89	1.45	66.34	5.33	0.20	-	0.01	-	6	8%
Maine (NEWE)	0.58	11.82	15.14	26.96	0.97	2.09	0.00	0.03	-	3	11%
Maryland (RFCE)	0.56	35.19	3.98	39.17	2.89	0.55	-	0.00	-	3	9%
Massachusetts (NEWE)	0.58	11.82	15.14	26.96	0.97	2.09	0.00	0.03	-	3	11%
Michigan (RFCM)	0.81	52.20	5.68	57.88	4.29	0.78	-	-	-	5	9%
Minnesota (MROW)	0.84	57.37	1.67	59.04	4.71	0.23	0.02	0.02	-	5	8%
Mississippi (SRSO)	0.79	50.51	4.53	55.04	4.15	0.62	-	0.02	-	5	9%
Missouri (SRMW)	0.88	64.89	1.45	66.34	5.33	0.20	-	0.01	-	6	8%
Montana (NWPP)	0.95	26.81	4.48	31.29	2.20	0.62	0.01	0.25	-	3	10%
Nebraska (MROW)	0.84	57.37	1.67	59.04	4.71	0.23	0.02	0.02	-	5	8%
Nevada (NWPP)	0.95	26.81	4.48	31.29	2.20	0.62	0.01	0.25	-	3	10%
New Hampshire (NEWE)	0.58	11.82	15.14	26.96	0.97	2.09	0.00	0.03	-	3	11%
New Jersey (RFCE)	0.56	35.19	3.98	39.17	2.89	0.55	0.00	0.00	-	3	9%
New Mexico (AZNM)	0.81	35.70	13.06	48.76	2.93	1.80	0.00	0.02	0.00	5	10%
New York (YNLI/NYCW/NYUP)	0.44	5.60	11.73	17.33	0.46	1.62	0.00	0.05	-	2	12%
North Carolina (SRVC)	0.57	39.38	2.04	41.42	3.23	0.28	-	0.01	-	4	9%
North Dakota (MROW)	0.84	57.37	1.67	59.04	4.71	0.23	0.02	0.02	-	5	8%
Ohio (RFCW)	0.76	56.83	1.13	57.96	4.67	0.16	0.00	0.00	-	5	8%
Oklahoma (SPSO)	0.98	43.44	15.45	58.90	3.57	2.13	0.01	0.02	-	6	10%
Oregon (NWPP)	0.95	26.81	4.48	31.29	2.20	0.62	0.01	0.25	-	3	10%
Pennsylvania (RFCE)	0.56	35.19	3.98	39.17	2.89	0.55	0.00	0.00	-	3	9%
Rhode Island (NEWE)	0.58	11.82	15.14	26.96	0.97	2.09	0.00	0.03	-	3	11%
South Carolina (SRVC)	0.57	39.38	2.04	41.42	3.23	0.28	-	0.01	-	4	9%
South Dakota (MROW)	0.84	57.37	1.67	59.04	4.71	0.23	0.02	0.02	-	5	8%
Tennessee (SRTV)	0.78	52.08	1.48	53.56	4.28	0.20	-	0.04	-	5	8%
Texas (ERCT)	0.86	28.92	19.63	48.55	2.38	2.71	0.01	0.00	-	5	10%
Utah (NWPP)	0.95	26.81	4.48	31.29	2.20	0.62	0.01	0.25	-	3	10%
Vermont (NEWE)	0.58	11.82	15.14	26.96	0.97	2.09	0.00	0.03	-	3	11%
Virginia (SRVC)	0.57	39.38	2.04	41.42	3.23	0.28	-	0.01	-	4	9%
Washington (NWPP)	0.95	26.81	4.48	31.29	2.20	0.62	0.01	0.25	-	3	10%
West Virginia (RFCW)	0.76	56.83	1.13	57.96	4.67	0.16	0.00	0.00	-	5	8%
Wisconsin (MROE)	0.84	53.02	4.95	57.98	4.35	0.68	0.00	0.02	-	5	9%
Wyoming (NWPP)	0.95	26.81	4.48	31.29	2.20	0.62	0.01	0.25	-	3	10%

* Includes direct fuel combustion emissions from coal and natural gas power plants, as reported by Pacca and Horvath, 2002

** Includes indirect emissions from precombustion, steel, concrete and aluminum for hydro, wind and solar PV power plants, as reported by Pacca and Horvath, 2002

* Electricity generation from coal, natural gas, hydro, wind and solar as a fraction of the total resources mix, as reported by eGRID. Resouces not included are nuclear, oil, geothermal, biomass, other fossil fuel and unknown sources

5. Water and waste

The category “Water and other public services” in the CES includes: water and sewerage maintenance, trash and garbage collection and septic tank cleaning. Emission factors (CO_2e/$) for these services can be expected to vary widely from one location to the next. For example, according to the California Energy Commission (*38*) water supply, conveyance, distribution and treatment requires 5,411 kWh per million gallons of indoor consumption in Northern California compared to 13,022 kWh per million gallons in Southern California.

Regionalized emissions data on water and waste across the United States are not currently available and collection of these data was beyond the scope of the current study. Although EIO-LCA is not capable of providing estimates of water and waste emissions at regional scales, it provides a reasonable rough proxy for average emissions at the national level. Since total emissions from water and waste amount to less than 3% of total emissions, this error can be considered minor, when weighed against the total household carbon footprint. Emissions from waste and waste are approximated by multiplying expenditures on “water and other public services” in the CES by an emission factor of 4121 gCO_2e/$ provided by EIO-LCA (32) for the sector “water and remediation services”.

6. Shelter

Few life cycle assessment studies of housing construction in the United States are currently available. This is rather surprising given the recent emphasis on “green building” practices for home construction. Results from case studies vary widely, including estimates of 20 $mtCO_2e$ for construction of a home in Canada (*39*), 21 and 37 $mtCO_2$ for wood frame homes built in Atlanta and Minneapolis, respectively (*40*), and 80 $mtCO_2$ for two homes in Michigan (*41*). It is unclear the extent to which differences are the result of methodological choices (e.g., the boundary of system analyzed) or actual differences in housing construction materials and processes. These few case studies may also not be representative of typical homes built in the United States.

Using the top-down economy-wide EIO-LCA approach, Ochoa et al (*42*) estimates total emissions from U.S. housing construction of new residential 1-unit structures at 110 million mtCO_2e in 1997, which equates to 100 mtCO_2e per home for the 1.1M single-unit homes completed in that year (*43*). Amortizing these emissions over a 50 year expected life time for the average single-unit home built in 1997 of 2,150 square feet (*44*) results in an annualized emission factor of 930 gCO_2e per square foot.

Ochoa et al. acknowledge the high level of uncertainty associated with the EIO-LCA approach for housing construction and some of this research team proposed a hybrid approach in a later paper (*45*). In the absence of improved emission factors available for typical U.S. housing construction, we use the approximated EIO-LCA value of 930 gCO_2e per square foot. Further emissions from maintenance and repairs are accounted for under goods and services in the calculator under “Household maintenance and repair services” and “household furnishing and equipment”.

The average square feet of homes is determined by income level, as provided by the 2005 American Housing Survey (*46*) of the United States. When the user selects household size (one person, two person, etc.) the calculator displays average square footage of home (owned or rented) based on the average household income of a household of that size.

Income	sqft
Less than $10,000*	1420
$10,000 to $19,999*	1419
$20,000 tp $29,999*	1502
$30,000 to $39,999*	1591
$40,000 to $49,999	1689
$50,000 to $59,999	1750
$60,000 to $79,999	1854
$80,000 to $99,999	1993
$100,000 to $119,999	2217
$120,000 or more	2500

source: American Housing Survey, 2005
*average of two categories

7. Food, Goods and Services

We use the Economic Input-Output Life Cycle Assessment model (*10*), EIO-LCA, designed by the Green Design Institute at Carnegie Mellon University, and the Comprehensive Environmental Database Archive (*47*), CEDA4.0 to calculate emissions from food, goods and services. EIO-LCA and CEDA are widely used economy-wide models of cradle-to-gate emissions of all major greenhouse gases for >420 economic sectors of the U.S. economy, of which 289 sectors are applicable to consumer demand (the rest are intermediate goods). Since emission factors are provided per dollar of industry output, and not per dollar of consumer expenditure, only the fraction of consumer dollars that is received by manufacturing industries should be input into EIO-LCA to determine emissions from manufacturing (*48*). We further calculate separate emission factors for transport to market (truck, rail, air) and wholesale and retail trade by multiplying the fraction of consumer dollars received at each life cycle stage to the corresponding emission factor in EIO-LCA, similar to (*49,50*) and outlined in (*51*). In order to update these emission factors from 1997 benchmark year, we adjust for inflation using the Producer Price Index (PPI).(*52*)

New EIO-LCA greenhouse gas emission factors for 2005 are therefore estimated as:

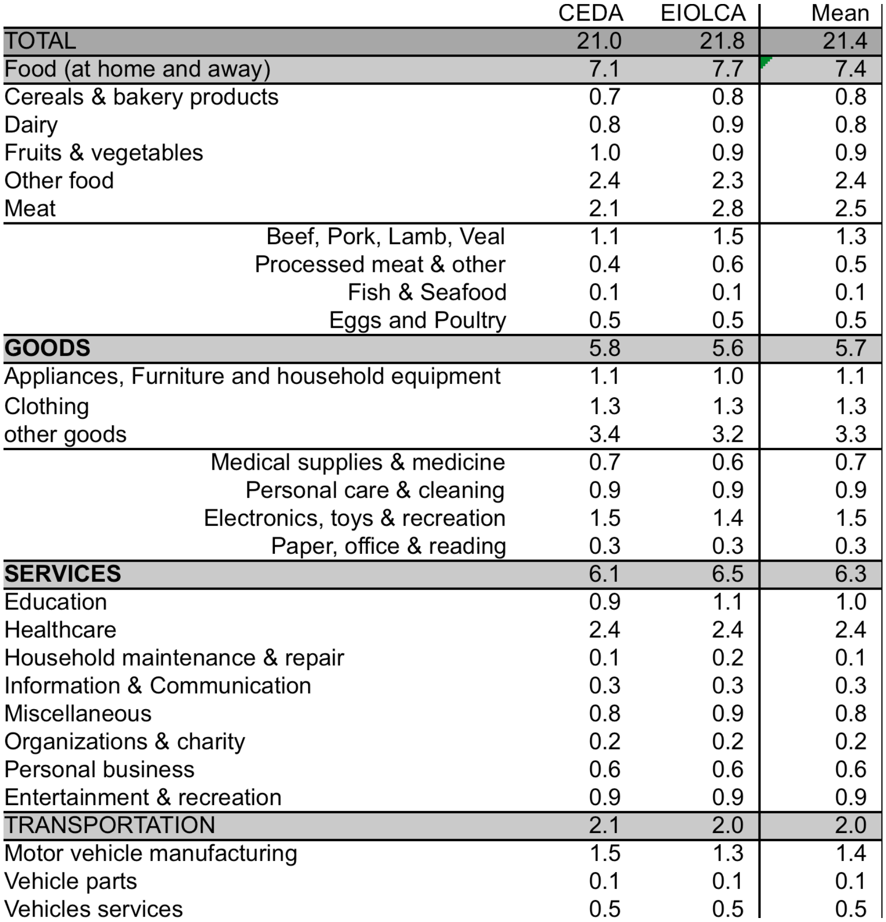
$$EF_{C,i} = \left(\frac{PV_i}{CV_i} * EF_{P,i} + \frac{Truck}{CV_i} * EF_{P,t} + \frac{Rail}{CV_i} * EF_{P,r} + \frac{Air}{CV_i} * EF_{P,a} + \frac{WT}{CV_i} * EF_{P,wt} + \frac{RT}{CV_i} * EF_{P,rt} \right) * PPI_i$$

where GHG emission factor (EF) is given in consumer dollars (C) or producer dollars (P) for each industry (i). PV represents the total value received by the producing industry (i) of dollars spent by consumers (CV) of commodities from industry (i). Truck, Rail and Air represent the value received by each sector to ship products to market, while wholesale trade (WT) and retail trade (RT) is the value-added from wholesale and retail trade.(*53*) Emission factors (EF) for trucking (t), rail transport (r), air transport (a), wholesale trade (wt) and retail trade (rt) are in given in producer dollars in EIO-LCA. The sum of all factors produces total emissions per consumer dollar at the point of sale for each of 589 commodities or services in the BEA accounts (*54*). PPI is the Producer Price Index for each (of 70) I-O sector (i).

Next, we created a concordance table between 589 products in BEA input-output accounts into 6 categories of food, 7 categories of goods, and 10 categories of services, consistent with the calculator and the CES datasets. Emissions for each category of consumption in the calculator are an average of emissions for all individual products in that category, weighted by average national expenditures on those products. For example, although adhesives and glues have an unusually high emission factor, at more than 700 gCO_2e/consumer $, they account for less than 2% of expenditures on office supplies. Therefore, the overall emission factor for office supplies is not greatly affected by the high emission factor of adhesives and glues. A list of final emission factors is provided in Appendix A of this report.

A note on uncertainty: While emission factors using input-output (I-O) analysis are generally robust on the aggregate, there are basic well-understood limitations of the approach. It is essential to understand that I-O assumes average cost and average emissions for product categories and emissions are scaled linearly based in dollars spent on each category of goods. The second major limitation is that all products produced within the same sector of the economy (of which there are about 420 in the EIO-LCA model used in this analysis) are assumed to have the same emissions per dollar of sector output. Other sources of uncertainty included: 1) geographic variation (e.g., accounting for the effect of imports), 2) time lag due to infrequent updates of emission factors, 3) source data uncertainty and error, 4) modeling error, and 5) user input error (*42*).

Given the inherent uncertainty in input-output analysis we considered it useful to compare results using two different models. The table below compares greenhouse gas emissions (metric tons CO_2e/yr) embodied in food, goods and services consumed by the average U.S. household using CEDA (*47*) and EIO-LCA (*10*), as well as the mean of the two datasets. Results for each category of emissions are generally within 10%, with the exception of red meat, for which results in EIO-LCA are about 30% higher. For the online version of the tool, we created customized emission factors for food, goods and services by dividing total annual emissions (mean of CEDA and EIO-LCA results) for each category in the model by average household consumption (in dollars, or calories for food) of the same category. Default consumption values for food are from USDA (*55*). Default consumption values for goods and services are from the Consumer Expenditures Survey (*4*).



	CEDA	EIOLCA	Mean
TOTAL	21.0	21.8	21.4
Food (at home and away)	7.1	7.7	7.4
Cereals & bakery products	0.7	0.8	0.8
Dairy	0.8	0.9	0.8
Fruits & vegetables	1.0	0.9	0.9
Other food	2.4	2.3	2.4
Meat	2.1	2.8	2.5
Beef, Pork, Lamb, Veal	1.1	1.5	1.3
Processed meat & other	0.4	0.6	0.5
Fish & Seafood	0.1	0.1	0.1
Eggs and Poultry	0.5	0.5	0.5
GOODS	5.8	5.6	5.7
Appliances, Furniture and household equipment	1.1	1.0	1.1
Clothing	1.3	1.3	1.3
other goods	3.4	3.2	3.3
Medical supplies & medicine	0.7	0.6	0.7
Personal care & cleaning	0.9	0.9	0.9
Electronics, toys & recreation	1.5	1.4	1.5
Paper, office & reading	0.3	0.3	0.3
SERVICES	6.1	6.5	6.3
Education	0.9	1.1	1.0
Healthcare	2.4	2.4	2.4
Household maintenance & repair	0.1	0.2	0.1
Information & Communication	0.3	0.3	0.3
Miscellaneous	0.8	0.9	0.8
Organizations & charity	0.2	0.2	0.2
Personal business	0.6	0.6	0.6
Entertainment & recreation	0.9	0.9	0.9
TRANSPORTATION	2.1	2.0	2.0
Motor vehicle manufacturing	1.5	1.3	1.4
Vehicle parts	0.1	0.1	0.1
Vehicles services	0.5	0.5	0.5

Carbon footprint of average U.S. Household using CEDA and EIO-LCA databases
Values in metric tons of CO2e per year

Food

Emissions from food are based on daily caloric consumption of meat (in total or separately for beef, chicken & poultry, other meat, and fish & seafood), dairy, cereals, fruits and vegetables, and other food. Default daily diets are based on the U.S. national average diet of 2505 calories per day (*55*). Users can select the number of adults and children in the household. By default, children are assumed to consume 75% of the calories of adults (*54*).

GHG emissions per calorie consumed of each food item are calculated using a top-down approach; all U.S. cradle-to-consumer GHG emissions from each food category (using EIO-LCA) are divided by all calories consumed of food in that category according to USDA (*54*). This process involves creating a concordance table between BEA and USDA food categories and categories used in the calculator. GHG emission factors for food categories are calculated as follows:

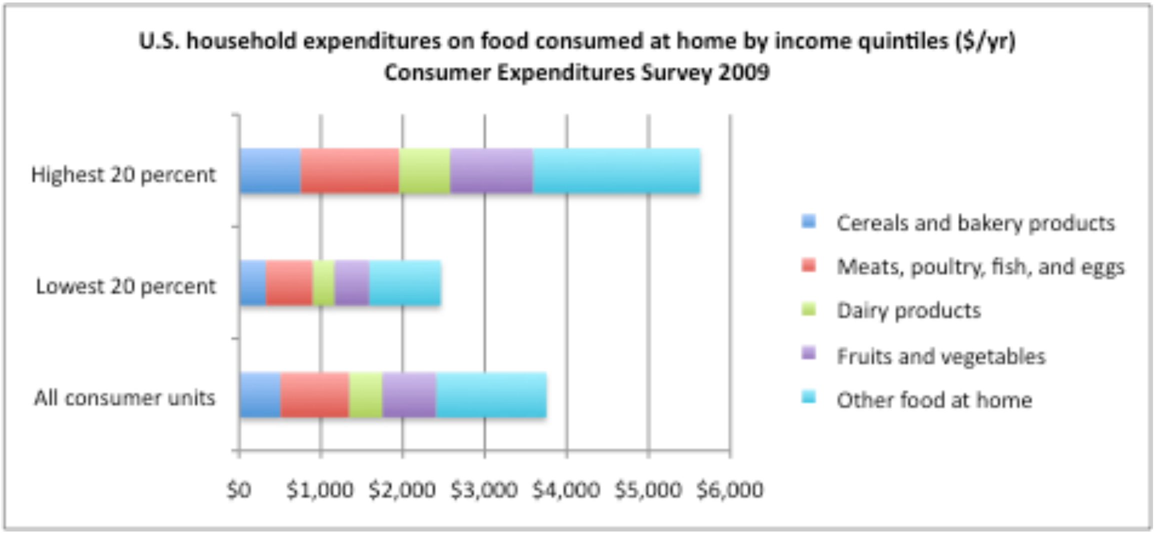
$$\$USfood,i * EFfood,i \ / 116.8M\ households] / \sum [Caloriesfood,i * 365days]$$

where total annual household emissions of each food category are created by multiplying total US dollars spent in each food category ($USfood,i) by the weighted GHG emission factor (EFfood,i), divided by the number of US households (116.8M) in 2005. Total daily calories of each food item were aggregated from USDA data. Estimates of calories, emission factors and total emissions for each food item for adults, children and households for the typical U.S. household is provided in the table below.

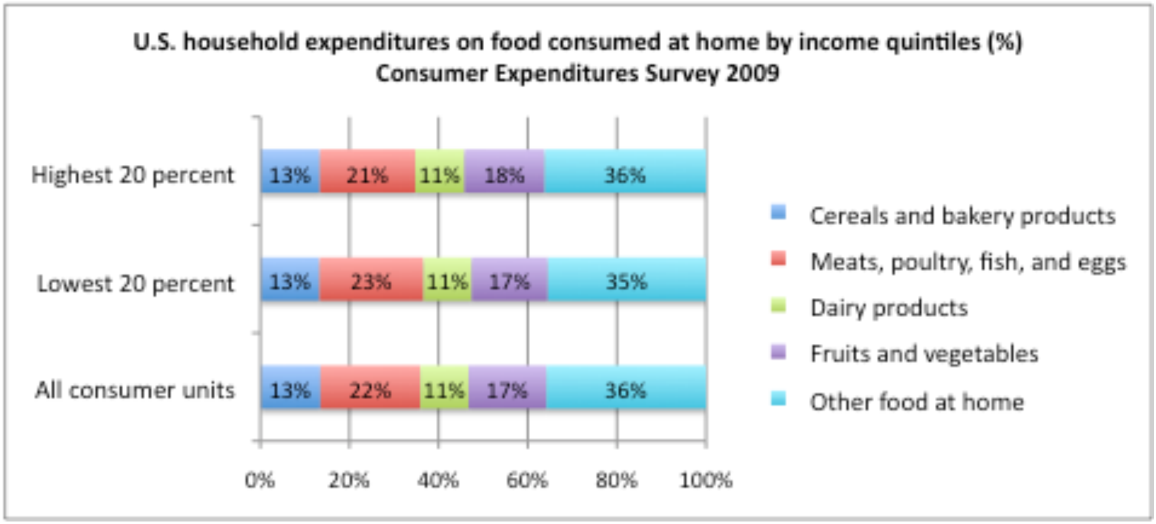
Conversion of Food Calories per day to gCO2 per year

	Total	Adult	children		
number of people	2.50	2.50	0		
	Calories/day-adult	Calories/day-child	Calories/day-household	emission factor gCO2/calorie	tCO2/year-household
Meat, fish, eggs	543	407	1,357	4.52	2.240
Beef, pork, lamb	247	185	618	4.81	1.084
Poultry & eggs	165	124	413	4.10	0.617
Other (processed meat, nuts....)	58	44	145	7.39	0.392
Fish & seafood	73	54	182	2.23	0.148
Dairy	286	215	715	4.66	1.217
Grains & baked goods	669	502	1,673	1.47	0.896
Fruits & vegetables	271	203	678	3.03	0.748
Other (snacks, drinks, etc.)	736	552	1,841	3.73	2.507
					-
Total	2,505	1,879	6,263	3.26	7.608

As noted in the main paper, we scale emissions based on household size, not based on expenditures on food. It is true that households in the upper income quintile spend more than twice as much on food than households in the lowest income quintile in the United States, as shown in the figure below. Previous studies have assumed a linear relationship between expenditures on food and emissions, thus households in the upper income quintile would be assumed to purchase twice as much food (in dollars and physical units).



Yet we see no evidence that upper income households actually eat more food than lower income households. For example, we know of no studies that suggest that higher income households in the United States are more overweight than lower income households. We also do not find evidence that upper income households within the United States consume more meat and dairy. According the Consumer Expenditures Survey (2009), households in the highest income quintile spend 21% of their food budget on meat, compared to 23% for the lowest income quintile. Expenditures on all other food categories are essentially identical between income quintiles: cereals 13%; meat ~22%; dairy 11%; fruits & vegetables ~17%, other foods ~36% (figure below). Thus, while upper income households spend more than 2x on meat and dairy than lower income households, they also spend more than 2x on all other food categories as well; presumably, upper income households simply buy more expensive products. Given this remarkable uniformity it seems reasonable to assume identical diets, on a caloric basis, between households of different incomes within the United States. It may be important for future studies to at least consider a looser relationship between expenditures and diets.



Food consumed in restaurants is considered to be similar to food consumed at home. Expenditures on food away from home are distributed proportionally between categories of food consumed at home. While upper income households spend much more on food away from home, we do not have evidence that this represents a larger fraction of total calories or that food consumed away from home is somehow different than food consumed at home. While there likely are important differences, this would be a topic for further research. It is also important to note that our study includes emissions from all purchased food, which is about 1.5 greater than food that is eaten, on a caloric basis (i.e., about one third of food is assumed to be wasted).

B. Supporting materials for the greenhouse gas mitigation actions

The Take Action page of the calculator allows individuals or households to estimate greenhouse gas and financial savings from a set of low carbon technology investments and behavior change opportunities, collectively called "Actions". Each individual Action is itself a mini-calculation tool, allowing users to adjust multiple settings (depending on the action) to reflect their personal options and preferences. Results are based on local energy and fuel prices (based on data from 28 major US metropolitan regions and all U.S. states), emissions from residential electricity production (at the level of U.S. states or utilities in the case of California), and local heating and cooling needs (for 250 U.S. regions).

Carbon footprint savings are presented in metric tons of CO_2 equivalent gases per year for each action and in total (including all pledged actions). Financial metrics include annual financial savings from changes in annual expenditures (e.g., reduced energy bills), 10-year net savings, upfront cost, 10-year net present value (NPV), return on investment (ROI) and simple payback period (in years). Users can adjust the discount rate (set to 8% by default) and annual inflation rate (set to 3% by default), which affects NPV and ROI. ROI is defined as ten year NPV over upfront cost. NPV is defined as:

$$NPV = \sum_{t=1}^{10} \frac{C_t}{(1+r)^t} - C_0 \tag{3}$$

where Ct is the financial saving at year t over 10 years, C_0 is the upfront cost in year 0 and r is the real discount rate of 5%.

Salvage value is assumed to be zero for all measures considered, only three of which include capital expenditures. In the case of motor vehicles, households are trading in existing used vehicles for other used vehicles so there is no additional salvage value. Similarly, refrigerators are not replaced, but rather

Energy Star refrigerators are chosen at the time of purchase, rather than a non-Energy Star model. In the case of light bulbs, we assume there is no market value for used incandescent light bulbs.

Where appropriate, interaction effects are considered. For example, fuel efficiency is increased by purchasing more fuel-efficient models, reducing top highway speeds, reducing rough braking, replacing air filters and keeping tires inflated. This new fuel efficiency is used to estimate savings from reducing vehicle miles traveled. Since many home upgrades include interaction effects, e.g., replacing water heaters and reducing water consumption, we have limited the number of actions in homes to actions the do not interact. While this limited number of actions does not present the full spectrum of benefits from home retrofits, it does serve our primary purpose of demonstrating the effects of the same basket of carbon footprint reduction strategies across different household types and geographic locations.

Calculation of carbon footprint reductions and life cycle costs of measures

1. Buy more efficient vehicles by 5 mpg: Let m_1 be the miles household drives its vehicles per year = (21,200)($\$_{hh,t}$) / \$2,100, where 11,000 is the average vehicle miles traveled for the typical primary vehicle (*2*), ($\$_{hh}$) is the annual expenditures on gasoline for each household type, *t*, in the CES and \$2,120 is the average U.S. household expenditures on gasoline. Carbon footprint savings (CFS) = $(m_1/fe_c - m_1/fe_n)(EF_{d+i})$, where f*e* is the fuel efficiency of current vehicle, *c*, and the new vehicle, *n*; EF_{d+i}, is the direct, *d*, and indirect, *i*, emission factor for gasoline. NPV = *equation 3*, where $C_t = (m_1 / p_c - m_1 / p_n)* g$, where g is the cost of fuel, assumed to be \$3 per gallon, and C_0 = \$4,000, covering sales tax, registration and other fees associated with trading in two vehicles for two more efficient vehicles of equal value.

2. Practice Eco-driving: CFS = $m / fe_n * \mathrm{EF}_{d+i} - m / fe_{new} (\mathrm{EF}_{d+i})$, where fe_n is the new fuel economy of the household's vehicle fleet after purchasing more efficient vehicles in Action 1, *m* = annual miles

driven by household, $fe_{\text{new}} = fe + (fe_n)(\%\text{HW})(\%\text{TS})(\text{TS} - \text{HS})(0.01) + (fe_n)(1 - \%\text{HM})(\text{TS} - \text{LS})(0.03)$, where 50% of vehicle miles, %HW, are highways miles (*56*), the driver reaches top speed 50% of the time, %TS, LW is 65 miles per hour, TS is 70 miles per hour, 0.01 is the amount reducing driving speed increases fuel efficiency (*57*), and 0.03 is the amount fuel efficiency increases by reducing rapid braking and acceleration (*58*). NPV = *equation 3*, where $C_t = m_5 / fe_n\ (G) - m / fe_{\text{new}}\ (G)$, and $C_0 = 0$.

3. Maintain vehicle(s): CFS = $m / fe_n * 2(EF_d)(I)$, where $I = fe_n\ (1 + 0.033 + 0.03)$, where 0.033 and 0.03 are the amounts fuel efficiency increases by keeping tires properly inflated and changing air filters regularly, respectively (*58*). NPV = equation 3, where where fe_n is the new fuel economy of the household's vehicle fleet after purchasing more efficient vehicles in Action 1 and Practicing Eco-driving in Action 2, m = annual miles driven by household, $C_t = m / fe\ (I)$ and C_0 = $20 for air filers.

4. Telecommute to work one day a week: CFS = $(m_2 / fe_n)(EF_{d+i})$ where fe_n is the new fuel economy of the household's vehicle fleet after Taking actions 1,2 and 3, Action 1, m_2 is the miles saved from telecommuting, which equals 1,400 miles per year (28 miles/day x 1day/week x 50 weeks/yr). NPV = equation 3, where $C_t = (m_2 / fe)(g)$ and $C_0 = 0$.

5. Ride a bicycle 20 miles per week: CFS = $(m_3 / fe_n)(EF_{d+i})$ where fe_n is the new fuel economy of the household's vehicle fleet after Taking actions 1,2 and 3, m_3 is 1,000 miles per year (20 miles/week x 50 weeks/year). NPV = equation 3, where $C_t = (m_3 / fe)(g)$ and $C_0 = 0$.

6. Ride the bus 20 miles per week: CFS = $(m_4 / fe_n)(EF_{d+i}) - m4(EF_b)$ where fe_n is the new fuel economy of the household's vehicle fleet after Taking actions 1,2 and 3, $m_4 = m_3$ and EF_b is 107 gCO_2e per passenger mile (*59*). NPV = equation 3, where $Ct = (m_4 / fe)(g) - \$_b(m4)$, where $\$_b$ is 0, with the cost of public transportation assumed to be offset by reducing vehicle depreciation and savings from parking, insurance, maintenance and other vehicle expenses.

7. Fly 20% less often: CFS = $m_7(EFair_{d+i})(0.20)$, where m_7 = miles housed travels by air each year, $EFair_d$ of 223 gCO_2e per passenger mile (*55*) is multiplied by 2 to account for indirect atmospheric warming effects (29). NPV = equation 3, where $C_t = m_7(0.20)(\$_{air})$, where $\$_{air}$ is \$0.12 per passenger mile (*60*) and $C_0 = 0$.

8. Replace 5 lightbulbs with CFLs: CFS = $5(0.075kW- 0.020kW)(1825)(EF_{elec})$, where (0.075kW – 0.020kW) is the different power consumption of the bulbs, 1825 is the hours bulb left on per year, EF_{elec} is the emission factor for electricity of the state (eGRID, Supporting Materials). NPV = equation 3, where C_0 = \$1.25 (*61*), C_t = 5(0.075kW- 0.020kW)(1825)(\$elec) + \$3, where \$elec is the price of electricity per U.S. state (*62*), \$3 is the net present value of replacing 4 incandescent bulbs over 10 years.

9. Turn down thermostat in winter: Let E_{PU} = CI * HDD(HSF/1000), where, HDD is the average heating degree days per U.S. state (*63*), HSF is the heated square feet of the home, CI is the average US heating consumption intensity (*64*) for natural gas = 0.517. CFS = $E_{PU} * T_\Delta * 0.06 * 5470$, where T_Δ is the time-weighted average decrease in thermostat setting, assuming thermostat is turned down 8 degrees for 8 hours at night and 2 degrees for 10 hours during the day (*65*), 0.06 is the amount of heating saved per degree thermostat is turned down (*64*) and natural gas produces 5470 gCO_2/therm. NPV = equation 3, where $C_t = E_{PU} (T_\Delta)0.06(\$ng)$, where \$ng is cost of natural gas per U.S. state (*66*) and $C_0 = 0$.

10. Turn up thermostat in summer: Let E_{PU} = CI * CDD(CSF/1000), where CDD is the average cooling degree days per U.S. state (*67*), CSF is the conditioned square feet of home, CI is the average U.S. cooling consumption intensity for electricity = 6.283 (*61*). CFS **=** $E_{PU} (T_\Delta) 0.06 * EF_{elec}$, where T_Δ is the time-weighted average increase in thermostat setting, assuming thermostat is turned up 2 degrees for 10 hours on summer days and 4 degrees for 8 hours on summer nights (*64*), 0.06 is the amount of

cooling saved per degree thermostat is turned up (*64*). NPV = equation 3, where $C_t = E_{PU}(T_\Delta)0.06(\$elec)$, where \$elec is cost of electricity per U.S. state (*65*) and $C_0 = 0$.

11. Choose Energy Star refrigerator: This action assumes the household is ready to purchase a new refrigerator and chooses an Energy Star model over a non-Energy Star model. Let $E_{con} = (Fr + 1.63*Fz)(I) + Bl$, where E_{con} is annual electricity consumption, Fr is the refrigerator volume = 14.8 cubic feet, Fz is the freezer volume = 6.8 cubic feet, I = 9.8 kW per cubic foot, Bl = 276 kWh/yr. CFS = $(E_{con} - E_{es})(EF_{elec})$, where $E_{es} = 0.8(E_{con})$. NPV = equation 3, where $C_t = (E_{con} - E_{es})(\$elec)$ and $C_0 = \$50$ (*68*).

12. Dry clothes on the line: CFS = L (I) (EF_{elec}), where L = 130 loads per year, I = 3.16 kWh per load (63). NPV = equation 3, where C_t = L (I) ($\$_{elec}$) and $C_0 = 0$.

13. Diet switching: Compares CFS of user's diet with lower carbon, and lower calorie diet. CFS = $\sum(m_cEFm_c,d_cEFd_c,c_cEFc_c,f_cEFf_c,o_cEFo_c) - (m_nEFm_n,d_nEFd_n,c_nEFc_n,c_nEFc_n,f_nEFf_n,o_nEFo_n)$, where the household caloric consumption of meat, dairy, cereals, produce and other food items is multiplied by emission factors, EF, for each item (Supporting Materials) for the household current, c, and recommended new, n. NPV = equation 3, where C_t is the difference in cost between the two diets, with food prices from (*69*) and average caloric consumption of each food item from (*70*).

Calculation of marginal abatement cost curves in main paper

The marginal abatement cost (MAC) curves in the main paper (Figures 5 and 6) show annual reductions of CO_2e for each measure on the x-axis and the levelized annual cost per metric ton of CO_2e conserved annually on the y-axis. Levelized annual cost is calculated by converting the net present value (NPV) of a project (see calculations above) into a uniform series of annual payments over the expected project lifetime. This is accomplished by multiplying NPV by a uniform capital recovery factor (UCRF)(*73*).

$$UCRF = \frac{d}{1-(1+d)^{-n}}$$

Where d is the discount rate, which we assume is a 5% real discount rate for all measures. The area under the curves thus represents average annual financial savings of each measure.

Appendix A. Emission Factors and uncertainty estimates

Emissions category	Factor	Units	Estimated error (+/-)	Source
Gasoline (direct)	8,874	gCO2e/gal	1%	(1)
Gasoline (indirect)	2,307	gCO2e/gal	15%	(2)
Diesel (direct)	10,153	gCO2e/gal	1%	(1)
Diesel (indirect)	2,335	gCO2e/gal	20%	(2)
Vehicle manufacturing	56	gCO2e/mile	10%	(3)*
Average flight	223	gCO2/passenger-mile	10%	(4)
Short flights (<400 mi)	254	gCO2/passenger-mile	10%	(4)
Medium flights (400-1500)	204	gCO2/passenger-mile	10%	(4)
Long flights (1500-3000)	181	gCO2/passenger-mile	10%	(4)
Extended flights (>3000)	172	gCO2/passenger-mile	10%	(4)
Air travel indirect effects	1.00	x direct emissions	30%	(5)*
Public transportation	179	gCO2/passenger-mile	10%	(4)
Miles on bus	107	gCO2/passenger-mile	10%	(4)
Miles on commuter rail (light&heavy)	163	gCO2/passenger-mile	10%	(4)
Miles on transit rail (subway, tram)	163	gCO2/passenger-mile	10%	(4)
Miles on Amtrak	185	gCO2/passenger-mile	10%	(4)
Housing contruction	930	gCO2e/sq. ft.	20%	(3)
Electricity usage ($)	11,789	gCO2/$	19%	(7,8,10)
Electricity Indirect factor	0.08		15%	(11,12)
Electricity usage (U.S.average shown)	835	gCO2/kwh	5%	(7)
Natural gas usage (U.S.average shown)	4,317	gCO2/$	5%	(7,8)
Therms natural gas (U.S.average shown)	5,470	gCO2/therm	1%	(1)
Cubic feet natural gas (U.S.average shov	54.7	gCO2/cu.ft.	1%	(1)
natural gas indirect factor	0.14		15%	(11)
Fuel oil and other fuels	682	CO2e/$(2005)	15%	(3)
Water (California average)	444	gCO2e/person	15%	(9)
Water, sewage, wastes ($)	4,121	CO2e/$(2005)	15%	(3)*
Waste (California average)		gCO2e/person	15%	(9)
Food	2.92	gCO2e/calorie	15%	(3)*
Meat, fish & eggs	5.53	gCO2e/calorie	15%	(3)*
Beef, pork, lamb, veal	6.09	gCO2e/calorie	15%	(3)*
Processed meat & other	2.24	gCO2e/calorie	15%	(3)*
Fish & seafood	5.71	gCO2e/calorie	15%	(3)*
Eggs and poultry	4.27	gCO2e/calorie	15%	(3)*
Cereals & bakery products	1.45	gCO2e/calorie	15%	(3)*
Dairy	4.00	gCO2e/calorie	15%	(3)*
Fruits & vegetables	3.35	gCO2e/calorie	15%	(3)*
Other (snacks,beverages, alcohol,oils,etc.	2.24	gCO2e/calorie	15%	(3)*
Goods (sum of below)	565	CO2e/$(2005)	15%	(3)*
Clothing	750	CO2e/$(2005)	15%	(3)*
Furnishings, appliances, other household	614	CO2e/$(2005)	15%	(3)*
Other goods	971	CO2e/$(2005)	15%	(3)*
Medical	696	CO2e/$(2005)	15%	(3)*
Entertainment	1,279	CO2e/$(2005)	15%	(3)*
Reading	2,100	CO2e/$(2005)	15%	(3)*
Personal care & cleaning	954	CO2e/$(2005)	15%	(3)*
Auto parts	558	CO2e/$(2005)	15%	(3)*
Services (sum of below)	507	CO2e/$(2005)	15%	(3)*
Vehicle services	433	CO2e/$(2005)	15%	(3)*
Household maintenance and repair	134	CO2e/$(2005)	15%	(3)*
Education	1,065	CO2e/$(2005)	15%	(3)*
Health care	1,151	CO2e/$(2005)	15%	(3)*
Personal business and finances	197	CO2e/$(2005)	15%	(3)*
Entertainment & recreation	711	CO2e/$(2005)	15%	(3)*
Information and communication	291	CO2e/$(2005)	15%	(3)*
Organizations and charity	122	CO2e/$(2005)	15%	(3)*
Miscellaneous services	720	CO2e/$(2005)	15%	(3)*
Water Emissions per gallon	27.2	g CO2e/gal	15%	(9)

* emission factor has been modified (beyond unit conversion), as described elsewhere in this report
(1) EIA(a), Voluntary Reporting of Greenhouse Gases Program
(2) GREET, 2.8a
(3) EIO-LCA, CEDA, authors' calculations
(4) WRI/WBCSD, Greenhouse Gas Protocol
(5) Air indirect effects assumed 0.9 plus 0.1 from airports
(6) Housing consctrution: Assume 90 tCO2/50yrs=1.8tCO2/1800sqft
(7) eGRID
(8) EIA(b)
(9) California Air Resources Board
(10) Uncertainty parameter from Weber et al., 2010. See citation 72 for full reference
(11) Jaramillo et al., 2007. See citation 37
(12) Pacca, S., Horvath, A. 2002. See citation 36

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