Global Warming Potentials (GWPs)/CO_2-equivalent (CO_2e) and the importance of time horizons

There are many different pollutants that contribute to global climate change, and they have varying **lifetimes** and **potencies** that define their climate impacts beyond pure "mass" emitted into the atmosphere. **Climate metrics** (e.g. GWP and CO_2e) **help to compare or combine** the emissions of pollutants according to their impact on the global climate.

GWP and the related CO2e are the most common climate metrics used for climate analysis and policy.

A climate pollutant's **global warming potential** is its relative potency as an agent of climate change compared to CO_2 over a specified time interval. It is calculated via the cumulative radiative forcing over a specified time horizon caused by a unit emission of a pollutant relative to an equivalent mass of CO_2.

Emissions of either non-CO2 climate pollutants or a sum of multiple climate pollutant emissions are often expressed in **carbon dioxide equivalents (CO2e),** which is calculated by multiplying the mass of a non-CO_2 climate pollutant by its GWP. CO_2e denotes the amount of carbon dioxide that would have the same climate impact over a specified time horizon. Note that if a time horizon is not specified, it is usually 100 years.

GWP values depend on the time horizon of interest, and the more a greenhouse gas's lifetime differs from CO2's, the more the time horizon affects the GWP value. GWP values for the same time horizon also change slightly with advancements of the underlying science (such as how potent a gas is or how long it lasts in the atmosphere). GWP values are reported in the IPCC assessment reports.

Most commonly used GWPs for methane and nitrous oxide:

IPCC Report	Time Horizon	CO2	CH4	N2O
AR4 2007	GWP20	1	72	289
	GWP100	1	25	298
AR5 2013	GWP20 *(including fossil methane)*[1]	1	84 *(85)* With climate-carbon feedback: 86 *(87)*[2]	264 With climate-carbon feedback: 268
	GWP100 *(including fossil methane)*	1	28 *(30)* With climate-carbon feedback: 34 *(36)*	265 With climate-carbon feedback: 298
AR6 2021	GWP20 *(fossil methane)*	1	81 (83)	273
	GWP100 *(fossil methane)*	1	27 (30)	273

Here we report CO_2e **using BOTH 20 and 100 year time horizons**, because this conveys climate impacts of emissions over all timescales (Ocko et al. 2017). We also show the full time series of CO_2e (year 1-100) based on the most recent IPCC sixth assessment report (2021).

[1] CO2 produced from methane oxidation in the atmosphere is only additional to the climate from fossil sources.
[2] Most metrics for non-CO2 pollutants do not yet incorporate the "climate-carbon feedback" – the effect of a changing climate on the carbon cycle (such as warmer ocean, more CO2 emitted into the atmosphere).

Equivalent activities

We follow emissions referenced in EPA calculations with modifications and additions listed below. Note that the EPA equivalency calculations are based on 100-year climate impact only.

Passenger vehicles driven for one year

We include methane and N_2O emissions from passenger vehicles explicitly. An average vehicle emits 4.58 metric tons of CO_2, 0.3 kg of methane, and 0.13 kg of N_2O every year[3].

Pounds of beef produced

On average, the life cycle of 1 kg of beef emits 4.5 kg of CO2, 1.3 kg of methane, and 0.02 kg of N2O[4].

Individual GHG emissions

		CO_2	CH_4	N_2O
Home Energy (lb gas)				
	Gas	3100	2.5	
	Electricity	5400		
Waste (lb gas)				
	MSW		28	
	Wastewater		3	0.6
Food (lb gas)				
		3500	52	5
Transportation (lb gas)				
	Car	10300	0.7	0.2
	Bus	50	0.02	0.001
	Rail	40	0.005	0.001
	Air	1100		
Total				
	lb/year	23500	86	6
	ton/year	11	0.04	0.003

Individual items and sources are listed below. Note that hydrofluorocarbon (HFC) emissions are not included in individual GHG emission estimates. Data has been rounded up due to various uncertainties.

[3] EPA (2020). Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2018. Chapter 3 (Energy), Tables 3-13, 3-14, and 3-15. Environmental Protection Agency, Washington, D.C. EPA #430-R-20-002 (PDF)

[4] Poore, J. & Nemecek, T. Reducing food's environmental impacts through producers and consumers. *Science* **360**, 987–992 (2018). The breakdown of GHGs follows the average percentage breakdown from multiple studies (Alemu et al. 2016, Basarab et al. 2012, Cardoso et al. 2016, Cederberg et al. 2009, Mazzetto et al. 2015, Phetteplace et al. 2001, Ridoutt et al. 2011, Verge et al. 2008, Veysset et al. 2011, White et al. 2014, White et al. 2015, Zhu et al. 2015)

Home Energy

The two primary energy sources for home heating are electricity and natural gas, and we use the average GHG emissions from the two as an average household's home energy emissions. Estimates for emissions from the gas or electricity used in individual homes are from EPA[5]. They represent EPA's estimates for an average individual's home energy consumption in the U.S., based primarily on data from 2011.

- *Gas*: assumes 5,500 cubic feet of natural gas per household per month (with an average household size of 2.57 people).
    - The CH_4 emissions from gas assume a 2% leakage in upstream gas production and transmission[6], which is released as primarily methane.
- *Electricity*: assumes 943 kWh per household per month (the emissions factor per kWh varies across the country depending on the source of electricity, and the emissions factor used here represents a national average).

Waste

The EPA estimates that the average individual in the U.S. produced 4.4 lb of MSW per person per day as of 2011. EPA's GHG-calculator then estimates that 692 lb CO_2e is generated per person per year from waste. According to EPA's annual Inventory of U.S. GHG Emissions and Sinks (1990-2019), all emissions from municipal solid waste are CH_4 emissions – so this translates to ~28 lb CH_4 per person per year.

Per capita wastewater emissions were estimated by dividing the total methane and nitrous oxide wastewater emissions (the sum of domestic treatment emissions and domestic effluent emissions, from the EPA annual GHG inventory) by the U.S. population according to the census bureau. Data was used from the most recent EPA GHG inventory report for 2019 emissions.

Mt	CH_4	N_2O
Domestic treatment	0.412	0.069
Domestic effluent	0.072	0.0178

U.S. 2019 population: 334 million

Food

Emissions estimates from food were derived from the Jones & Kammen 2011 methodology[7], using the aggregated emissions factors for major food groups in their report and applying a percentage breakdown by gas for each food group as derived from the EIO-LCA model[8]. Average household size is 2.5 people.

Estimates of average calories eaten per individual adult per day:

- 543 cal/day from meat, fish and eggs
- 286 cal/day from dairy

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[5] https://www3.epa.gov/carbon-footprint-calculator/

[6] Alvarez, R. A. *et al.* Assessment of methane emissions from the U.S. oil and gas supply chain. *Science* **361**, eaar7204 (2018).

[7] https://pubs.acs.org/doi/10.1021/es102221h

[8] http://www.eiolca.net/cgi-bin/dft/use.pl

- 669 cal/day from grains and baked goods
- 271 cal/day from fruits and vegetables
- 736 cal/day from other (snacks, drinks, etc.)

	tCO_2e/yr/household	tCO_2/yr/household	tCH_4/yr/household	tN_2O/yr/household
Other (snacks and drinks)	2.507	1.86	0.01	0.001
Fruits and vegetables	0.748	0.52	0.002	0.0006
Grains and baked goods	0.896	0.42	0.003	0.001
Dairy	1.217	0.54	0.02	0.0006
Beef, pork, lamb	1.084	0.21	0.021	0.001
Poultry and eggs	0.617	0.32	0.004	0.0007
Fish and seafood	0.148	0.14	0.0004	0.000002

Transportation

Emissions from personal car use were adjusted from the EPA GHG calculator, with a breakdown of vehicle emissions by gas (derived from the EPA annual GHG inventory) applied to the non-CO_2 portion of car emissions, as recalculated using the EPA annual GHG inventory and updated GWPs. The EPA assumes 219 miles traveled per week per vehicle with a 21.6 mpg.

EPA's lb CO_2e/car/yr: 10484.17

EPA's CO_2/non-CO_2 ratio for car emissions: 0.9865

Recalculated CO_2/non-CO_2 ratio: 0.9586 where CH_4 = 4%, N_2O = 13%, and HFCs (not included in this analysis) = 83% of non-CO_2 car emissions.

Estimates of emissions from public transit were derived from the Jones & Kammen 2011 estimates of average miles traveled per mode of public transit, and average emissions factors for each mode, then separated by gas using the EPA annual GHG inventory.

	Miles traveled/year/person	g CO_2e/mile
Bus	73	300
Rail	106	172
Air (all CO_2)	2566	200