January 18, 2021

Guide to the Science of Climate Change in the 21st Century

Chapter 15
Greenhouse Gases

David H. Manz
PhD., P. Eng., AOE, FCAE
2020

Eco-print, “Ivy”, Nora Manz 2020

Table of Contents

15.14 Information support

List of Figures

https://www.ipcc.ch/site/assets/uploads/2018/02/ipcc_wg3_ar5_chapter1.pdf

Figure 15.11 Greenhouse gas emissions for major economies, 1990-2030. https://www.c2es.org/content/international-emissions/#:~:text=Globally%2C%20the%20primary%20sources%20of,72%20percent%20of%20all%20emissions.

Figure 15.12 Greenhouse gas emissions for top emitters, 2017 https://www.c2es.org/content/international-emissions/#:~:text=Globally%2C%20the%20primary%20sources%20of,72%20percent%20of%20all%20emissions.

Figure 15.13 Cumulative greenhouse gas emissions for major economies, 1751-2017. https://www.c2es.org/content/international-emissions/#:~:text=Globally%2C%20the%20primary%20sources%20of,72%20percent%20of%20all%20emissions.

Figure 15.14 Per Capita greenhouse gas emissions for major economies, and the world, 2017. https://www.c2es.org/content/international-emissions/#:~:text=Globally%2C%20the%20primary%20sources%20of,72%20percent%20of%20all%20emissions.

Figure 15.15 Per capita emissions for different income brackets. https://www.ipcc.ch/site/assets/uploads/2018/02/ipcc_wg3_ar5_chapter1.pdf

Figure 15.16 Per capita GHG emissions by country from IPCC. https://www.ipcc.ch/site/assets/uploads/2018/02/ipcc_wg3_ar5_chapter1.pdf

Figure 15.17 Greenhouse gas intensity for major economies and the World, 2017. https://www.c2es.org/content/international-emissions/#:~:text=Globally%2C%20the%20primary%20sources%20of,72%20percent%20of%20all%20emissions

Figure 15.18 Greenhouse gas intensity for cross-section of countries. https://www.ipcc.ch/site/assets/uploads/2018/02/ipcc_wg3_ar5_chapter1.pdf

Figure 15.19 Land and ocean-based sampling of GHG's, ozone, and aerosols. https://www.esrl.noaa.gov/gmd/dv/iadv/index.php?code=mlo

Figure 15.20 Aircraft GHG sampling program operated by NOAA. http://www.esrl.noaa.gov/gmd/ccgg/aircraft/

Figure 15.21 Greenhouse Gases Observing Satellite, GOSAT or Ibuki (Japanese) is the first satellite dedicated to GHG monitoring. It measures carbon dioxide and methane. https://en.wikipedia.org/wiki/Greenhouse_Gases_Observing_Satellite

Figure 15.22 NASA Orbiting Carbon Observatory-2. https://www.nasa.gov/mission_pages/oco2/index.html

Figure 15.23 Averaged carbon dioxide concentration Oct 1 – Nov 11, 2014 from OCO-2. https://www.nasa.gov/jpl/oco2/pia18934

Figure 15.24 Carbon monoxide measurements from NASA's Atmospheric Infrared Sounder (AIRS). https://climate.nasa.gov/news/3019/nasa-monitors-carbon-monoxide-from-california-wildfires/

Figure 15.25 Geostationary carbon cycle observatory, EVM-2, GeoCarb. https://eospso.nasa.gov/missions/geostationary-carbon-cycle-observatory-evm-2

Figure 15.26 Methane leak from space as detected by Earth Observing-1 (EO-1) satellite. https://earthobservatory.nasa.gov/images/88245/imaging-a-methane-leak-from-space

Figure 15.27 NASA Methane source model. https://climate.nasa.gov/news/2961/new-3d-view-of-methane-tracks-sources-and-movement-around-the-globe/

Figure 15.28 Global methane emissions monitoring. https://www.ghgsat.com/

Figure 15.29 Global-average radiative forcing estimates and ranges – AR5. https://www.ipcc.ch/site/assets/uploads/2018/02/WG1AR5_Chapter08_FINAL.pdf

Figure 15.30 Collection of carbon tax and distribution of dividend to population.

https://en.wikipedia.org/wiki/Carbon_fee_and_dividend

List of Tables.

Table 15.1 Global warming potential and atmospheric lifetime for major greenhouse gases. https://www.ipcc.ch/report/ar4/wg1/

Table 15.2 Energy density of different fuels. https://energyeducation.ca/encyclopedia/Energy_density

Table 15.3 Carbon dioxide equivalent emissions by fuel type.
https://www.eia.gov/environment/emissions/co2_vol_mass.php
and https://www.eia.gov/tools/faqs/faq.php?id=73&t=11

Table 15.4 Natural sources of methane.
https://en.wikipedia.org/wiki/Methane_emissions#Natural

Table 15.5 Anthropogenic sources of methane.
https://en.wikipedia.org/wiki/Methane_emissions#Natural

Chapter 15.0 Greenhouse Gases

15.1 Introduction

The monitoring of carbon dioxide in the atmosphere on Moana Loa, Hawaii by Dr. Keeling of the Scripps Institution of Oceanography was a huge ‘wake-up call’ that Earth was headed toward serious problems with global warming. Figure 15.1 shows the ‘Keeling Curve’ which illustrates how the concentration of carbon dioxide in the atmosphere varies throughout the year at that location and how the concentration has increased since 1958 when the monitoring was started. The significant role carbon dioxide and all of the other greenhouse gases (GHGs) is beginning to play in shaping Earth’s climate is fully realized. This is particularly evident from examinations of carbon dioxide concentration of Earth’s atmosphere captured in ice cores taken from the Antarctic ice sheet. This data goes back 800,000 years and clearly shows how unusual current increases in the concentration of carbon dioxide actually are (see Figure 15.2).   Figure 15.3 shows how the global concentration of carbon dioxide in the atmosphere has changed since the mid nineteenth century.

There are now hundreds of GHG monitoring stations distributed around the world and several satellites, orbiting and geostationary, collecting information on the concentration of all GHG’s (carbon dioxide, methane and nitrous oxide and others) on a continuous basis. This information is critical to numerical modelling of climate change and also to pinpoint opportunities to control GHG emissions.

Figure 4.5, shown below, illustrates the global energy budget and the importance of greenhouse gases (GHGs). In the process of absorbing long wave (infrared) radiation emitted from the Earth, heating the atmosphere and reradiating the energy back to Earth and space, GHGs are ultimately responsible for a warmer terrestrial and atmospheric environment on Earth.

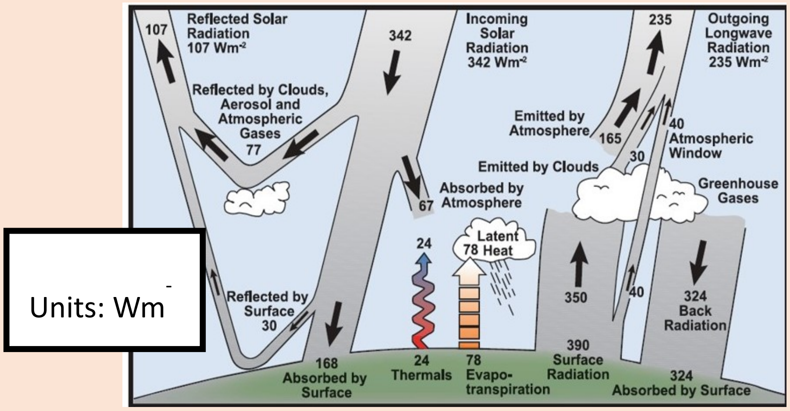

Figure 4.5 Global Energy Budget taken from http://climateknowledge.org/figures/Rood_Climate_Change_AOSS480_Documents/Kiehl_Trenberth_Radiative_Balance_BAMS_1997.pdf

The concentration of GHGs has increased steadily since 1958. The National Oceanic and Atmospheric Administration (NOAA) began taking measurements in 1974. The red line is a plot of average monthly values. The 'saw tooth' shape reflects the growing season in the northern hemisphere. The concentration of carbon dioxide in the atmosphere in 1958 was approximately 100 ppm less than today. NOAA observes that the observations at Mauna Loa are taken at an elevation of 3400m and may not be the same as globally averaged values at the surface.

Figure 15.2 show how carbon dioxide concentration is reflected by season (plant growth) from the far north, tropics, equator to South Pole. The South Pole exhibits no affect similar to the measurements taken near the Equator, American Samoa. The average for each is the same.

Figure 15.3 shows a graph of atmospheric carbon dioxide concentration in ice cores taken from the Antarctic ice sheet – 800,000 years of record. The global average was 409.8 ppm for 2019 and 413.56 ppm for 2020. The highest concentration of carbon dioxide in the 800,000 years prior to 1850 was observed to be 300 ppm. Figure 15.4 shows a graph of carbon dioxide measured in millions of tons from the beginning of the industrial era to present and projected to 2040.

Clearly, global atmospheric carbon dioxide concentration today and its rate of increase is unusual and concerning.

Anthropogenic production of GHGs is the major contribution to increases in radiative forcing and resulting global warming.

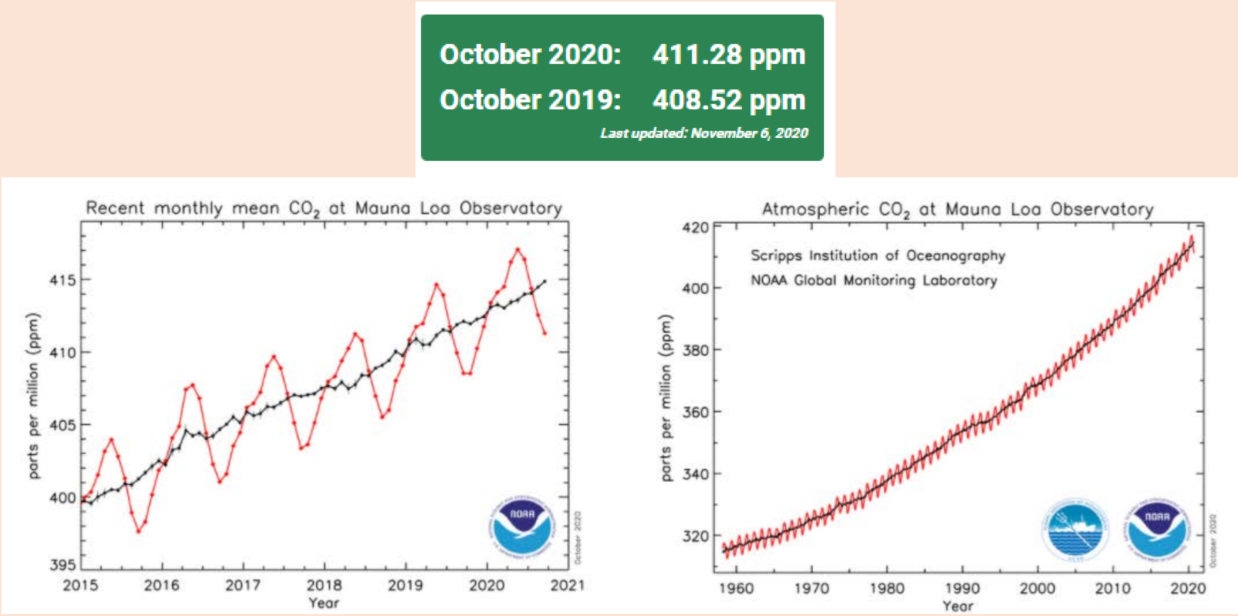

Figure 15.1 The Keeling Curve, monthly mean carbon dioxide measured at Mauna Loa Observatory, Hawaii. https://www.esrl.noaa.gov/gmd/ccgg/trends/

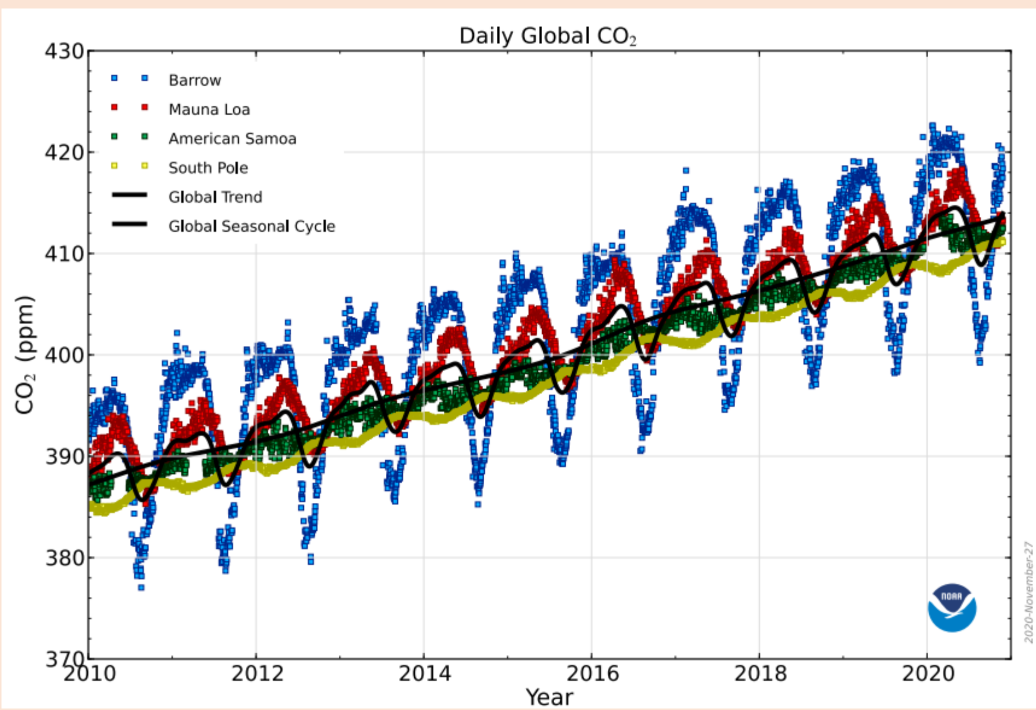

Figure 15.2 Daily averaged carbon dioxide concentration measured at Barrow, Alaska, Mauna Loa, Hawaii, American Samoa and South Pole, Antarctica. https://www.esrl.noaa.gov/gmd/ccgg/trends/gl_trend.html

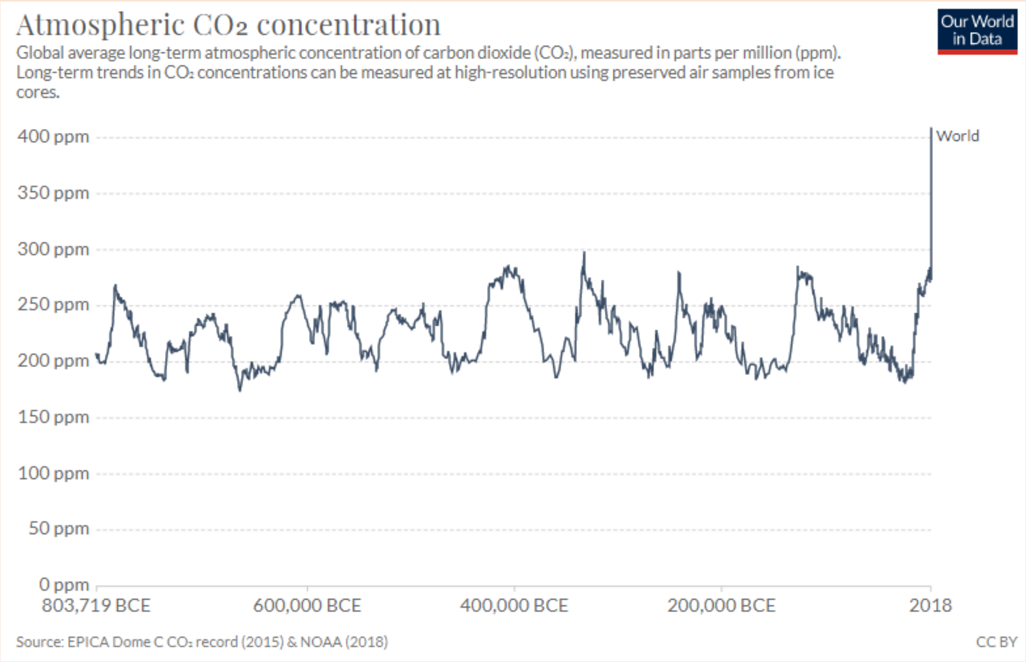

Figure 15.3 Atmospheric carbon dioxide concentration in ice cores taken from the Antarctic ice sheet. https://ourworldindata.org/atmospheric-concentrations and https://www.esrl.noaa.gov/gmd/ccgg/trends/

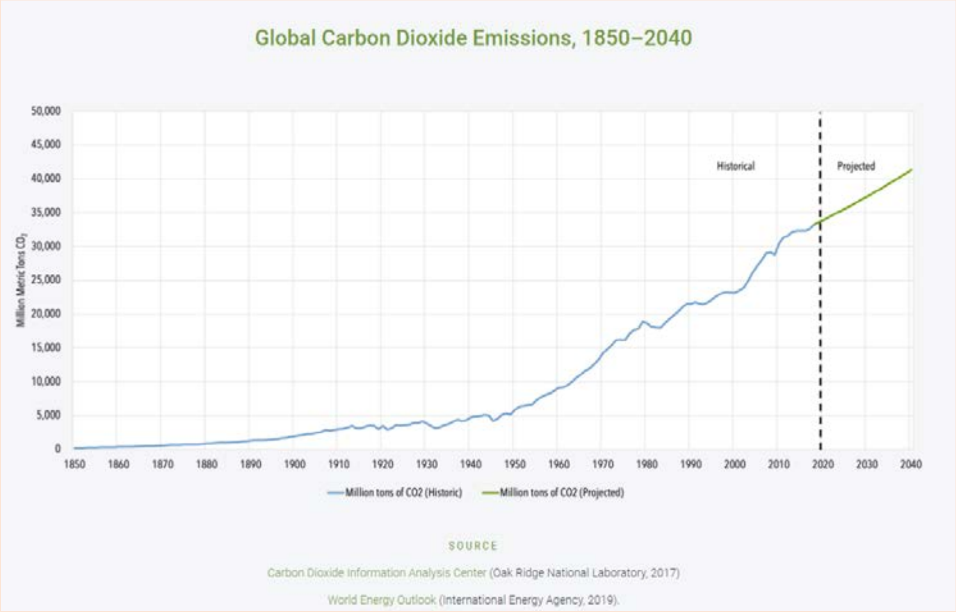

Figure 15.4 Global carbon dioxide emissions, 1850 to 2040. https://www.c2es.org/content/international-emissions/#:~:text=Globally%2C%20the%20primary%20sources%20of,72%20percent%20of%20all%20emissions.

15.2 Types of greenhouse gas emissions.

The principle GHGs (except for water) emitted in the United States for 2018 by gas are shown in Figure 15.5. Similar global emissions breakdown for 2015 is shown in Figure 15.6. The radiative forcing for CO_2, N_2O and CH_4 (carbon dioxide, nitrous oxide and methane) may be calculated based on the concentration of the gas in the atmosphere (Etminan, Myhre, Highwood and Shrine 2016 https://agupubs.onlinelibrary.wiley.com/doi/full/10.1002/2016GL071930).

The term, global warming potential, is used to describe the relative potency, molecule for molecule, of a greenhouse gas, taking account of how long it remains active in the atmosphere. The global warming potentials, GWPs, are those calculated over 100 years. Carbon dioxide is taken as the gas of reference and given a 100-year GWP of 1.

A carbon dioxide equivalent, or CO_2 equivalent, CO_2-eq is a measure used to compare emissions from various greenhouse gases on the basis of their global-warming potential. (For example; The GWP of methane is 25. If there are 1.5 metric tonnes of methane, the CO_2-eq is 37.5 metric tonnes. The GWP for nitrous oxide is 298.).

Water vapour is the primary greenhouse gas in Earth's atmosphere, approximately two to three times carbon dioxide. The difference between water vapour and the other greenhouse gases is that when the atmosphere cools water vapour condenses into water droplets or ice particles and precipitates. Water vapour does not accumulate in the atmosphere but the concentration of water vapour in the atmosphere increases as the temperature increases (approximately 6% increase for every one degree Centigrade). Note that anthropogenic sources of water vapour are negligible compared to natural evaporation and evapotranspiration. All of the other GHG's do accumulate in the atmosphere until natural processes remove them. The duration a GHG remains in the atmosphere is called its atmospheric lifetime.

As shown in Figure 5.1, the carbon cycle, a principal source of carbon dioxide emissions is the burning of fossil fuel and the production of cement. The production and use of fossil fuels produce both carbon dioxide and methane. Methane is also produced from agricultural operations (rice production and livestock), biofuels, landfills, wastewater and naturally from wetlands, forest fires and thawing permafrost.

GHGs are monitored using land based, air borne and satellite instrumentation.

Countries report the GHG emissions from industries operating in their jurisdiction to the United Nations Framework Convention on Climate Change using protocols established by the UNFCCC.

Knowledge of how and where GHGs are produced facilitates the development of mitigation strategies (plans to decrease emissions).

There are a number of terms used to describe GHG emissions, carbon dioxide equivalents in particular. These are used to describe sources and sinks of GHG and aid in the development and implementation of strategies to limit GHG emissions.

The global warming potential and atmospheric lifetime for major GHGs is shown in Table 15.1.

Greenhouse gas	Chemical formula	Global Warming Potential, 100-year time horizon	Atmospheric Lifetime (years)
Carbon Dioxide	CO2	1	100*
Methane	CH4	25	12
Nitrous Oxide	N2O	265	121
Chlorofluorocarbon-12 (CFC-12)	CCl2F2	10,200	100
Hydrofluorocarbon-23 (HFC-23)	CHF3	12,400	222
Sulfur Hexafluoride	SF6	23,500	3,200
Nitrogen Trifluoride	NF3	16,100	500

Table 15.1 Global warming potential and atmospheric lifetime for major greenhouse gases. https://www.ipcc.ch/report/ar4/wg1/

Figure 15.7 shows how the concentration of the various GHGs have changed over the past two thousand years. The dramatic increases coincide with the beginning of the industrial revolution in the mid nineteenth century.

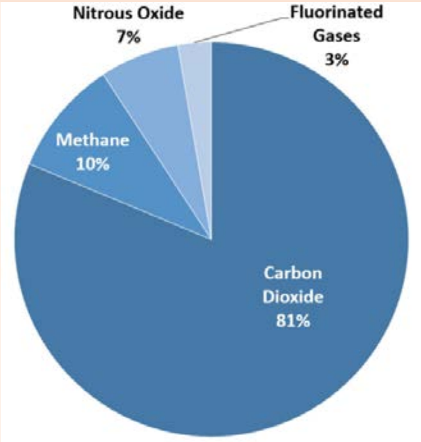

Figure 15.5 Emissions of GHGs in 2018 in the U. S. by gas.
https://www.epa.gov/ghgemissions/overview-greenhouse-gases

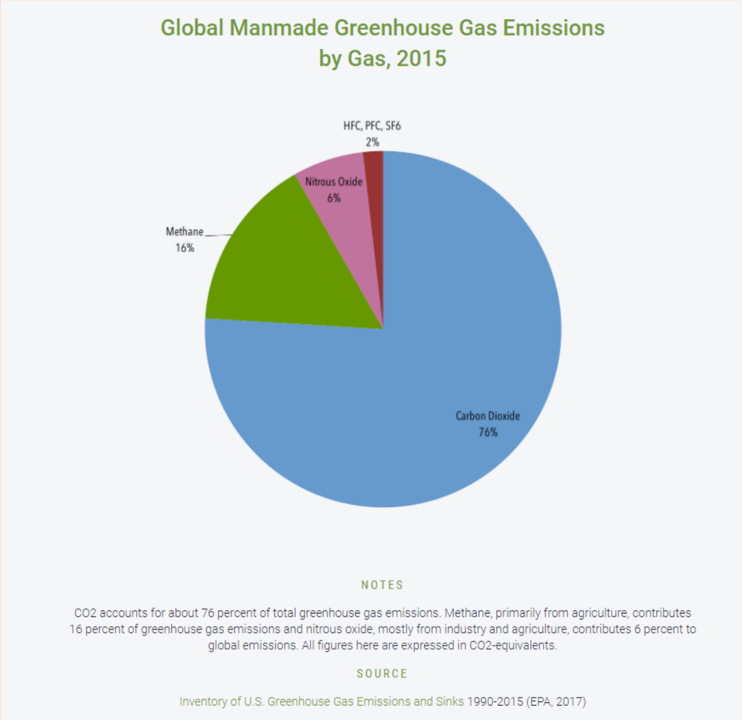

Figure 15.6 Global manmade greenhouse gas emissions by gas, 2015.
https://www.c2es.org/content/international-emissions/#:~:text=Globally%2C%20the%20primary%20sources%20of,72%20percent%20of%20all%20emissions

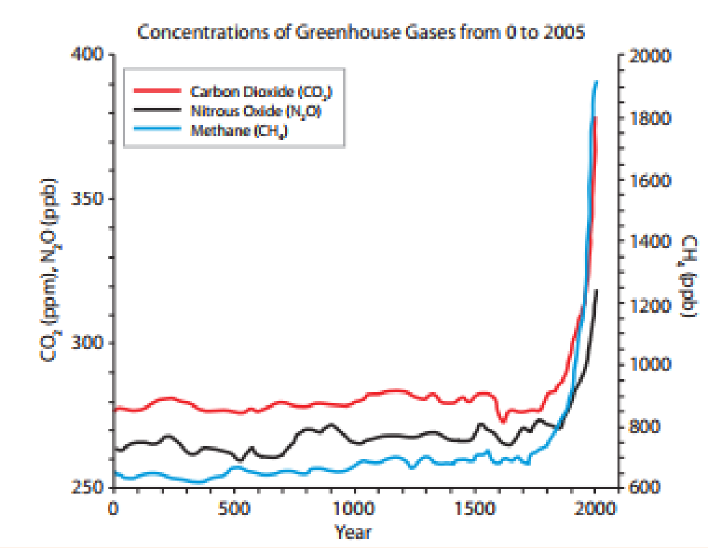

Figure 15.7 Concentration of GHGs from 0 to 2005.
https://www.canr.msu.edu/resources/greenhouse_gas_basics_e3148

15.3 Carbon dioxide emissions by fuel type

The amount of energy in a fuel is measured in terms of its energy density which is the amount of energy that can be stored in a given volume or mass of the fuel. Units might be watt-hours per litre or megajoules/litre and watt-hours per kilogram or megajoules per kilogram. Table 15.2 lists several types of fuel and their energy density.

Fuel Type	Reaction Type	Energy Density (MJ/kg)	Typical uses
Wood	Chemical	16	Space heating, Cooking
Coal	Chemical	24	Power plants, Electricity generation
Ethanol	Chemical	26.8	Gasoline mixture, Alcohol, Chemical products
Biodiesel	Chemical	38 [8]	automotive engine
Crude oil	Chemical	44	Refinery, Petroleum products
Diesel	Chemical	45	Diesel engines
Gasoline	Chemical	46	Gasoline engines
Natural gas	Chemical	55	Household heating, Electricity generation
Uranium-235	Nuclear	3 900 000	Nuclear reactor electricity generation

Table 15.2 Energy density of different fuels.
https://energyeducation.ca/encyclopedia/Energy_density

A very useful tool is the energy conversion calculator available at:
https://www.eia.gov/energyexplained/units-and-calculators/energy-conversion-calculators.php
and helpful explanations at: https://www.eia.gov/energyexplained/units-and-calculators/

The conversion of the chemical energy in fossil fuels to electricity varies from a low of 37% (or less) for coal fired plants to a potential high of 60% for combined-cycle gas fired plants, https://en.wikipedia.org/wiki/Fossil_fuel_power_station .

The efficiency of electricity production using fossil fuels may be expressed as its heat rate in terms of BTU/kilowatt hour or megajoules/kilowatt hour. For a thorough explanation see https://en.wikipedia.org/wiki/Heat_rate_(efficiency) .

The carbon dioxide emissions by fossil fuel type are listed in Table 15.3. This information is needed for the estimating carbon footprint. Note that the energy required to produce and transport the fossil fuel has not been considered.

Knowing which fossil fuel is used and its efficiency of electricity production allows emission comparison between different means of electricity production.

Carbon Dioxide Emissions Coefficients by Fuel

Carbon Dioxide (CO_2) Factors:	Pounds CO_2 Per Unit of Volume or Mass	Kilograms CO_2 Volume or Mass	Pounds CO_2 Million Btu	Kilograms CO_2 Million Btu
For homes and businesses				
Propane	12.70/gallon	5.76/gallon	139.05	63.07
Butane	14.80/gallon	6.71/gallon	143.20	64.95
Butane/Propane Mix	13.70/gallon	6.21/gallon	141.12	64.01
Home Heating and Diesel Fuel (Distillate)	22.40/gallon	10.16/gallon	161.30	73.16
Kerosene	21.50/gallon	9.75/gallon	159.40	72.30
Coal (All types)	4,631.50/short ton	2,100.82/short ton	210.20	95.35
Natural Gas	117.10/thousand cubic feet	53.12/thousand cubic feet	117.00	53.07
Gasoline	19.60/gallon	8.89/gallon	157.20	71.30
Residual Heating Fuel (Businesses only)	26.00/gallon	11.79/gallon	173.70	78.79
Other transportation fuels				
Jet Fuel	21.10/gallon	9.57/gallon	156.30	70.90
Aviation Gas	18.40/gallon	8.35/gallon	152.60	69.20
Industrial fuels and others not listed above				
Flared natural gas	120.70/thousand cubic feet	54.75/thousand cubic feet	120.60	54.70
Petroleum coke	32.40/gallon	14.70/gallon	225.10	102.10
Other petroleum & miscellaneous	22.09/gallon	10.02/gallon	160.10	72.62
Nonfuel uses				
Asphalt and Road Oil	26.34/gallon	11.95/gallon	166.70	75.61
Lubricants	23.62/gallon	10.72/gallon	163.60	74.21
Petrochemical Feedstocks	24.74/gallon	11.22/gallon	156.60	71.03
Special Naphthas (solvents)	20.05/gallon	9.10/gallon	160.50	72.80
Waxes	21.11/gallon	9.57/gallon	160.10	72.62
Coal by type				
Anthracite	5,685.00/short ton	2,578.68/short ton	228.60	103.70
Bituminous	4,931.30/short ton	2,236.80/short ton	205.70	93.30
Subbituminous	3,715.90/short ton	1,685.51/short ton	214.30	97.20
Lignite	2,791.60/short ton	1,266.25/short ton	215.40	97.70
Coke	6,239.68/short ton	2,830.27/short ton	251.60	114.12
Other fuels				
Geothermal (average all generation)	NA	NA	16.99	7.71
Municipal Solid Waste	5,771.00/short ton	2,617.68/short ton	91.90	41.69
Tire-derived fuel	6,160.00/short ton	2,794.13/short ton	189.54	85.97
Waste oil	924.0/barrel	419.12/barrel	210.00	95.25

Source: U.S. Energy Information Administration estimates.
Note: To convert to carbon equivalents multiply by 12/44. Coefficients may vary slightly with estimation method and across time.

Table 15.3 Carbon dioxide equivalent emissions by fuel type.
https://www.eia.gov/environment/emissions/co2_vol_mass.php
and https://www.eia.gov/tools/faqs/faq.php?id=73&t=11

15.4 Carbon dioxide emissions from cement production.

Depending on the source, the estimates of the contribution of the cement industry to global carbon dioxide emission varies from 5 to 10%.

A very good description of why production of cement is a significant producer of carbon dioxide emissions may be found in https://www.carbonbrief.org/qa-why-cement-emissions-matter-for-climate-change and https://en.wikipedia.org/wiki/Environmental_impact_of_concrete .

Basically, the reasons are two-fold; heating of the limestone releases carbon dioxide, (chemical reaction 60%), and the energy used to heat the limestone to produce the final product 40%.

15.5 Methane (CH_4) emissions

The major natural source of methane is wetlands. The remainder comes from gas hydrates, geologic seepages, volcanic gas, melting permafrost, ocean sediments, wildfires and termites.

The major manmade sources of methane are approximately double the volume of the natural occurring sources. These include agriculture – paddy rice fields and livestock production, biofuel production, biomass burning (as distinct from naturally occurring forest and wild fires), decomposition of organic waste in landfills and wastewater and fossil methane emission during the exploration, production and transport of fossil fuels.
https://en.wikipedia.org/wiki/Methane_emissions#Natural

The natural and anthropogenic sources of methane at listed in Tables 15.4 and 15.5.

Category	Major Sources	IEA Annual Emission[3] (Million Tons)
Wetlands	Wetland methane	194
Other natural	Geologic seepages Volcanic gas	39
	Arctic melting Permafrost	
	Ocean sediments	
	Wildfires	
	Termites	
	Total natural	**233**
Additional References: [1][18][19]		

Table 15.4 Natural sources of methane.
https://en.wikipedia.org/wiki/Methane_emissions#Natural

Category	Major Sources	IEA Annual Emission[3] (Million Tons)
Fossil fuels	Gas distribution	45
	Oil wells	39*
	Coal mines	39
Biofuels	Anaerobic digestion	11
Industrial agriculture	Enteric fermentation	145
	Rice paddies	
	Manure management	
Biomass	Biomass burning	16
Consumer waste	Solid waste Landfill gas	68
	Wastewater	
	Total anthropogenic	**363**

* An additional 100 million tons (140 billion cubic meters) of gas is vented and flared each year from oil wells.[17]
Additional References: [1][18][19][20][21]

Table 15.5 Anthropogenic sources of methane.
https://en.wikipedia.org/wiki/Methane_emissions#Natural

Off gassing from landfills and fossil methane are considered the most manageable. Fossil methane includes:

- Fugitive methane emissions occur from leakages that are not intended, for example because of a faulty seal or leaking valve.
- Vented methane emissions are the result of intentional releases, often for safety reasons, due to the design of the facility or equipment (e. g. pneumatic controllers) or operational requirements (e. g. venting a pipeline for inspection and maintenance).
- Incomplete flaring methane emissions can occur when natural gas that cannot be used or recovered economically is burned instead of being sold or vented. The vast majority of the natural gas is converted into CO_2 and water, but some portion may not be combusted and is released as methane into the atmosphere.
- Suspended/ inactive, abandoned and orphaned, wells, (oil or natural gas) and pipelines or other facilities prior to decommissioning.

The International Energy Agency produces what it calls the 'methane tracker database' listing the world fossil methane emission sources. https://www.iea.org/reports/methane-tracker-2021?utm_campaign=IEA%20newsletters&utm_source=SendGrid&utm_medium=Email Methane emissions are identified and monitored using a variety of airborne and satellite platforms as discussed in later sections.

15.6 Greenhouse gas emissions by sector

Global emissions of GHG's by sector are shown in Figure 15.8.   Figure 15.9 shows similar information for the United States.   Figure 15.10 shows detailed global emissions by sector. Details for the United States are typical for advanced western economies. This information is essential when establishing mitigation programs as discussed in Chapter 20.

All countries collect this information according to 2006 IPCC Guidelines for National Greenhouse Gas Inventories which are updated periodically, the most recent being 2019 (https://www.ipcc-nggip.iges.or.jp/index.html). This information is then provided to the United Nations Framework Convention on Climate Change, UNFCCC.

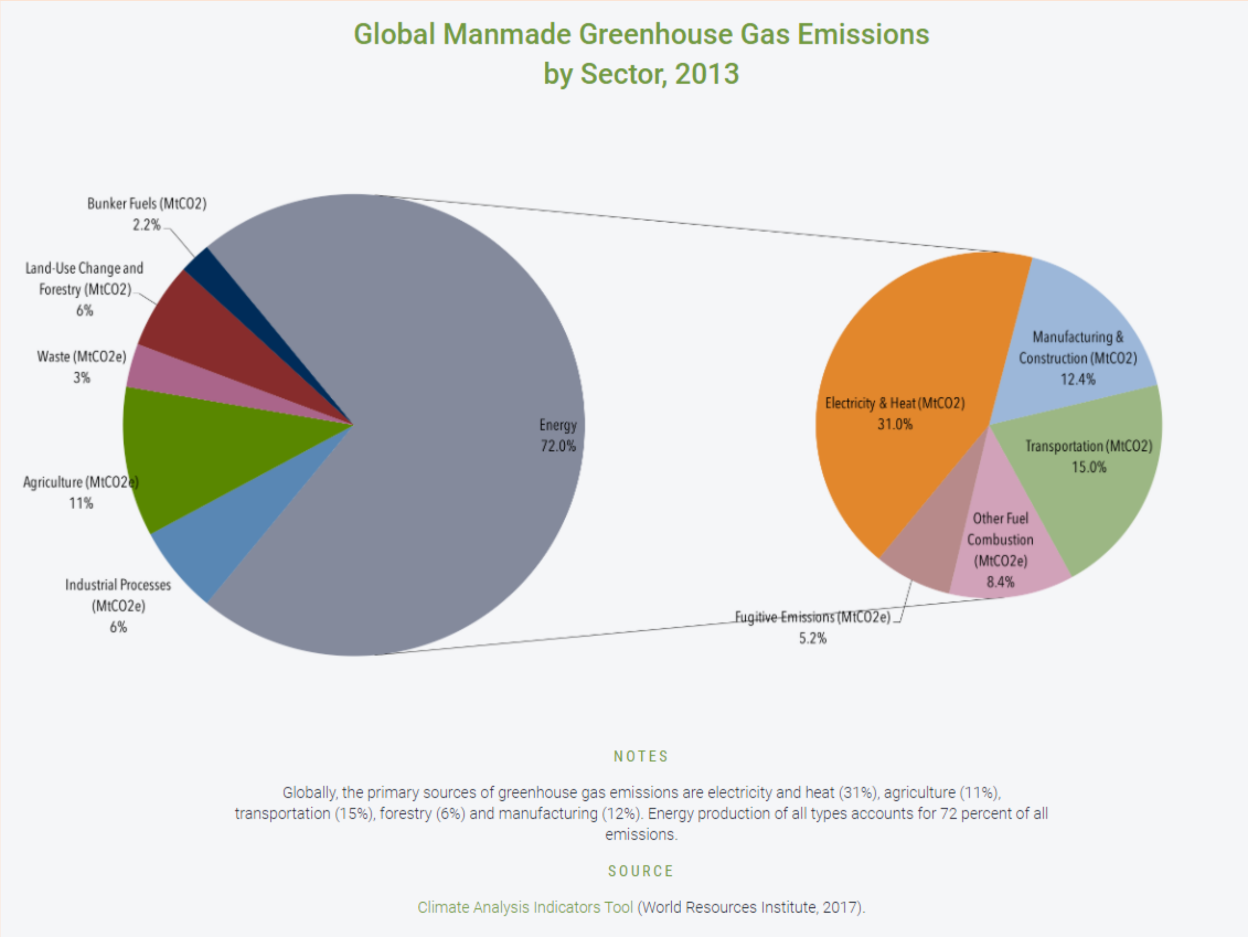

Figure 15.8 Global manmade greenhouse gas emissions by sector, 2013.
https://www.c2es.org/content/international-emissions/#:~:text=Globally%2C%20the%20primary%20sources%20of,72%20percent%20of%20all%20emissions

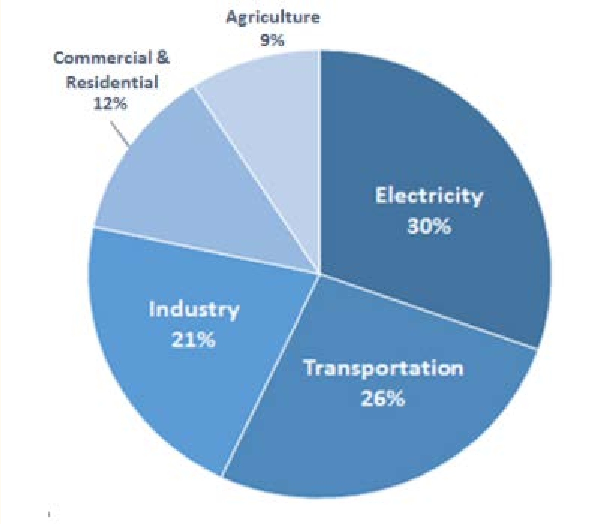

Figure 15.9 Greenhouse gas emissions by sector, U. S., 1990-2014.
https://www.epa.gov/ghgemissions/us-greenhouse-gas-inventory-report-1990-2014

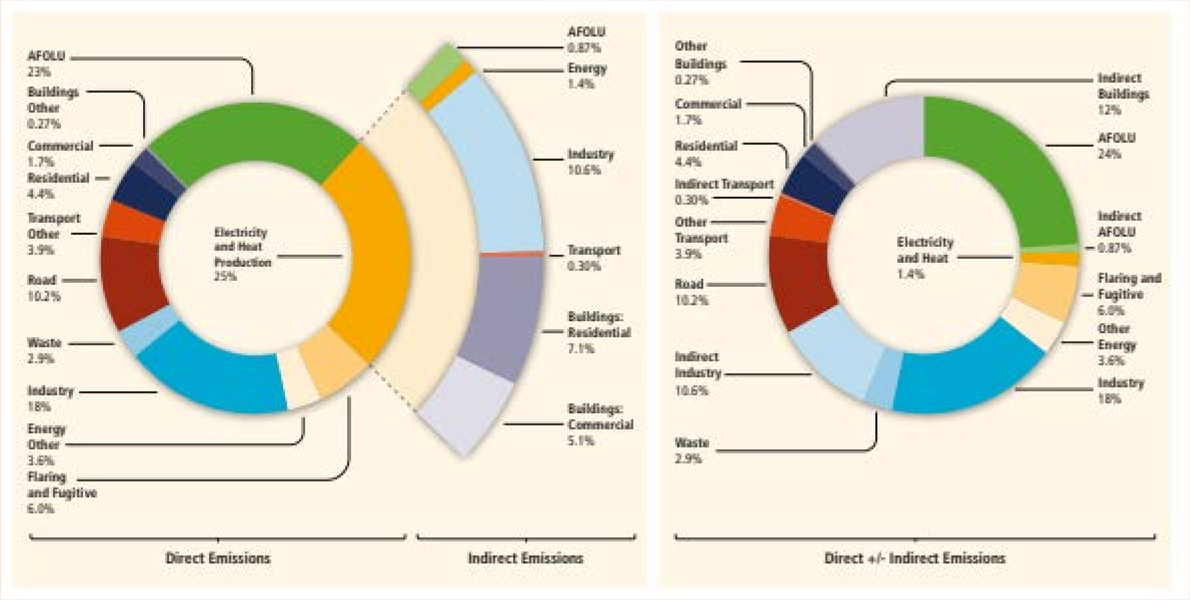

Figure 15.10 Detailed global emissions by sector.
https://www.ipcc.ch/site/assets/uploads/2018/02/ipcc_wg3_ar5_chapter1.pdf

The agriculture, forestry, and other land use (AFOLU) sector is very broad. Agriculture practices include soil management and the conversion of previously forested land into intensive farming or range land are recognized as significant contributors to green house gas emissions. Forest loss due to any cause has the impact of eliminating greenhouse has storage and release of previously stored greenhouse gases to the atmosphere. Changes in land use involving loss of forest and soil covered land areas eliminate opportunities for greenhouse gas storage and capture. To this has been added peatland management as reported by the International Union for the Conservation of Nature, ICUN, https://www.iucn.org/resources/issues-briefs/peatlands-and-climate-change. They describe peatlands as a type of wetlands that occur in almost every country covering 3% of the global land surface. The term 'peatland' refers to the peat soil and the wetland habitat growing on its surface. They go on to say that damaged peatlands contribute about 10% of greenhouse gases from the land use sector or 5.6% of anthropogenic carbon dioxide emissions. The damage is caused by drainage and conversion to agricultural land, fires, and harvesting as fuel. Loss of peatlands is considered to have a negative impact on local biodiversity.

Oceans are not specifically identified as a significant contributor of greenhouse gas emissions (maybe as part of 'other contributors). Oceans are normally viewed as greenhouse gas sinks. Recent studies on the impact of ocean fisheries, trawling practices in particular on ocean biodiversity and release of greenhouse gases have recently been reported, (https://www.nature.com/articles/s41586-021-03371-z, https://www.sciencedaily.com/releases/2021/03/210317141645.htm, https://www.bluemarinefoundation.com/2021/03/18/trawling-discovered-to-have-massive-climate-change-impact/, https://www.theguardian.com/environment/2021/mar/17/trawling-for-fish-releases-as-much-carbon-as-air-travel-report-finds-climate-crisis). The release of greenhouse gases is estimated to be as much as the entire airline industry and is viewed as a manageable activity.

15.7 Greenhouse gas emissions by country

It is very important to know which countries are producing GHG emissions so that global strategies for mitigation and adaptation can be developed and funded. This information is also useful when assessing progress in implementing mitigation strategies. Greenhouse gas emissions for major economies 1990-present and projections from present to 2030 are shown in Figure 15.11.

Greenhouse gas emissions for the top emitters is shown in Figure 15.12. These emitters account for most of GHG emissions. Cumulative GHG emissions from these emitters is shown in Figure 15.13. Comparison of Figure 15. 12 and 15.13 highlight the change in position of China and India and the presence of a new top emitter, Brazil.

Per capita greenhouse gas emissions for the major economies and the world are shown in Figure 15.14. This figure reflects standard of living. The difference between the lower income population and the high-income population is highlighted in Figure 15.15. Figure 15.16 shows the per capita GHG emissions by country. Aspects such as climate and affluence are reflected.

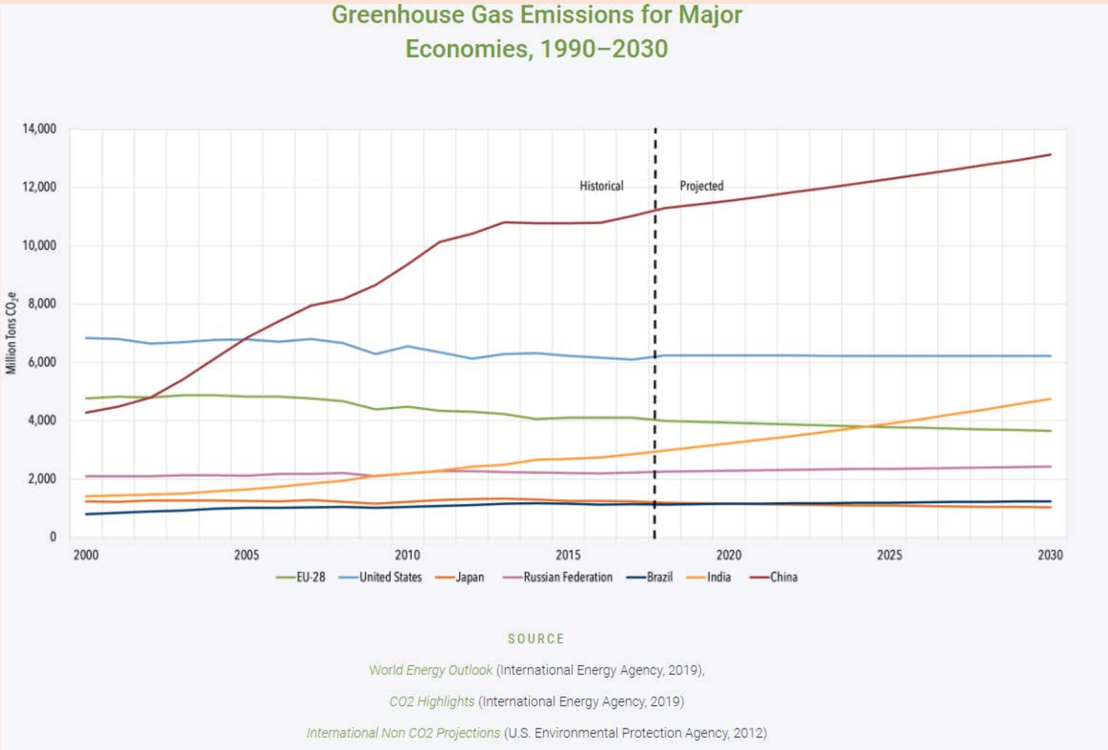

Figure 15.10 Greenhouse gas emissions for major economies, 1990-2030.
https://www.c2es.org/content/international-emissions/#:~:text=Globally%2C%20the%20primary%20sources%20of,72%20percent%20of%20all%20emissions

Greenhouse gas intensity for the major economies and the world is shown in Figure 15.17. Greenhouse gas intensity is measured in tonnes of carbon dioxide equivalent per thousand dollars of gross domestic product. The lower this number the more efficient the economy in terms of use of fossil fuel. Similar information is presented in Figure 15.18 which considers a cross-section of countries worldwide. More affluent countries tend to be more efficient.

It is clear that there is considerable information available regarding present GHG emissions by sector and by country. This information is critical when projecting future GHG emissions.

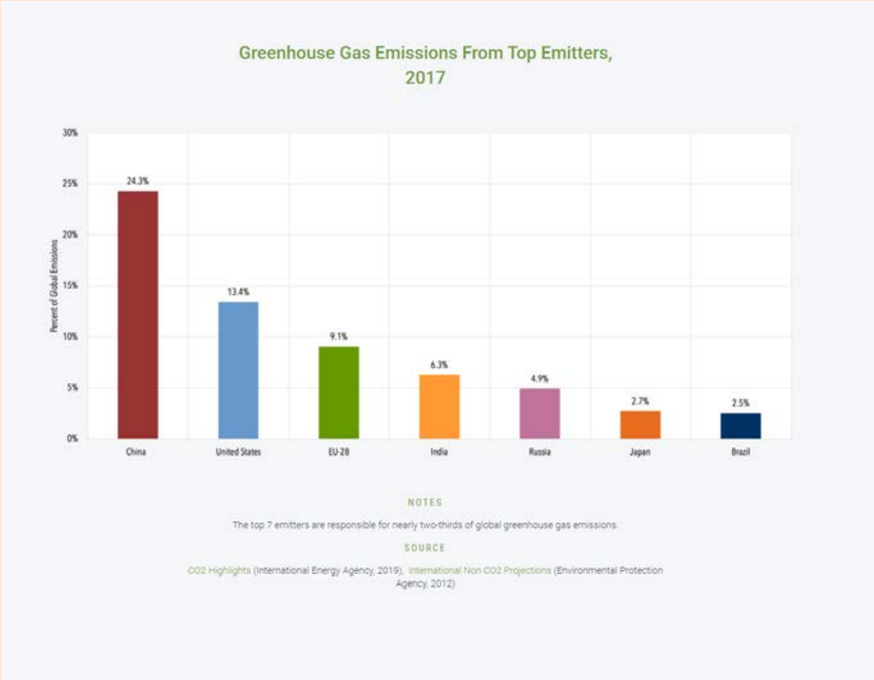

Figure 15.12 Greenhouse gas emissions for top emitters, 2017.
https://www.c2es.org/content/international-emissions/#:~:text=Globally%2C%20the%20primary%20sources%20of,72%20percent%20of%20all%20emissions

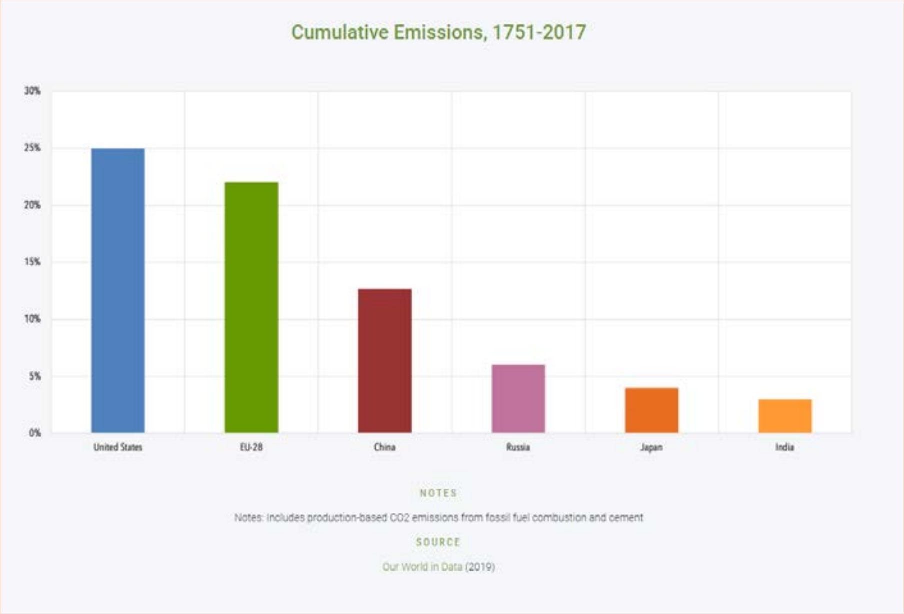

Figure 15.13 Cumulative greenhouse gas emissions for major economies, 1751-20172.
https://www.c2es.org/content/international-emissions/#:~:text=Globally%2C%20the%20primary%20sources%20of,72%20percent%20of%20all%20emissions

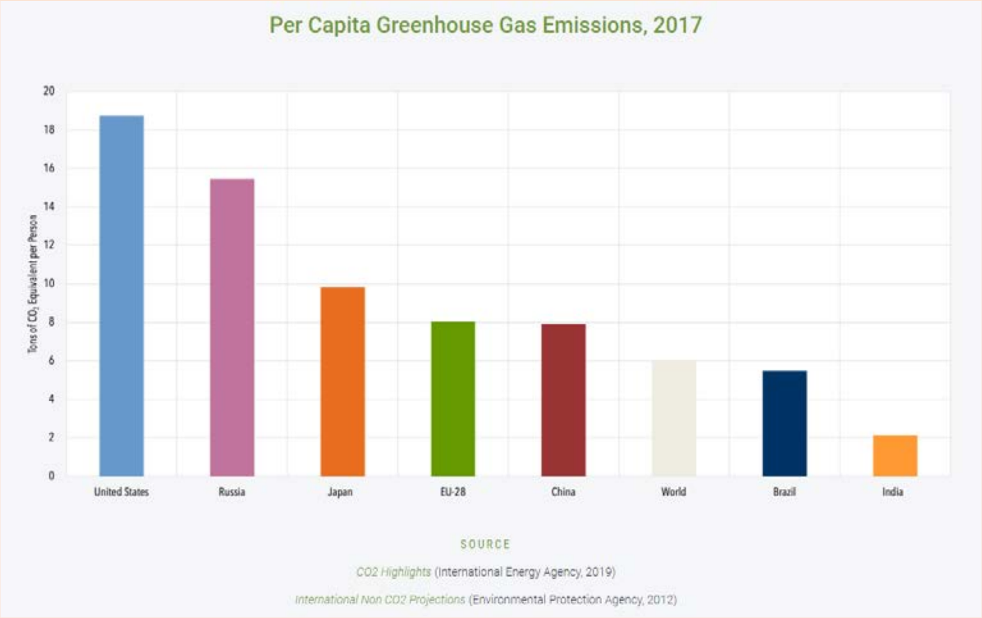

Figure 15.14 Per Capita greenhouse gas emissions for major economies, and the world, 2017.
https://www.c2es.org/content/international-emissions/#:~:text=Globally%2C%20the%20primary%20sources%20of,72%20percent%20of%20all%20emissions

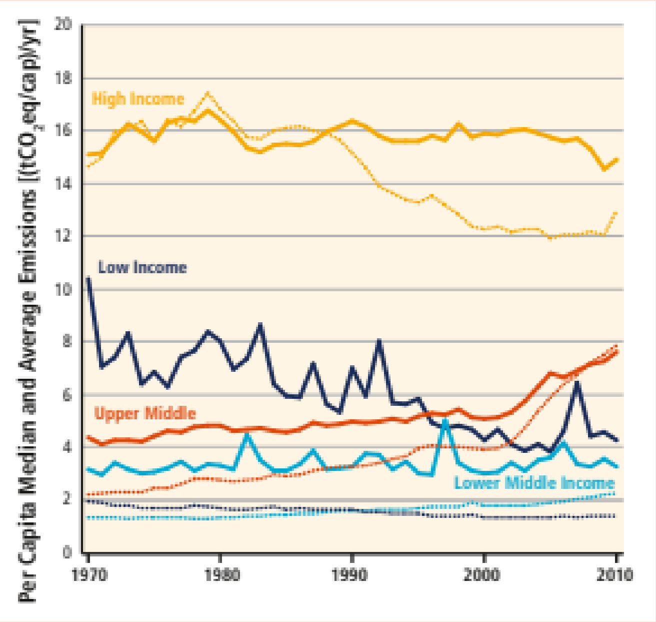

Figure 15.15 Per capita emissions for different income brackets.
https://www.ipcc.ch/site/assets/uploads/2018/02/ipcc_wg3_ar5_chapter1.pdf

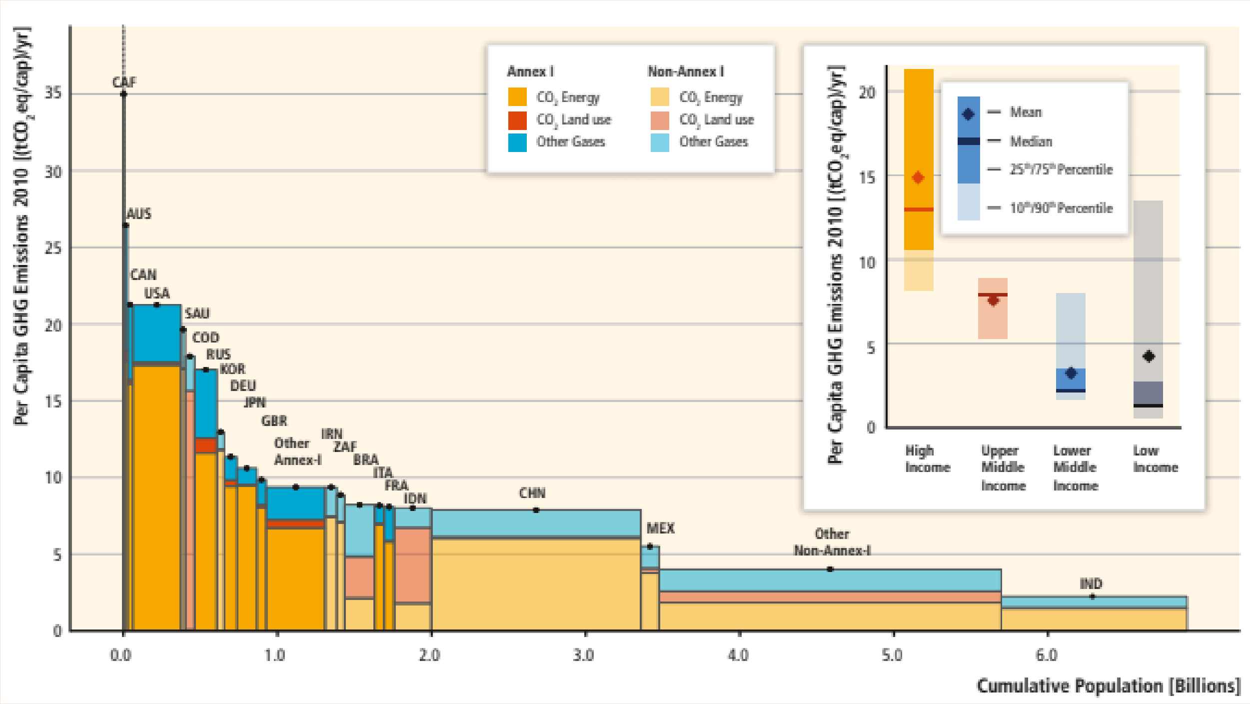

Figure 15.16 Per capita GHG emissions by country from IPCC.
https://www.ipcc.ch/site/assets/uploads/2018/02/ipcc_wg3_ar5_chapter1.pdf

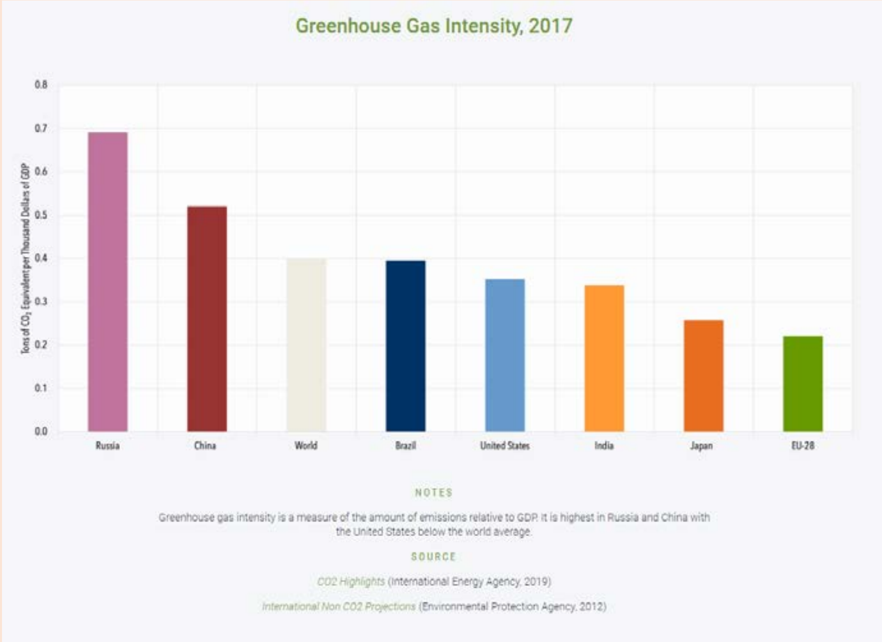

Figure 15.17 Greenhouse gas intensity for major economies and the World, 2017.
https://www.c2es.org/content/international-emissions/#:~:text=Globally%2C%20the%20primary%20sources%20of,72%20percent%20of%20all%20emissions

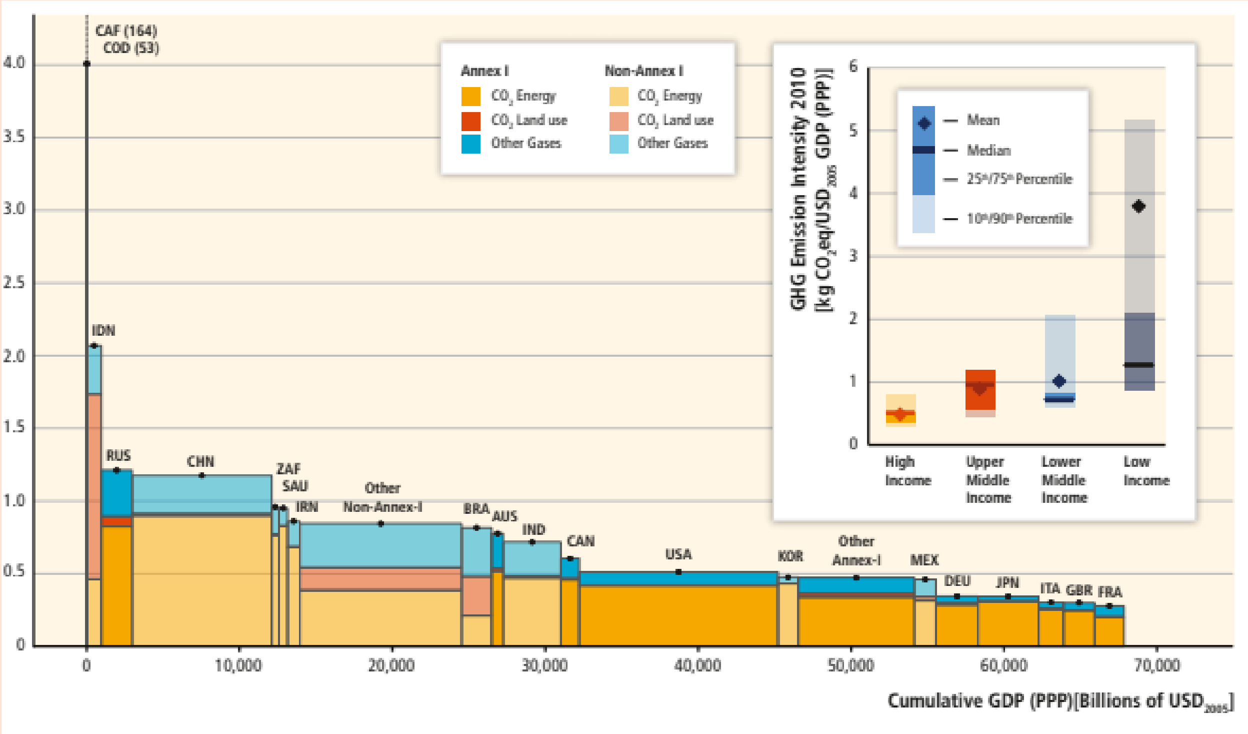

Figure 15.18 Greenhouse gas intensity for cross-section of countries.
https://www.ipcc.ch/site/assets/uploads/2018/02/ipcc_wg3_ar5_chapter1.pdf

15.8 Collection of greenhouse gas data

Information on GHG concentration in the atmosphere is collected using a variety of platforms including land based, aircraft and satellite. The collection system is able to monitor global concentration of each of the variety of greenhouse gases and are able to pinpoint where the emissions originate. This greatly improves opportunities for modelling and mitigation.

15.8.1 Land and ocean-based monitoring and sampling
Figure 15.19 shows the location of a variety of land and ocean-based sampling points for monitoring GHG's, usually carbon dioxide, ozone and aerosols. The exact nature of what is being collected is available on the NOAA web site:
https://www.esrl.noaa.gov/gmd/dv/iadv/index.php?code=mlo .

15.8.2 Aircraft GHG sampling
Figure 15.20 show the aircraft GHG sampling program. See NOAA web site for most up-to-date information, http://www.esrl.noaa.gov/gmd/ccgg/aircraft/ .

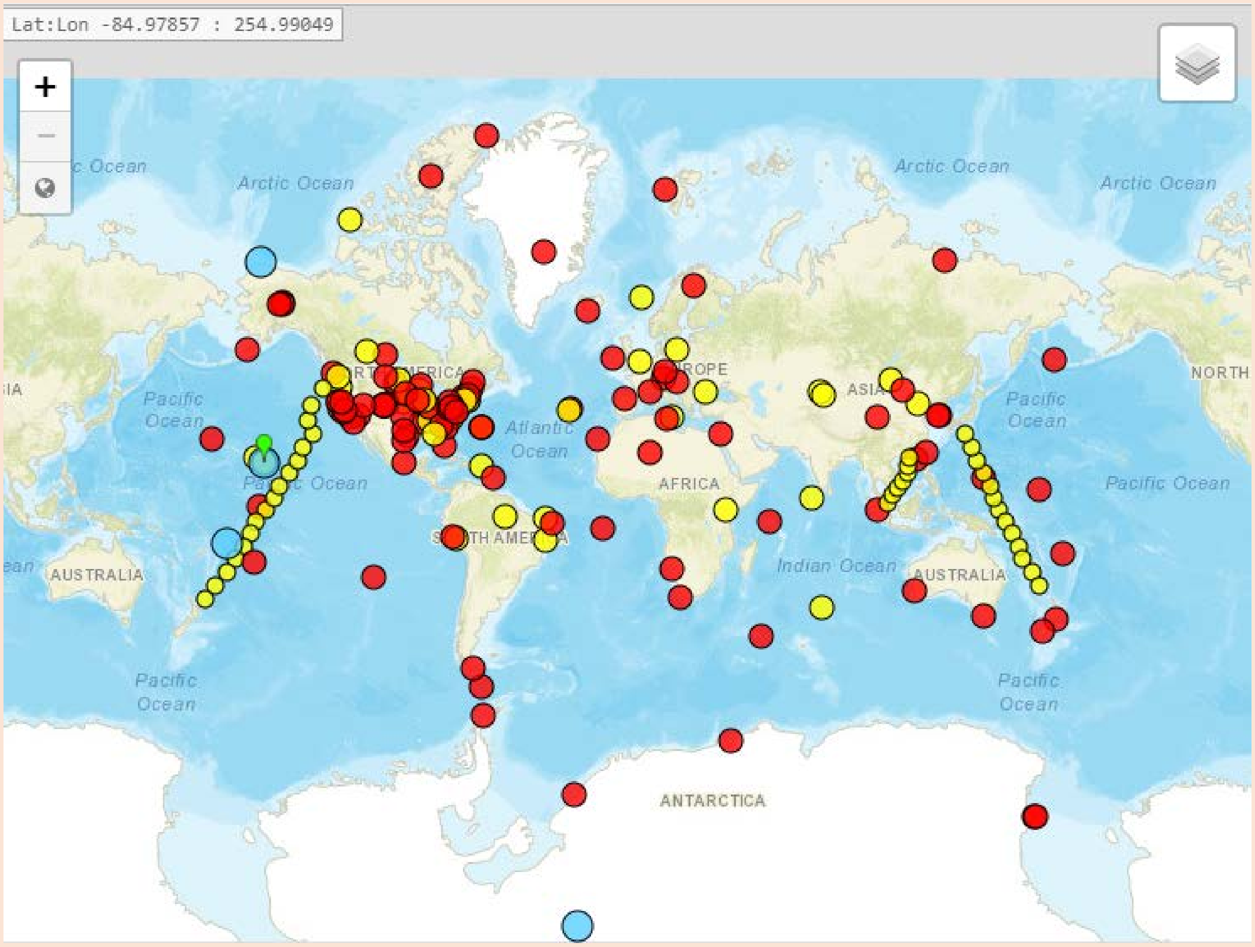

Figure 15.19 Land and ocean-based sampling of GHG's, ozone, and aerosols.
https://www.esrl.noaa.gov/gmd/dv/iadv/index.php?code=mlo

Figure 15.20 Aircraft GHG sampling program operated by NOAA.
http://www.esrl.noaa.gov/gmd/ccgg/aircraft/

15.8.3 Satellite based monitoring

Figure 15.20 illustrates the NASA Earth science spacecraft and instruments in orbit. Several of these are able to monitor GHG's in Earth's atmosphere.

Figure 15.21 shows the Greenhouse Gases Observing Satellite, GOSAT or Ibuki (Japanese) which is the first satellite dedicated to GHG monitoring. It measures carbon dioxide and methane.

Figure 15.22 shows the NASA orbiting carbon observatory, OCO-2. Data received from this satellite shows where the carbon emissions are coming from and the intensity of those carbon emissions as shown in Figure 15.23. OCO-3 will extend NASA's carbon monitoring program from the International Space Station.

Figure 15.24 shows results from NASA's Atmospheric Infrared Sounder (AIRS) which scans for carbon monoxide sources. In this figure it has sensed carbon monoxide from the wildfires in California.

Figure 15.25 shows an instrument mounted on a communications satellite named the Geostationary Carbon Cycle Observatory (EVM-2) or (GeoCarb). GeoCarb will collect 10 million daily observations of the concentrations of carbon dioxide, methane, carbon monoxide and solar-induced fluorescence (SIF) at a spatial resolution of about 3 to 6 miles (5 to 10 kilometers).

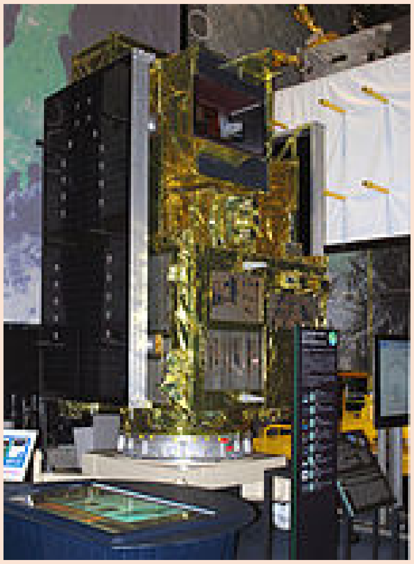

Figure 15.21 Greenhouse Gases Observing Satellite, GOSAT or Ibuki (Japanese) is the first satellite dedicated to GHG monitoring. It measures carbon dioxide and methane.
https://en.wikipedia.org/wiki/Greenhouse_Gases_Observing_Satellite

NASA's rendering of its Orbiting Carbon Observatory-2. Credit: NASA

Figure 15.22 NASA Orbiting Carbon Observatory-2.
https://www.nasa.gov/mission_pages/oco2/index.html

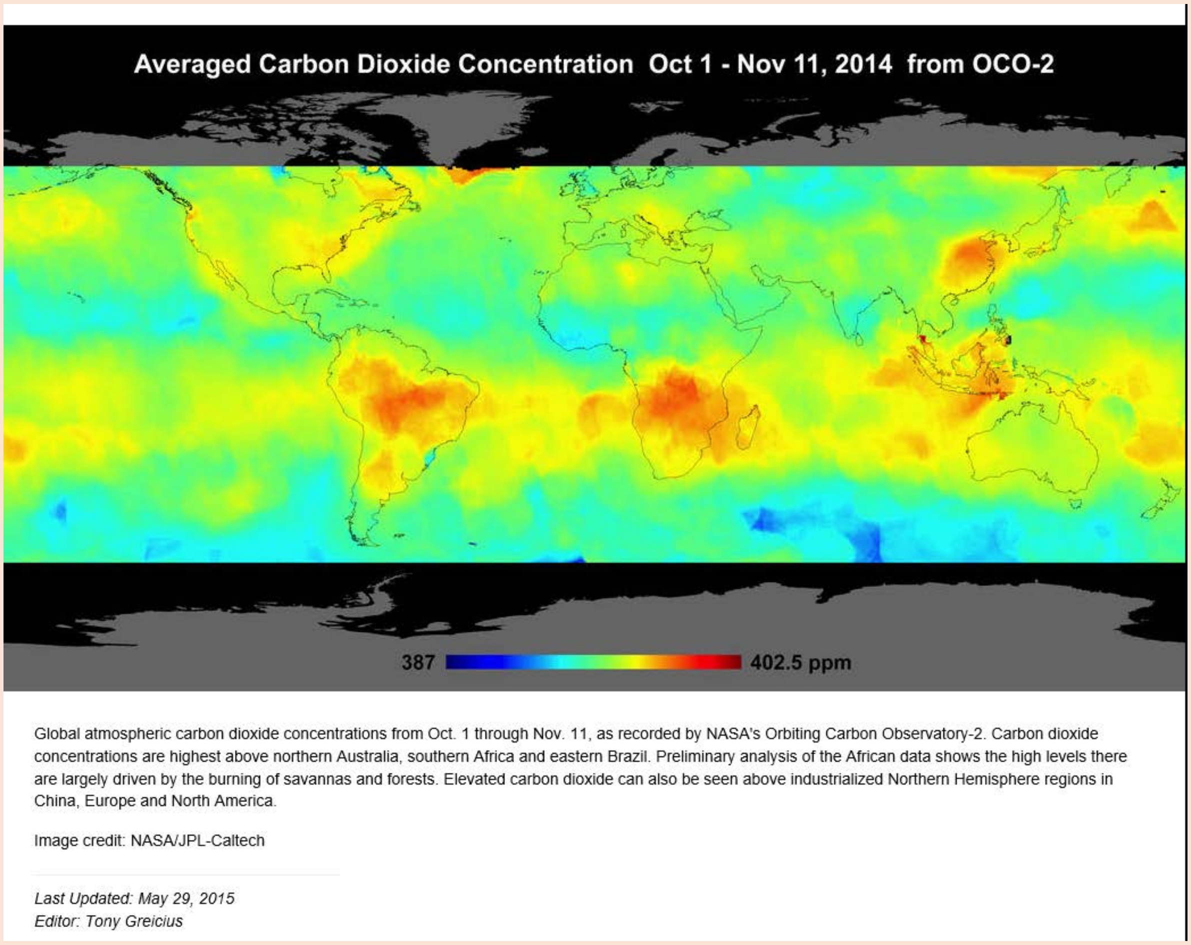

Figure 15.23 Averaged carbon dioxide concentration Oct 1 – Nov 11, 2014 from OCO-2.
https://www.nasa.gov/jpl/oco2/pia18934

Figure 15.24 Carbon monoxide measurements from NASA's Atmospheric Infrared Sounder (AIRS).
https://climate.nasa.gov/news/3019/nasa-monitors-carbon-monoxide-from-california-wildfires/

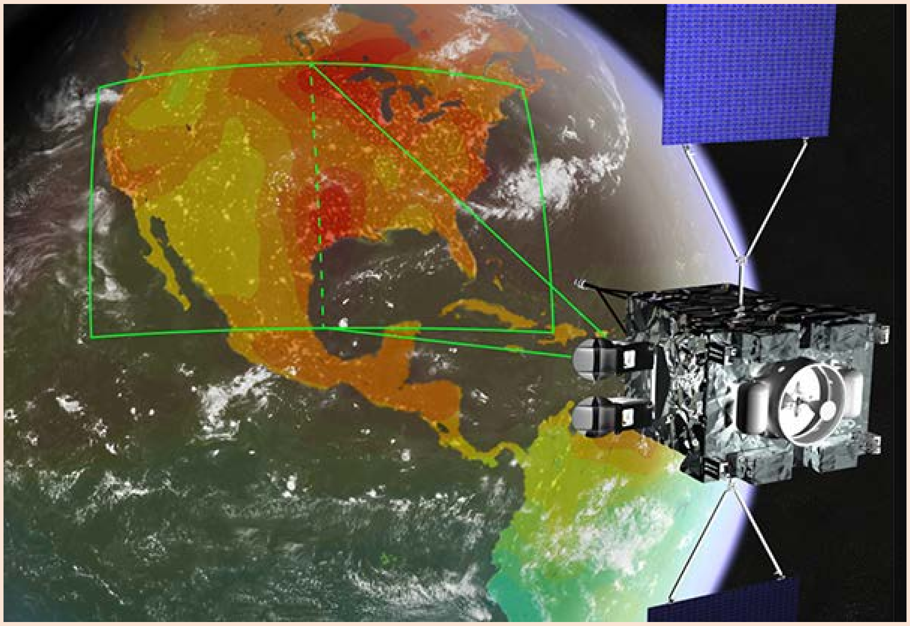

Figure 15.25 Geostationary carbon cycle observatory, EVM-2, GeoCarb.
https://eospso.nasa.gov/missions/geostationary-carbon-cycle-observatory-evm-2

Figure 15-26 shows a methane leak from space as detected by Earth Observing-1 (EO-1) satellite.

Figure 15-27 refers to NASA's 3-dimensional portrait of methane concentrations by combining multiple data sets from emissions inventories such as fossil fuel, agricultural activities, biomass burning, and biofuels and simulations of wetland sources. This project is an international success story. The full potential of this tool is described on the web site: https://climate.nasa.gov/news/2961/new-3d-view-of-methane-tracks-sources-and-movement-around-the-globe/. Methane sources can be identified and opportunities for mitigation determined.

Figure 15-28 illustrates the use of a satellite recently launched by a private company, GHGSat, named Iris detecting a methane plume (controlled release) in Alberta, Canada. This is their second satellite. The company's products and services use a proprietary multi-platform system for collecting emissions data.

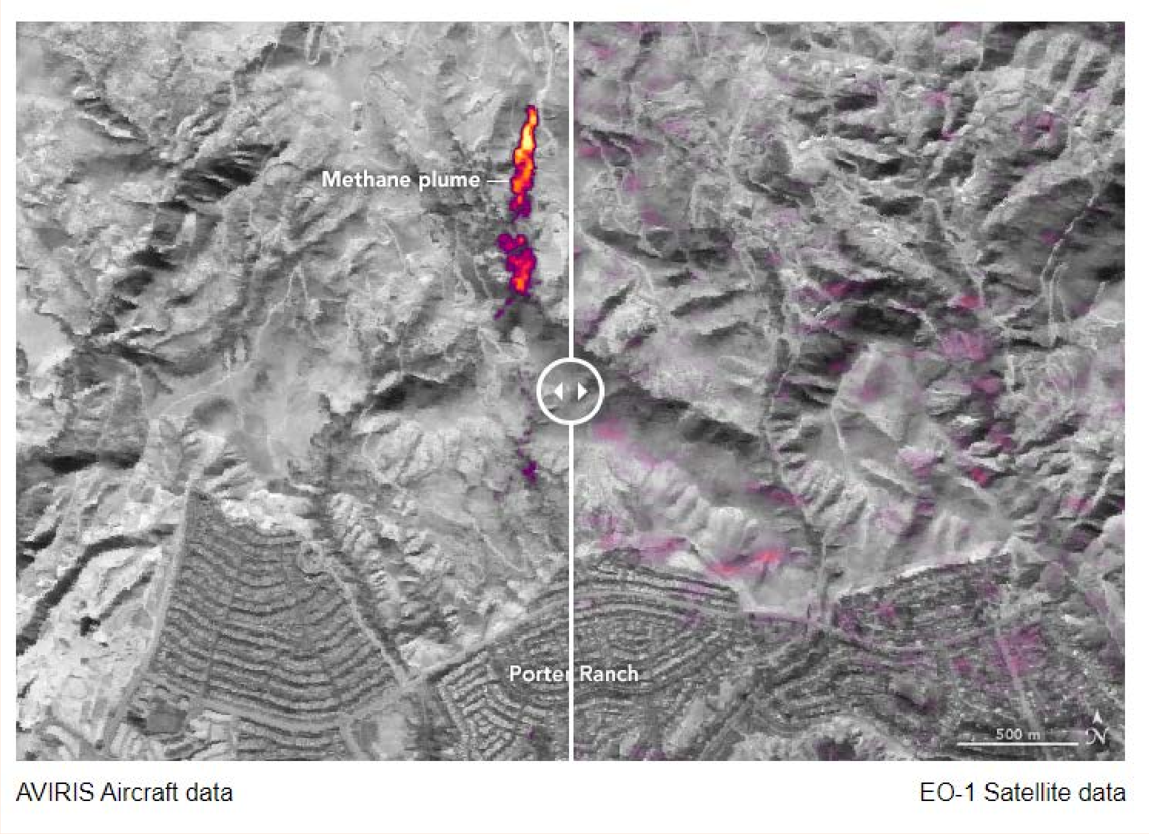

Figure 15.26 Methane leak from space as detected by Earth Observing-1 (EO-1) satellite. https://earthobservatory.nasa.gov/images/88245/imaging-a-methane-leak-from-space

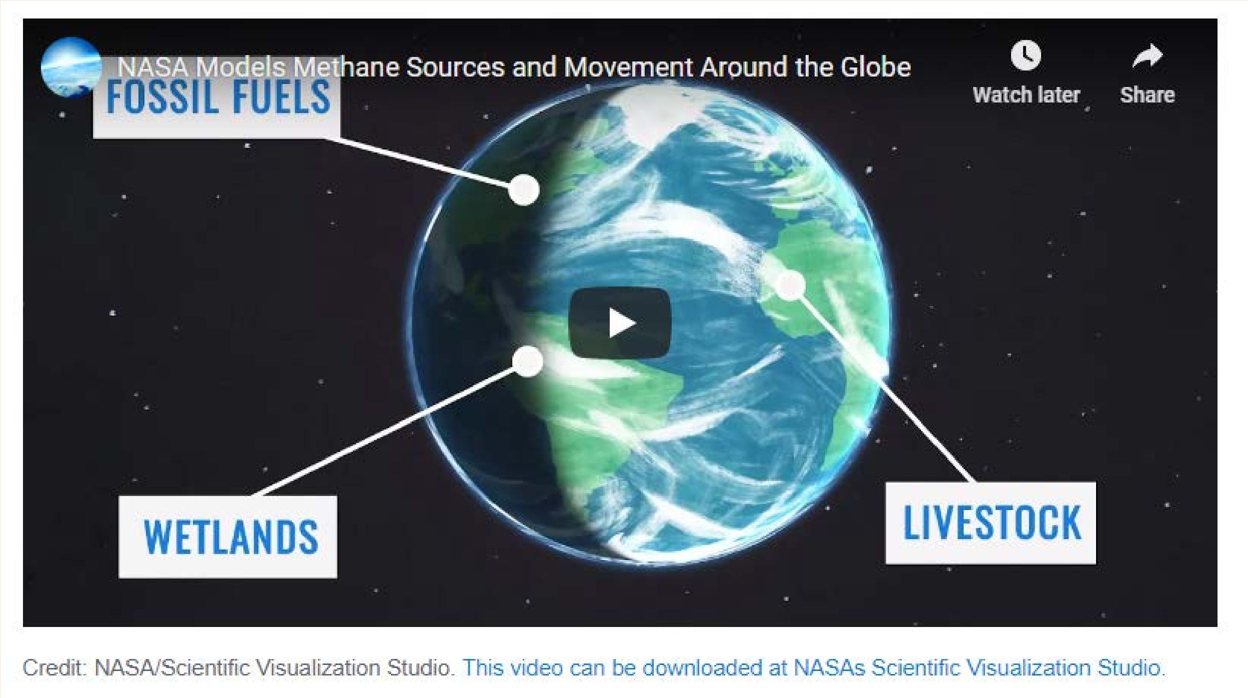

Figure 15.27 NASA Methane source model. https://climate.nasa.gov/news/2961/new-3d-view-of-methane-tracks-sources-and-movement-around-the-globe/

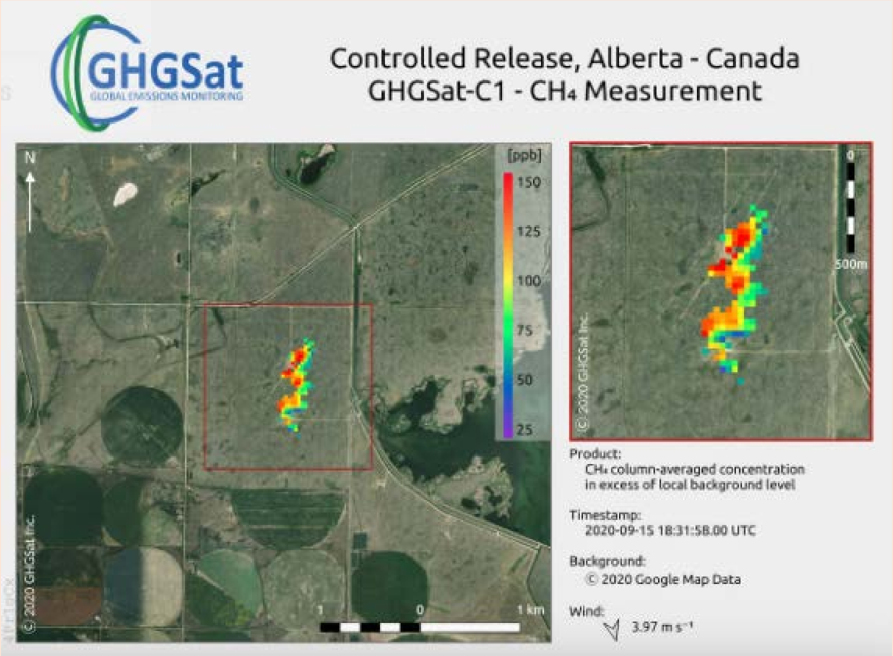

Figure 15.28 Global methane emissions monitoring.
https://www.ghgsat.com/

Satellite data, combined with land and ocean-based data, provide a very good quantitative statement of global greenhouse gas emissions. The ability to detect and monitor GHG emissions is steadily growing and so allowing greater ability to mitigate this cause of global warming and climate change.

15.9 Natural and anthropogenic radiative forcing

The importance of anthropogenic forces contributing to global warming as compared to natural forces is evident from the graph shown in Figure 15.29. Natural forcing or solar radiative forcing, is 0.05 Wm^{-2}. Total anthropogenic radiative forcing is 2.29 Wm^{-2}. most of which is due to GHGs.

There is considerable confidence in the ability to detect, measure and monitor GHG's globally and this is steadily improving.

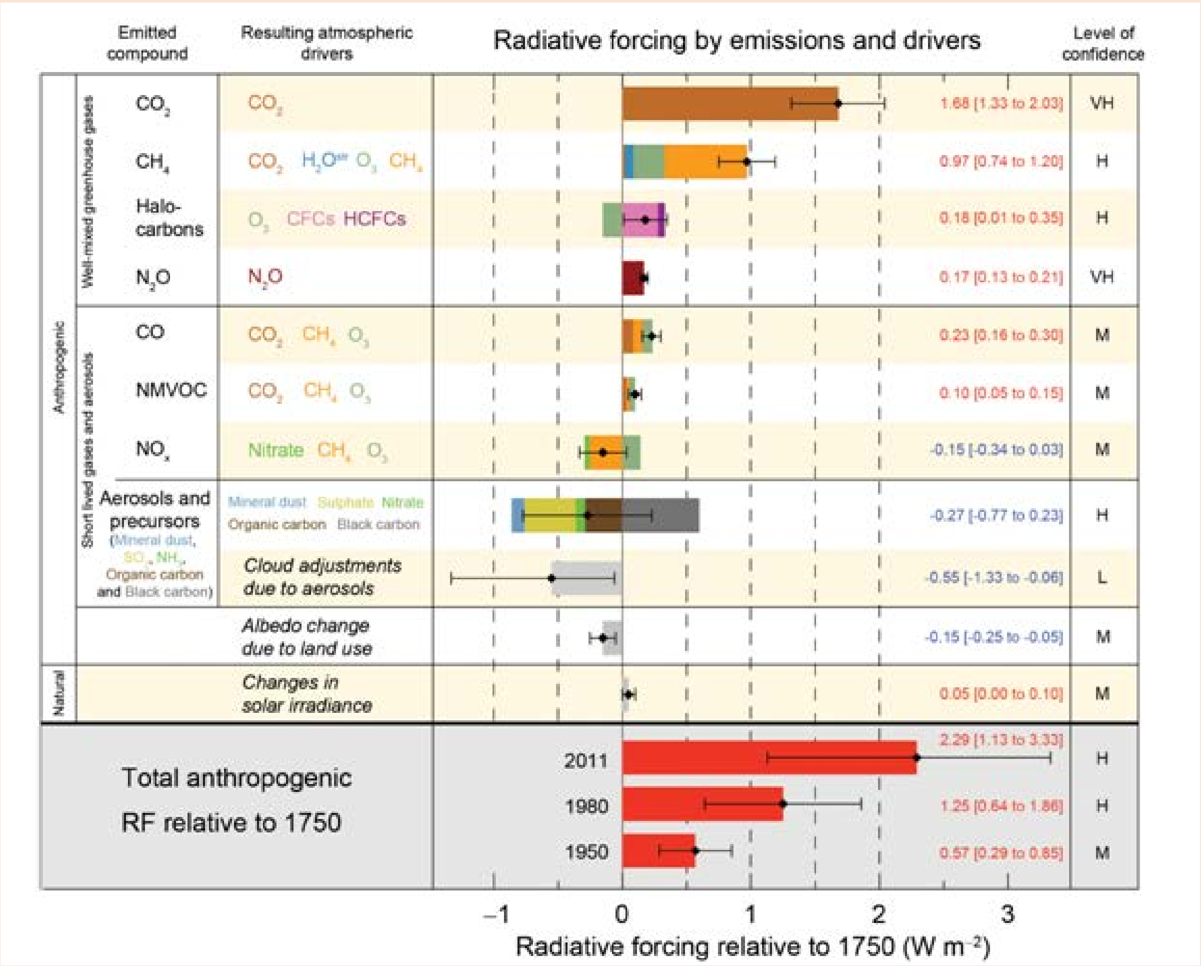

Figure 15.29 Global-average radiative forcing estimates and ranges – AR5.
https://www.ipcc.ch/site/assets/uploads/2018/02/WG1AR5_Chapter08_FINAL.pdf

15.10 Carbon footprint and auditing

A carbon footprint is the total greenhouse gas emissions caused by an individual, event, organization, service or product expressed as carbon dioxide equivalent, Wikipedia https://en.wikipedia.org/wiki/Carbon_footprint#:~:text=A%20carbon%20footprint%20is%20the,expressed%20as%20carbon%20dioxide%20equivalent and the University of Michigan Center for Sustainable Systems, http://css.umich.edu/factsheets/carbon-footprint-factsheet.

The carbon footprint may be determined using a variety of software available on the internet. Of course, these are estimates but some are about as good as anyone needs. Examples are:

1. Terrapass, https://www.terrapass.com/carbon-footprint-calculator?gclid=CjwKCAiAgJWABhArEiwAmNVTB1nzx5DFqZOnTKo9gTnWFUFWgbfSTpqYMUX_t4G-3TAHqw6IPBlM8BoC0gUQAvD_BwE#

2. The Nature Conservancy. https://www.nature.org/en-us/get-involved/how-to-help/carbon-footprint-calculator/

3. Carbon Footprint. https://www.carbonfootprint.com/

4. University of Michigan, Center for Sustainable Systems. http://css.umich.edu/factsheets/carbon-footprint-factsheet

5. United States EPA, Carbon footprint calculator. https://www3.epa.gov/carbon-footprint-calculator/

6. World Wildlife Fund. https://footprint.wwf.org.uk/#/

7. Science Direct. https://www.sciencedirect.com/topics/earth-and-planetary-sciences/carbon-footprint

The determination of a carbon footprint may be complex and a 'carbon audit' might be required. The process is governed by protocols such as PAS 2050 and the World Resources Institute, GHG Protocol Standard described in https://ghgprotocol.org/sites/default/files/standards_supporting/GHG%20Protocol%20PAS%202050%20Factsheet.pdf or https://ghgprotocol.org/ . The UN FAO publishes a guide as to how to assess carbon footprint of goods and services in http://www.fao.org/sustainable-food-value-chains/library/details/en/c/266040/. The ISO 14067:2018 is a standard with which the carbon footprint of products can be determined. It outlines the requirements and guidelines for quantification. https://www.iso.org/standard/71206.html. Training courses are provided by organizations certified to provide the courses for individuals and organizations so that their assessments are accepted.

This is usually provided by companies accredited to provide the PAS and ISO assessments. One organization that provides this service and a variety of certifications is Carbon Trust, https://www.carbontrust.com/what-we-do/assurance-and-certification/product-carbon-footprint-label?kw=%20carbon-%20footprint-%20audit-Broad.

These certifications are very important for reporting requirements and for the insight they provide to design and management of production and other operations. They are also important because they determine whether a product or organizations is meeting its allowable GHG emissions (nationally or provincially established); and, perhaps the carbon offsets they may be able to contribute (valued asset) or need to acquire (expense). These issues are further discussed in The Guide to Mitigation of Climate Change soon to be published in www.manzwaterinfo.ca.

15.11 Emission intensity or carbon intensity

Emission intensity or carbon intensity, (CI) are synonymous. It is the emission rate of as given pollutant relative to the intensity of a specific activity, or an industrial production process, https://en.wikipedia.org/wiki/Emission_intensity .

Another common usage of emission intensity is the ratio of greenhouse gas emissions produced to gross domestic product. It is a measure of a country's economic dependence on greenhouse gas producing activity (fuel for example). If a country transitions to the use of renewable energy while maintaining or increasing its GDP, this ratio would decrease.

Other measures could be the amount of greenhouse gas emissions produced per number of products produced, number of animals raised to harvest, resulting from production of a unity of electricity, distance traveled, etc.

The Government of British Columbia, Canada uses the term carbon intensity as follows; 'Carbon intensity is the measure of greenhouse gas (GHG) emissions associated with producing and consuming a transportation fuel, measured in grams of carbon dioxide equivalent per megajoule of energy (g CO_2-eq /MJ). Carbon intensity accounts for the GHG emissions associated with extracting, producing, transporting, and consuming a unit of energy of transportation fuel. It is a measure of the GHG emissions from the complete life cycle assessment (LCA) of a fuel.' https://www2.gov.bc.ca/assets/gov/farming-natural-resources-and-industry/electricity-alternative-energy/transportation/renewable-low-carbon-fuels/rlcf006_-_carbon_intensity_records.pdf . This is also known as the 'wells-to-wheels' carbon intensity. This definition of carbon intensity is also known as 'thermal intensity' – the specifics of what is considered must be clearly understood. This is similar to the protocol recently introduced by the Government of Canada named the 'Clean Fuel Standard'.

Whole life cycle assessments (LCA) include emissions resulting from the entire production of a given product including the machinery used to produce product, materials used in product, energy consumed during manufacturing, and energy consumed in marketing.

15.12 Carbon neutral, decarbonizing, net zero, carbon efficiency

There are a number of terms used to describe the various states of 'carbon' use by various entities including countries, companies, organizations, products, services, events or people. In this sense carbon means carbon equivalent unless explicitly defined differently.

1. Carbon neutral, (climate neutral) results when the reduction in carbon emissions equals carbon emission production. Net zero means the same as carbon neutral.
2. Decarbonizing is the process of reducing carbon emissions in a particular activity. For example, replacing energy sources from fossil fuels with energy from renewable sources such as wind or hydro. Carbon reduction potential is the maximum amount of decarbonizing possible.
3. Carbon efficiency or energy efficiency, has several definitions including carbon or emission intensity. Another is the amount of carbon emissions resulting from manufacturing a product or providing a service (relative term), again similar to intensity.

There are number of other terms that are derivatives of the above definitions such as carbon performance and carbon budget, https://www.wri.org/blog/2015/12/cop21-glossary-terms-guiding-long-term-emissions-reduction-goal .

15.13 Carbon management

Carbon management refers to the actions available to governments to limit the production of carbon emissions, that is, greenhouse gas emissions. There are several ways to regulate carbon emissions (reduce them) and several new descriptors have been introduced to describe how carbon emission management is accomplished. These concepts are important when linking mitigation strategies to the science.

15.13.1 Cap-and-trade (carbon allowance, carbon cap, carbon credits, carbon offsets, negative carbon emission)

The maximum net amount of carbon emissions that a particular industrial activity is allowed to produce is established by a regulatory body (government). This is called the carbon allowance, carbon credit or cap. Penalties are assessed if the cap is exceeded. If an entity is not using all of its allowance it can bank them for use later or sell the excess to another entity which wants to increase their allowance (selling their carbon credits). (See the following web sites for more

complete description of a carbon credits;
https://www.investopedia.com/terms/c/carbon_credit.asp and
https://en.wikipedia.org/wiki/Carbon_credit.)

If the entity in need of a higher allowance is unable to purchase additional allowance it might purchase a carbon offset to stay within its allowance. Carbon offsets, also called offset credits, are the amount of reduction in carbon emissions that result from an activity somewhere else which removes carbon from the atmosphere. It is a kind of negative carbon emission. The purchase of a carbon offset has the effect of increasing the purchaser's cap or cancelling some of their carbon emissions. (Tree planting is good example of an activity that produces negative carbon emission or marketable carbon offsets.) Carbon offsets are a type of carbon credit.

The David Suzuki Foundation and the Pembina Institute published a guide for purchasing carbon offsets for Canadian consumers, businesses and organizations, https://davidsuzuki.org/wp-content/uploads/2019/10/purchasing-carbon-offsets-guide-for-canadians.pdf. See https://en.wikipedia.org/wiki/Carbon_offset for full description as to what carbon offsets are, types of projects, accounting and verifying reductions, quality assurance, markets and controversies. Also see https://native.eco/2017/12/carbon-offset-vs-carbon-credit/ , and https://www.edf.org/climate/how-cap-and-trade-works .

Emissions trading (carbon market) is the name given to the activity of selling and purchasing carbon offsets and allowances.

15.13.2 Carbon tax

A carbon tax is a fee imposed on any company (particularly the energy, cement and other heavy industry and transportation sectors) that burns fossil fuels and produces carbon emissions. It is based on how much carbon dioxide (or equivalent) they emit.
https://www.thebalance.com/carbon-tax-definition-how-it-works-4158043,
https://www.carbontax.org/whats-a-carbon-tax/#:~:text=A%20carbon%20tax%20is%20a,destabilizing%20and%20destroying%20our%20climate. The incentive is to consume less fossil fuel or use fossil fuels that produce less carbon dioxide emissions and so pay less tax.

15.13.3 Carbon dividend

A carbon dividend is the distribution of the revenue of the carbon tax over the entire population (equally, on a per-person basis) as a monthly income or regular payment. This is illustrated in

Figure 15.30. In this way a carbon tax is said to be revenue neutral.

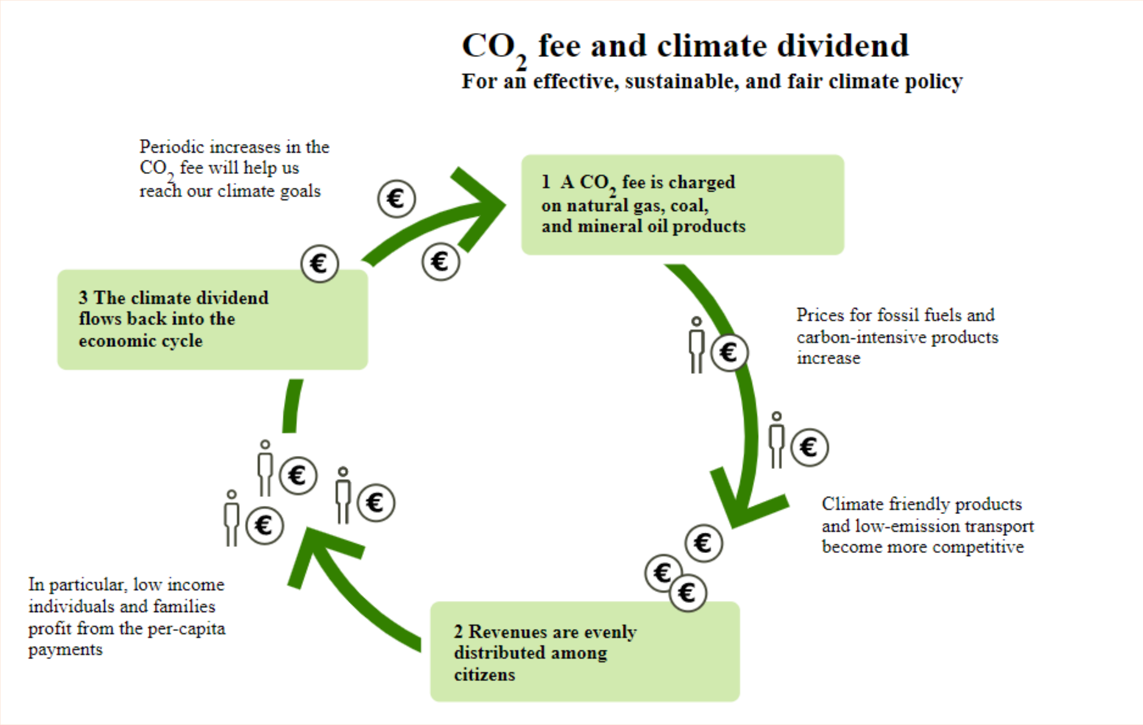

Figure 15.30 Collection of carbon tax and distribution of dividend to population. https://en.wikipedia.org/wiki/Carbon_fee_and_dividend

15.13.4 Carbon leakage

Carbon leakage refers to the situation that may occur if, for reason of costs related to climate policies, businesses were to transfer production to other countries with laxer emission constraints and bring their products back into the national economy. This type of activity could actually lead to an increase in their total emissions.

15.13.5 Carbon tariff

Other names for carbon tariff are; carbon levy, carbon border adjustment, border carbon adjustment, carbon border tariff, embodied carbon tariff, carbon border tax and green border levy.

Carbon tariffs levy a charge on goods crossing the border. While ordinary tariffs are based on the value of a good, carbon tariffs are based on the amount of greenhouse gases emitted during the production of a good; that is, the amount of carbon emissions embedded in the production of the goods. For example, the charge for a tonne of cement would be based on the amount carbon dioxide emitted during its production. The more carbon emissions that tonne of cement has caused, the higher the charge.

The purpose is to strengthen domestic carbon pricing and counter the problem of carbon leakage.

It has the effect of countries extending the reach of their domestic carbon regulations; and, it may adversely affect exports from developing countries.

A carbon tariff can also have the effect of increasing the cost of production for goods that require elements that are imported.

15.13.6 Carbon pricing

The World Bank, https://www.worldbank.org/en/programs/pricing-carbon, describes carbon pricing as follows: 'Carbon pricing attempts to capture what are known as the external costs of carbon emissions – costs that the public pays for in other ways, such as damage to crops and health care costs from heat waves and droughts or to property from flooding and sea level rise – and tie them to their sources through the price of carbon.' This is also known as the 'social price of carbon'.

A price on carbon helps shift the burden for the damage back to those who are responsible for it, and who can reduce it. Instead of dictating who should reduce emissions where and how, a carbon price gives an economic signal and polluter decide for themselves whether to discontinue their polluting activity, reduce emissions, or continue polluting and pay for it. In this way, the overall environmental goal is achieved in the most flexible and least-cost way to society. The carbon price also stimulates clean technology and market innovation, fueling new, low-carbon driver of economic growth.

Carbon (carbon dioxide emissions) pricing is a key element in cap-and-trade systems where the price the carbon is determined by the market (carbon cap and carbon offset trading) and of carbon tax and dividend initiatives.

15.13.7 Avoided emissions

Avoided emissions are emission reductions that occur outside of a product's life cycle or value chain, but as a result of the use of that product. This is explained very well on the Mission Innovation website, http://mission-innovation.net/1-5-degree-compatibility-framework/ as follows:

The 1.5 C Compatibility Initiative is aligned with Mission Innovation's Delivering the Action Plan 2018-2020 and aims to support efforts to limit the global temperature increase to 1.5 degrees Celsius, as per the Paris Agreement and the IPCC 1.5 C special report. This includes the development of an avoided emissions framework that provides guidance for how to quantify the potential for clean energy innovations to reduce emissions in society.

It supports investors and funders to identify those system solutions and technologies that have significant ability or potential to contribute to reduced greenhouse gas (GHG) emissions in society, so called “avoided emissions”.

To accelerate emission reductions, companies cannot only be driven by cost and risk reductions, but must also use their capacity for innovation to deliver the solutions that we need. Hence, solutions providers need the tools and credibility to be able to demonstrate their positive impacts in society. The framework is developing, implementing and launching an initial set of tools to achieve this aim.

The framework is supporting an accelerated uptake of disruptive solutions by supporting increased transparency regarding actual and potential GHG reductions, making it easier to identify, support and invest in the next generation of solution providers.

For example, Company A manufactures a product to perform a certain function. Other products on the market use much more energy to perform the same function. Company A can claim the energy savings resulting from the use of their product in the form of avoided emissions.

The World Resources Institute, the International Energy Agency and the International Renewable Energy Agency provide additional information as how avoided emissions are determined. See https://ghgprotocol.org/estimating-and-reporting-avoided-emissions, https://www.iea.org/data-and-statistics/charts/change-in-global-energy-related-co2-emissions-and-avoided-emissions-2018-compared-to-2019-3 and https://www.irena.org/.

The International Renewable Energy Agency also provides a method for calculating avoided emissions, https://www.irena.org/climatechange/Avoided-Emissions-Calculator

Avoided emissions should not be confused with carbon offsets though they can be used in a similar way.

15.13.8 Renewable energy certificates

Investopedia (https://www.investopedia.com/terms/r/rec.asp) describes a renewable energy certificate or REC as follows:

Renewable Energy Certificates (RECs) are a market-based instrument that certifies the bearer owns one megawatt-hour (MWh) of electricity generated from a renewable energy resource. Once the power provider has fed the energy into the grid, the REC received can then be sold on the open market as an energy commodity. RECs earned may be sold, for example, to other entities that are polluting as a carbon credit to offset their emissions.

RECs can go by other names, including Green Tags, Tradable Renewable Certificates (TRCs), Renewable Electricity Certificates, or Renewable Energy Credits.

An REC is a tradable market-based instrument that represents the property rights to the environmental, social and other non-power attributes of renewable electricity generation. RECs are issued when one megawatt-hour of electricity is generated and delivered to the electricity grid from a renewable energy resource. RECs can be sold separately from the physical electricity that it is associated with.

RECs are certified and tracked by a third party such as the Canadian EcoLogo in https://callmepower.ca/en/faq/ecolabel .

A good description of an REC is provided by Call Me Power on their web site, https://callmepower.ca/en/faq/renewable-energy-certificates-rec.

Utilities Consumer Advocate explains how they are used in Alberta, Canada on their web site, https://ucahelps.alberta.ca/Green_Energy_Plans_Explained.aspx

15.14 Information support

Key web sites:

1. Charles David Keeling. https://en.wikipedia.org/wiki/Charles_David_Keeling

2. Overview of greenhouse gases. https://www.epa.gov/ghgemissions/overview-greenhouse-gases

3. Greenhouse gases, Wikipedia. https://en.wikipedia.org/wiki/Greenhouse_gas#Atmospheric_lifetime

4. Main greenhouse gases, Center for climate and energy solutions. https://www.c2es.org/content/main-greenhouse-gases/

5. Greenhouse Gas Emissions. https://www.epa.gov/ghgemissions/us-greenhouse-gas-inventory-report-1990-2014

6. Changes in atmospheric constituents and in radiative forcing. https://www.ipcc.ch/site/assets/uploads/2018/02/ar4-wg1-chapter2-1.pdf

7. History of the Keeling curve. https://sioweb.ucsd.edu/programs/keelingcurve/2013/04/03/the-history-of-the-keeling-curve/#:~:text=The%20Keeling%20Curve%20is%20a,until%20his%20death%20in%202005

8. Trends in atmospheric carbon dioxide. https://www.esrl.noaa.gov/gmd/ccgg/trends/

9. Atmospheric concentrations. https://ourworldindata.org/atmospheric-concentrations

10. NASA scientists react to 400 ppm carbon milestone. https://climate.nasa.gov/400ppmquotes/

11. Climate change indicators: atmospheric concentrations of greenhouse gases. https://www.epa.gov/climate-indicators/climate-change-indicators-atmospheric-concentrations-greenhouse-gases#:~:text=Carbon%20dioxide%20concentrations%20have%20increased,is%20due%20to%20human%20activities.

12. Global monitoring laboratory. https://www.esrl.noaa.gov/gmd/dv/iadv/index.php?code=mlo

13. Geostationary carbon cycle observatory (EVM-2) (GeoCarb). https://eospso.nasa.gov/missions/geostationary-carbon-cycle-observatory-evm-2

14. Global atmospheric carbon dioxide. https://www.nasa.gov/jpl/oco2/pia18934

15. Orbiting carbon observatory 2. https://www.nasa.gov/mission_pages/oco2/index.html

16. Greenhouse gases observing satellite. https://en.wikipedia.org/wiki/Greenhouse_Gases_Observing_Satellite

17. New 3D view of methane, tracks sources and movement around the globe. https://climate.nasa.gov/news/2961/new-3d-view-of-methane-tracks-sources-and-movement-around-the-globe/

18. GHGSAT global emissions monitoring. https://www.ghgsat.com/

19. NASA-led study solves a methane puzzle. https://climate.nasa.gov/news/2668/nasa-led-study-solves-a-methane-puzzle/

20. NASA monitors carbon monoxide from California wildfires. https://climate.nasa.gov/news/3019/nasa-monitors-carbon-monoxide-from-california-wildfires/

21. Methane leak from space. https://earthobservatory.nasa.gov/images/88245/imaging-a-methane-leak-from-space

22. Global precipitation measurement mission. https://www.nasa.gov/mission_pages/GPM/overview/index.html

23. Carbon dioxide emissions by fuel type, U.S. Energy Information Administration. https://www.eia.gov/environment/emissions/co2_vol_mass.php and https://www.eia.gov/tools/faqs/faq.php?id=73&t=11

24. Energy conversion calculator, USIA. https://www.eia.gov/energyexplained/units-and-calculators/energy-conversion-calculators.php and https://www.eia.gov/energyexplained/units-and-calculators/

25. Cement, emissions from production, Carbon Brief. https://www.carbonbrief.org/qa-why-cement-emissions-matter-for-climate-change

26. Cement, emissions from production, Wikipedia. https://en.wikipedia.org/wiki/Environmental_impact_of_concrete

27. Electricity production fossil fuels. https://www.nrdc.org/stories/fossil-fuels-dirty-facts and https://en.wikipedia.org/wiki/Fossil_fuel_power_station

28. Heat rate, Wikipedia. https://en.wikipedia.org/wiki/Heat_rate_(efficiency)

29. Methane emissions, IEA. https://www.iea.org/reports/methane-tracker-2021?utm_campaign=IEA%20newsletters&utm_source=SendGrid&utm_medium=Email

30. Methane, oil and gas wells, abandoned or orphaned prior to decommissioning. https://www.canadianenergycentre.ca/understanding-inactive-and-orphan-wells-in-alberta/

31. Methane emissions, Wikipedia. https://en.wikipedia.org/wiki/Methane_emissions#Natural

32. Trawling, impact on release of greenhouse gases and biodiversity, https://www.nature.com/articles/s41586-021-03371-z, https://www.sciencedaily.com/releases/2021/03/210317141645.htm, https://www.bluemarinefoundation.com/2021/03/18/trawling-discovered-to-have-massive-climate-change-impact/ and https://www.theguardian.com/environment/2021/mar/17/trawling-for-fish-releases-as-much-carbon-as-air-travel-report-finds-climate-crisis

33. Peatlands and climate change, International Union for Conservation of Nature. https://www.iucn.org/resources/issues-briefs/peatlands-and-climate-change

34. Climate watch. http://cait.wri.org/

35. Global emissions. https://www.c2es.org/content/international-emissions/#:~:text=Globally%2C%20the%20primary%20sources%20of,72%20percent%20of%20all%20emissions.

36. IPCC Task Force on National Greenhouse Gas Inventories. https://www.ipcc-nggip.iges.or.jp/index.html

37. IPCC guidelines for national greenhouse gas inventories 2006. https://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/0_Overview/V0_1_Overview.pdf

38. 2019 refinement to 2006 guidelines. https://www.ipcc.ch/site/assets/uploads/2019/12/03COP25_2019-Refinement.pdf

39. See page 123. https://www.ipcc.ch/site/assets/uploads/2018/02/ipcc_wg3_ar5_chapter1.pdf

40. Calculation of radiative forcing, Etminan, M., Myhre, G., Highwood, E. J. and Shrine, K. P. 2016. https://agupubs.onlinelibrary.wiley.com/doi/full/10.1002/2016GL071930

41. Carbon dioxide equivalent. https://ec.europa.eu/eurostat/statistics-explained/index.php/Glossary:Carbon_dioxide_equivalent

42. Global warming potential. https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Glossary:Global-warming_potential_(GWP)

43. Anthropogenic and natural radiative forcing. https://www.ipcc.ch/site/assets/uploads/2018/02/WG1AR5_Chapter08_FINAL.pdf

44. Greenhouse Gas Protocol, World Resources Institute. https://ghgprotocol.org/

45. Carbon footprint. https://en.wikipedia.org/wiki/Carbon_footprint#:~:text=A%20carbon%20footprint%20is%20the,expressed%20as%20carbon%20dioxide%20equivalent.

46. Carbon footprint calculator, Terrapass. https://www.terrapass.com/carbon-footprint-calculator?gclid=CjwKCAiAgJWABhArEiwAmNVTB1nzx5DFqZOnTKo9gTnWFUFWgbfSTpqYMUX_t4G-3TAHqw6IPBlM8BoC0gUQAvD_BwE#

47. Carbon footprint calculator, The Nature Conservancy. https://www.nature.org/en-us/get-involved/how-to-help/carbon-footprint-calculator/

48. Carbon footprint, University of Michigan Center for Sustainable Systems. http://css.umich.edu/factsheets/carbon-footprint-factsheet

49. Carbon footprint calculator, USEPA. https://www3.epa.gov/carbon-footprint-calculator/

50. Environmental Footprint, World Wildlife Fund. https://footprint.wwf.org.uk/#/

51. Carbon Footprint, Science Direct. https://www.sciencedirect.com/topics/earth-and-planetary-sciences/carbon-footprint

52. Guide to PAS 2050, UNFAO. http://www.fao.org/sustainable-food-value-chains/library/details/en/c/266040/

53. ISO 14067:2018. https://www.iso.org/standard/71206.html

54. Company which provides carbon footprint certifications, Carbon Trust. https://www.carbontrust.com/what-we-do/assurance-and-certification/product-carbon-footprint-label?kw=%20carbon-%20footprint-%20audit-Broad

55. Emission intensity, Wikipedia. https://en.wikipedia.org/wiki/Emission_intensity

56. Carbon intensity for fuel, Government of British Columbia, Canada. https://www2.gov.bc.ca/assets/gov/farming-natural-resources-and-industry/electricity-alternative-energy/transportation/renewable-low-carbon-fuels/rlcf006_-_carbon_intensity_records.pdf

57. Cap and trade, Environmental Defense Fund. https://www.edf.org/climate/how-cap-and-trade-works

58. Carbon credit, Investopedia. https://www.investopedia.com/terms/c/carbon_credit.asp

59. Carbon credit, Wikipedia. https://en.wikipedia.org/wiki/Carbon_credit

60. Carbon offset. https://en.wikipedia.org/wiki/Carbon_neutrality

61. Carbon offsets and carbon allowances. https://native.eco/2017/12/carbon-offset-vs-carbon-credit/

62. Carbon offsets, Wikipedia. https://en.wikipedia.org/wiki/Carbon_offset

63. Pembina Institute. https://www.pembina.org/

64. Purchasing carbon offsets, Canada, David Suzuki Foundation and the Pembina Institute, https://davidsuzuki.org/wp-content/uploads/2019/10/purchasing-carbon-offsets-guide-for-canadians.pdf

65. Carbon tax Carbon Tax Center. https://www.carbontax.org/whats-a-carbon-tax/#:~:text=A%20carbon%20tax%20is%20a,destabilizing%20and%20destroying%20our%20climate.

66. Carbon tax, The Balance. https://www.thebalance.com/carbon-tax-definition-how-it-works-4158043

67. Carbon leakage, European Union. https://ec.europa.eu/clima/policies/ets/allowances/leakage_en#:~:text=Carbon%20leakage%20refers%20to%20the,increase%20in%20their%20total%20emissions.

68. Carbon tariff. AXA. https://www.axa-research.org/en/project/marco-springmann

69. Carbon dividend, Wikipedia. https://en.wikipedia.org/wiki/Carbon_fee_and_dividend

70. Carbon pricing, World Bank. https://www.worldbank.org/en/programs/pricing-carbon

71. Carbon pricing, S & P. https://www.spglobal.com/en/research-insights/articles/what-is-carbon-pricing

72. Carbon terminology, IPCC. https://www.wri.org/blog/2015/12/cop21-glossary-terms-guiding-long-term-emissions-reduction-goal

73. Avoided emissions, Missions Innovation. http://mission-innovation.net/1-5-degree-compatibility-framework/, http://mission-innovation.net/1-5-degree-compatibility-framework/ and https://misolutionframework.net/

74. Avoided emissions, World Resources Institute. https://ghgprotocol.org/estimating-and-reporting-avoided-emissions

75. Avoided emissions, International Energy Agency. https://www.iea.org/data-and-statistics/charts/change-in-global-energy-related-co2-emissions-and-avoided-emissions-2018-compared-to-2019-3

76. Avoided emissions, International Renewable Energy Agency. https://www.irena.org/ and their avoided emissions calculator https://www.irena.org/climatechange/Avoided-Emissions-Calculator

77. Renewable energy certificates, Alberta Utilities Advocate. https://ucahelps.alberta.ca/Green_Energy_Plans_Explained.aspx

78. Renewable energy certificates, Call Me Power. https://callmepower.ca/en/faq/renewable-energy-certificates-rec and EcoLogo https://callmepower.ca/en/faq/ecolabel

79. Renewable energy certificates, Investopedia. https://www.investopedia.com/terms/r/rec.asp

Videos:

1. NASA atmospheric chemistry. https://www.youtube.com/watch?v=54ECqX2tq9k&feature=emb_rel_end

2. Our particulate atmosphere: aerosols and black carbon in a changing climate. https://www.youtube.com/watch?v=oadRn0BrzLU

3. Black carbon. https://www.youtube.com/watch?v=fNoBBObL5tM

4. Fresh water in the Arctic. https://www.youtube.com/watch?v=FxXaT7yO4TQ