Chapter 2

Greenhouse Gases

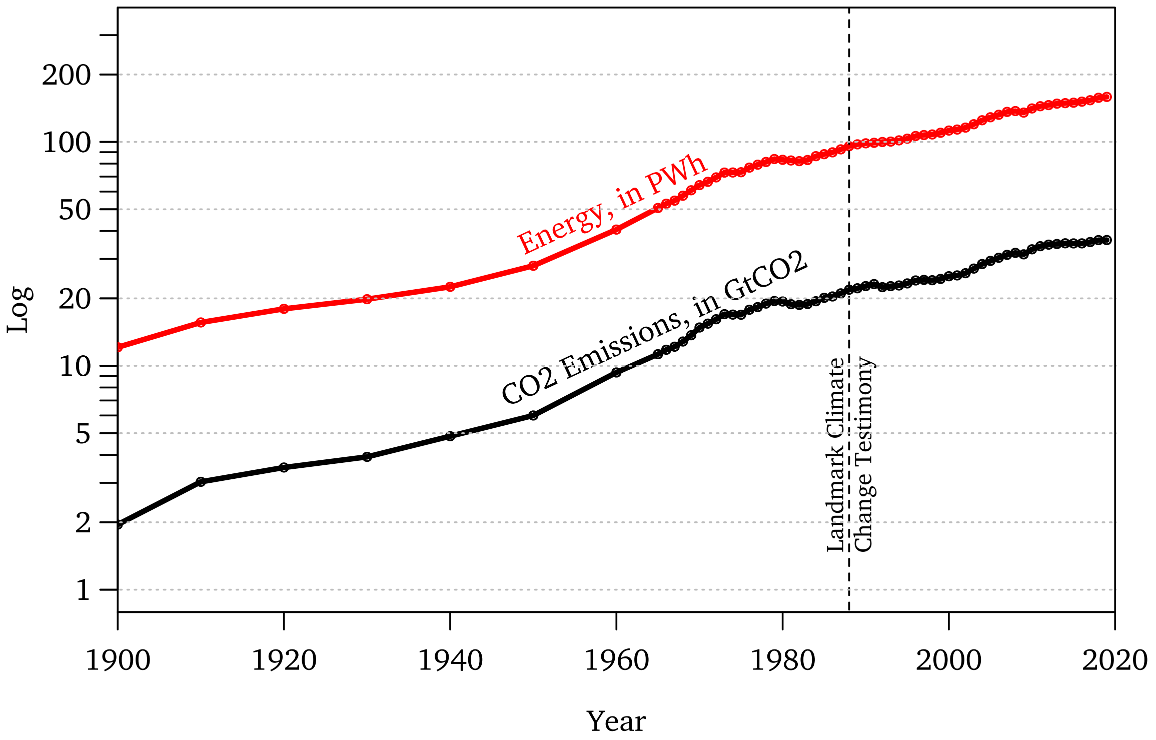
"THE NEXT DECADE OF INDECISION COULD BE DECISIVE"

The previous chapter showed that the combination of population growth and economic development have translated almost one-to-one into increased primary energy consumption. In turn, our near-total energy reliance on fossil fuels has translated human energy consumption nearly one-to-one into human carbon-dioxide (CO_2) emissions. Figure 2.1 shows the near-perfect association over the last century.

These close linkages have held not only in the global aggregate, but also within most individual regions and countries. Ultimately, wherever and whenever primary energy use has increased, so have GHG emissions. And most of the global growth in energy use in the last 50 years has come from China, typically in the form of coal. Therefore, most emissions growth has also come from China. But the situation has been much the same in other regions of the world, only on a smaller scale.

This chapter explains the effects of human emissions on the greenhouse gases lingering in the atmosphere. The scientific and popular concern about these effects are fairly recent. It was only in 1988 that global emissions entered the popular conscience in the context of climate change (through **landmark testimony** by NASA scientist **James Hansen** to Congress). Has this increased awareness made much of a difference in reducing CO_2 emissions? Probably not. Figure 2.1 shows that world CO_2 emissions grew just as (un-)healthily after 1988 as they did before.

Figure 2.1. Annual Primary Energy Use and Annual CO_2 Emissions



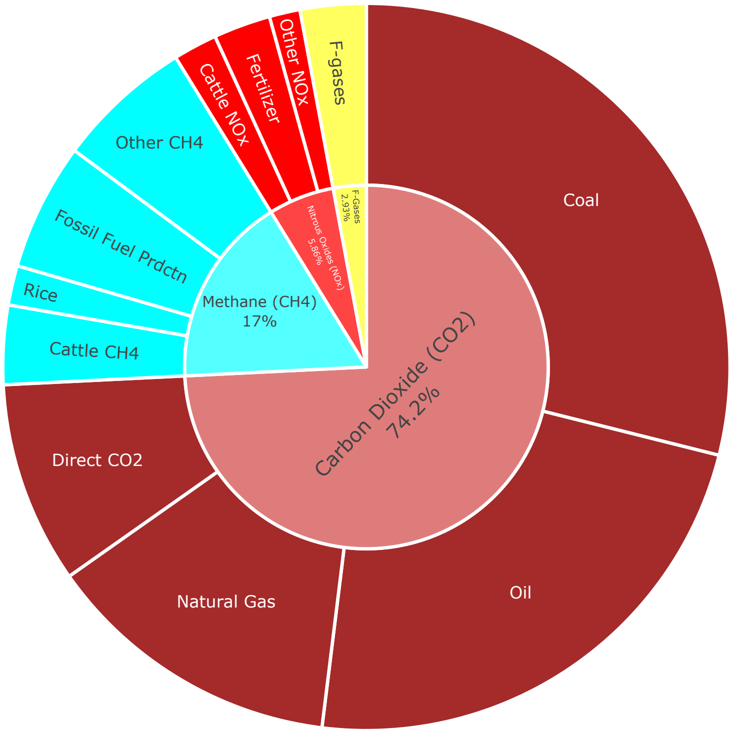
Source: **Our World in Energy [global primary energy]** and **Our World in Data [CO_2 emissions]**.

So what has the world *really* done? Pundits have been lamenting year after year that no meaningful progress has been made — and have then repeated the same script the following year. You may or may not agree with **Greta Thunberg**, but she does have one incontrovertible point: humanity has not done much so far to curb its emissions.

1 Measuring Human Emissions

The inner circle in Figure 2.2 shows the four greenhouse gases that scientists believe to be most troublesome. The most important one by far is CO_2. Methane is a distant second. The other two, nitrous oxide and F-gases, are even less important. Let's discuss each gas in turn.

Figure 2.2. Global Annual Greenhouse Gas (GHG) Emissions (ca 2020)



Source: See detailed explanation in Table 2.1.

Carbon Dioxide

Carbon-dioxide is a colorless, odorless, non-toxic gas. It is the most natural of all emissions. All animals create it when they breathe. And all plants need it to photosynthesize.

The problem is not that CO_2 is intrinsically bad, but that too much CO_2 is bad. From our perspective, just as it was for energy, it's not enough to understand that humanity has been emitting more CO_2. Instead, it's a numbers game. It's important to know *how much more* we have been emitting and *how much more* has accumulated in the atmosphere. Therefore, we first need to explain how to measure it.

One cubic yard of **anthracite coal** weighs about **1540 pounds or 0.70 metric tons**. When burned, the added oxygen transforms it into **2.57 metric tonnes** of CO_2. The "**metric tonne** of CO_2 (tCO_2)" is the principal unit of CO_2 emissions. When we want to put the scale of civilization's emissions into perspective — with billions of humans (consuming trillions of KWh of energy) — we have to measure global emissions in billions, too — specifically, in **Giga**-tonnes of CO_2 (**$GtCO_2$**).

As was the case with energy, you may be dismayed to learn that the experts also love confusing their readers about emissions. (It's almost as if they are having some devious fun at our expense.) The most important and painful ambiguity is their common, casual equating of carbon and carbon-dioxide: Many experts talk about "tonnes of carbon," when they really mean "tonnes of carbon-dioxide."[1] We will try to stick to tonnes of CO_2 only *and* spell it out, but you must be aware of this common ambiguity when you read other books or articles.

Remarkably, our human population has grown so large that even our breathing now matters to the planet! The average person exhales about 1 kg (2.3 pounds) of CO_2 per day. Multiplying that amount by 7.8 billion people by 365 days in a year implies that human metabolisms emit about 3 $GtCO_2$ per year. About 8% of humanity's emissions (of 38 $GtCO_2$) is just breathing. (Wow!) However, most of this is 'just' re-emitting carbon that already was in our **food**. To some extent, humans were responsible for removing this CO_2 from the atmosphere by growing plants and animals in the first place.

Table 2.1 (and Figure 2.2) show the main sources of our CO_2 emissions. (Un-)naturally, our global industrial activities and the burning of fossil fuels (ca 2021) emit a lot more CO_2 than breathing — about 35 $GtCO_2$.

If we want to hold humanity responsible for increased CO_2 in the atmosphere, we also have to take into account that humans have reduced green land. This depletion mainly has to do with forests, which previously removed and sequestered CO_2 from the atmosphere and stored it primarily in the form of wood. The current state of planetary deforestation accounts for a loss of "CO_2 scrubbing" equivalent to about 10-15% of all human CO_2 emissions — somewhere between 3-5 $GtCO_2$ per year.

Furthermore, civilization emits CO_2 not only by burning fossil fuels, but also through some agricultural and chemical processes (principally cement production) — roughly accounting for another 5 $GTCO_2$.

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[1] This is especially problematic when they discuss "carbon taxes" (which we will cover in Chapter 5). It makes a big difference whether they mean a tax of $50/tonne of carbon or $50/tonne of carbon-dioxide — a dollar difference of 3.67 times!

Table 2.1. Global Annual Greenhouse Gas (GHG) Emissions (ca 2020)

Carbon Dioxide (CO_2), 74.5%		38.0 GtCO_2
Coal, 39%	14.8 GtCO_2	
Oil, 31%	11.8 GtCO_2	
Gas, 18%	6.8 GtCO_2	
Not Fossil Fuel Combustion, 12%	4.6 GtCO_2	
Methane (CH4), 17.0%		8.7 GtCO_2e
Cattle, 21%	1.8 GtCO_2e	
Rice, 10%	0.9 GtCO_2e	
Fossil Fuel Production, 33%	2.9 GtCO_2e	
Nitrous Oxides (NOx), 8.5%		3.0 GtCO_2e
Cattle, 23%	1.0 GtCO_2e	
Fertilizer, 42%	1.3 GtCO_2e	
Other (fluorinated) Greenhouse Gases		1.5 GtCO_2e
All GHG Emissions, Gates (2021)		51 GtCO_2e
Plus Land Charge (GCP via NL), 3.8 GtCO_2e		55 GtCO_2e

Explanations: These numbers were patched together from multiple sources and years and extrapolated to 2018–2022. The primary source was **Olivier and Peters (2020), Netherlands EAA 2019 Report**. Reasonable variations are about 3%. We adopted **Gates' (2021)** overall GHG estimate of 51 GtCO_2e, and used CAIT/PIK/Olivier-Peters percentage estimates to extrapolate gas ingredients. The detailed subcategory estimates are also scaled from the EAA report and do not add to 100% for each category, because they omit some components.

Not shown, the same sources state that GHG emissions were about 34 GtCO_2e in 1990, compared to 51 GtCO_2e today, a growth rate of about 1.4% per annum.

There are also other greenhouse vapours that are not listed in this table. The most important GHG is water vapor (think humidity), responsible for about 70-90% of the greenhouse effect of our atmosphere. There are also soot and other less common substances. Global warming is the subject of the next chapter.

Other Greenhouse Gases

Table 2.1 also describes the effects of three other GHGs. The two more important ones are Methane (CH4) and Nitrous Oxides (NOx). **Methane** is essentially the odorless natural gas that runs most stoves and heating systems in the United States today. **Nitrous oxide** is also called laughing gas and was especially popular with dentists before there were good local anesthetics.

Methane and nitrous oxides are at least a thousand times rarer than CO_2 in the atmosphere, but they also have more potent warming effects. To make it easier to measure the entire sum of human greenhouse gases in terms of warming contribution, their emissions are often quoted in terms of CO_2 **e**quivalents (**CO_2e**). There is some subjectivity regarding how CH4 and NOx should be counted with respect to their lifetime planetary warming contributions, but the standard approximations are good enough for our needs.

Based on these standard equivalents, the most common estimates are that CO_2 is responsible for about 75% of global warming gases attributable to human activity, Methane for about 10%, and Nitrous oxides (NOx) for about 7%.

Summing up, direct human greenhouse gas emissions now run at about **50 GtCO_2e/year**. They increase to about **55 GtCO_2e/year** if we add the land charge — the reduction of green land. None of these estimates are perfect. Reasonable ranges would be plus or minus 5%.

Sources of Greenhouse Gases

Different activities produce different GHG pollution mixes. Burning coal produces relatively more nitrous oxides than burning natural gas. Agriculture produces relatively more methane than carbon-dioxide (mostly from cows and rice farming). Nevertheless, it is generally the case that where there is more CO_2, there are also more other GHGs.

More systematically, where do all these greenhouse gases come from? Table 2.2 breaks the sources into broad categories. Unsurprisingly, fossil-fuel combustion looms large, but agriculture and land use are important non-combustion sources of greenhouse gases, too.

When reading about climate change, we are often struck by how easy it is to misunderstand authors. For example, many articles discuss CO_2 emissions, but that misses one-quarter of all effective GHG emissions, and it is rarely entirely clear if the authors' figures include the land use charge. Fortunately, because CO_2 emissions are generally reasonably in line with GHG emissions (except for agriculture), and authors quote percentages, one can often mentally scale up the CO_2 picture. Countries and activities that emit more CO_2 typically emit more GHGs, too.

Table 2.2. Annual Emissions, ca 2018–2022

Power, Heat, Agriculture, All GHGs		51 GtCO$_2$e
Agriculture, 19% (of 51 GtCO$_2$e)	9.7 GtCO$_2$e	
Non-Ag Emissions, All GHGs		41 GtCO$_2$e
Combustion, CO$_2$ Only	33.4 GtCO$_2$	
Combustion, NOx Only	0.5 GtCO$_2$e	
Transport, 16% (of 51 GtCO$_2$e)	8.2 GtCO$_2$e	
Electricity, 27%	13.8 GtCO$_2$e	
Heating, 7%	3.6 GtCO$_2$e	
Industrial, 31%	15.8 GtCO$_2$e	
Potentially Reasonably Electrifiable Emissions		25–35 GtCO$_2$e
(Heating=3.6, less fossil-fuel extraction=5, some industrial=5, cars/trucks=5.5.)		
Difficult/Costlier To Electrify		15–25 GtCO$_2$e
(Some high industrial heat and cement=10, agriculture=10, ships/airplanes=1.6.)		

Explanations: The primary source was **Olivier and Peters (2020)** and **Gates (2021)**. Gates (2021) estimates are reasonably close. Both are based on similar sources. Our own guesses of potentially electrifiable emissions were a little less optimistic than Gates', but generally similar. (**WRI** reports that agricultural emissions are about 40% livestock, 25% fertilizer, 15% burning, and 10% rice cultivation.)

Table 2.2 hints at a more serious confusion. It arises when articles discuss total decarbonization but refer only to electricity. As we explained in Chapter 1, electric power generation accounts for less than one-third of human primary energy use today. Even zero carbon emissions in electric generation does not mean zero total emissions — far from it. In a few decades, electrification of ground transportation and heating could realistically increase the share of electric power to two-thirds and come closer. The final third will be much more difficult to decarbonize — agriculture, airplanes, ships, industrial heat, etc. — and perhaps never rely exclusively on electricity. But remain aware that zero emissions in electricity production is just half of what civilization needs to decarbonize.

And, of course, humanity is still on the move. With continued population growth and economic development, the demand for energy continues to increase. As we explained in the first chapter, humanity will use a lot more energy sooner rather than later, primarily in population-rich developing regions — whether we like it or not.

Other Fossil-Fuel Pollution

Fossil fuels emit not only greenhouse gases, but also other pollution that is more local. Most importantly, coal and oil emit tiny aerosol particles (such as **smog** and **soot**). The negative health effects of these local emissions more than justify drastically curbing fossil-fuel use regardless of their global consequences.

Without local pollution caused by fossil fuel emissions, the average life expectancy of the world's population could perhaps increase by **3 to 5 years**, and global economic and health costs could fall by more than **$3 trillion** (out of a world GDP of about $90 trillion). High estimates are that as many as **5 million** to **9 million** people die prematurely every year due to direct pollution caused by fossil-fuel combustion, not counting further climate-change-related effects (such as droughts and heat waves). Between one in five and one in ten deaths may be due to the same fossil-fuel processes that generate our energy and emit greenhouse gases.

To be fair, these numbers are rough estimates and other reasonable scientists might halve them. But they are not outlandish and there is no doubt: The local adverse health effects and health care costs of fossil fuels are severe.

Ironically, not all fossil-fuel pollutants are bad from a climate-change perspective. The burning of sulphur-laden coal produces tiny reflective aerosol **sulfur dioxide (SO_2)** particles in the lower atmosphere that enhance the planet's overall reflectivity (called **albedo**). A simple example of albedo, meaning literally "whiteness," is snow; it is white and thus absorbs little or no sunlight. SO_2 reflectivity has probably held down global temperature by about **0.6°C** (out of a total of 1.5°C).

2 Who Emits Greenhouse Gases?

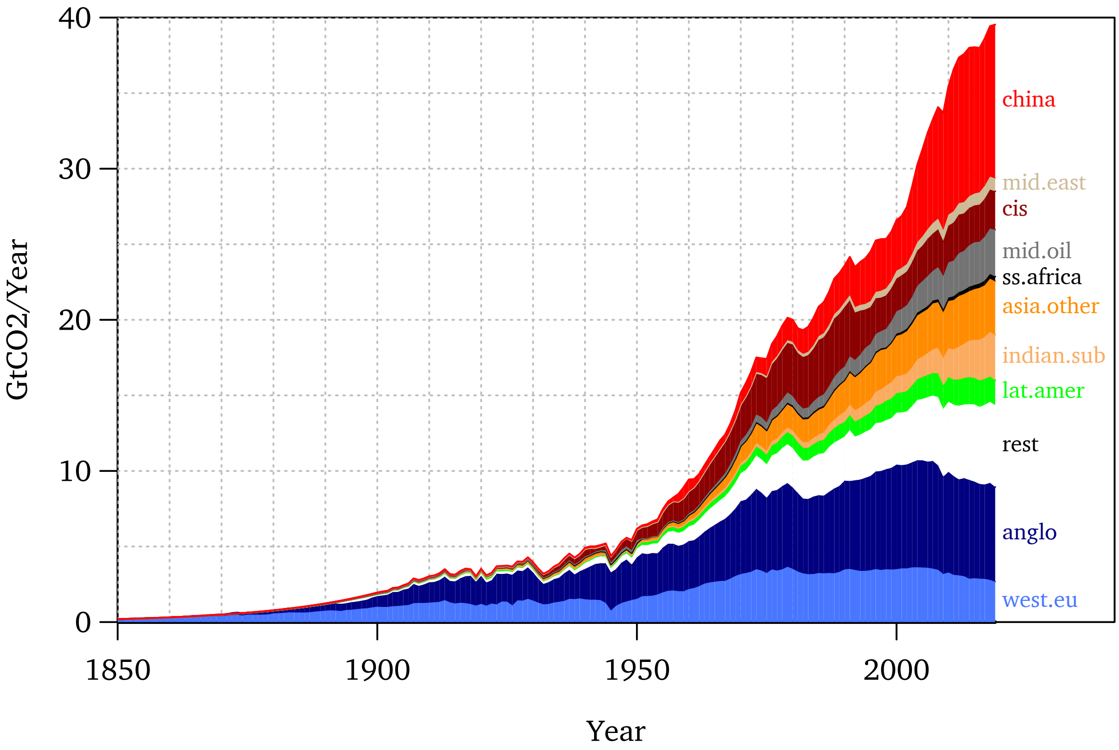
Looking across countries, regions and time, energy consumption has always meant more emissions. Thus, this section largely mirrors its equivalent section from Chapter 1. We are just going to briefly highlight it a little more.

Emissions by Country and Region

Figure 2.3 plots global CO_2 emissions by country/region over the decades. You can see how emissions have grown with population and economic development.

Before 1900, just as with energy use, emissions were negligible. Even by 1950, emissions were still running at the low rate of 6 $GtCO_2$ per year — only about twice what human respiration alone produces today. By 1988, our emissions had more than tripled to 22 $GtCO_2$ per year. Today, we emit the aforementioned 37 $GtCO_2$ per year, 51 $GtCO_2e$ including other greenhouse gases, and 55 $GtCO_2e$ if we add the land charge. This speedy *and ongoing accelerating* increase is outright frightening.

Figure 2.3. Annual CO_2 Emissions By Area/Country Over Centuries

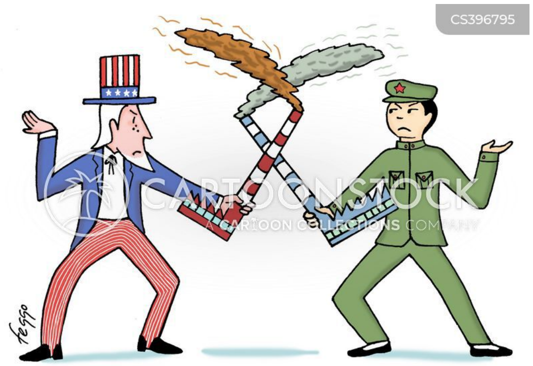


Explanations: Countries were grouped into regions, and ordered by emissions in 1850. See appendix for precise classification. In brief, “anglo” are the US, Canada, and Australia. The “rest” of the world contains many countries that are not easy to classify — such as South Africa, Israel, or Israel. The Middle East was split into oil-rich countries (such as Saudi Arabia) and others (such as Egypt or Jordan).

Source: **Our World in Data**. The figure does not include greenhouse gases other than CO_2 and the land charge, but it can be mentally scaled up proportionally.

In 1900, Europe was still the world leader in emissions. By World War I, the dubious-distinction baton had passed to North America, primarily the United States. By the turn of the millennium, it had passed again, this time to China and Asia.

Fortunately, many of the richer nations have now stabilized their emissions. Even the energy-prolific United States has followed this pattern. The **EPA** reports that U.S. GHG emissions have fallen by 10% since 2005, and power-sector emissions have fallen by 27% — even while the U.S. economy has grown by 25%. Some U.S. politicians have boasted that the United States was a world leader in protecting the environment, because it had, after all, reduced greenhouse gas emissions the most. Of course, this achievement was not too difficult, given that the United States was among the most polluting and least energy-efficient of the Western economies.



But it will not be enough for the richest countries alone to reduce their emissions. As of 2019, China, which is still only about halfway between rich and poor countries in per-capita income, now **emits more than all rich countries combined**. Trying to solve the global emissions problem without China would be futile. Fortunately, China appears to be relatively stable in its emissions now, despite the country's ongoing rapid economic growth. Its population growth has slowed, and its emissions efficiency is improving faster than its GDP growth. Unfortunately, China is also **building new coal plants at a record pace**, and its ambitious public climate-change promises are set to kick in mostly after 2050 — long after the promises will still be remembered.

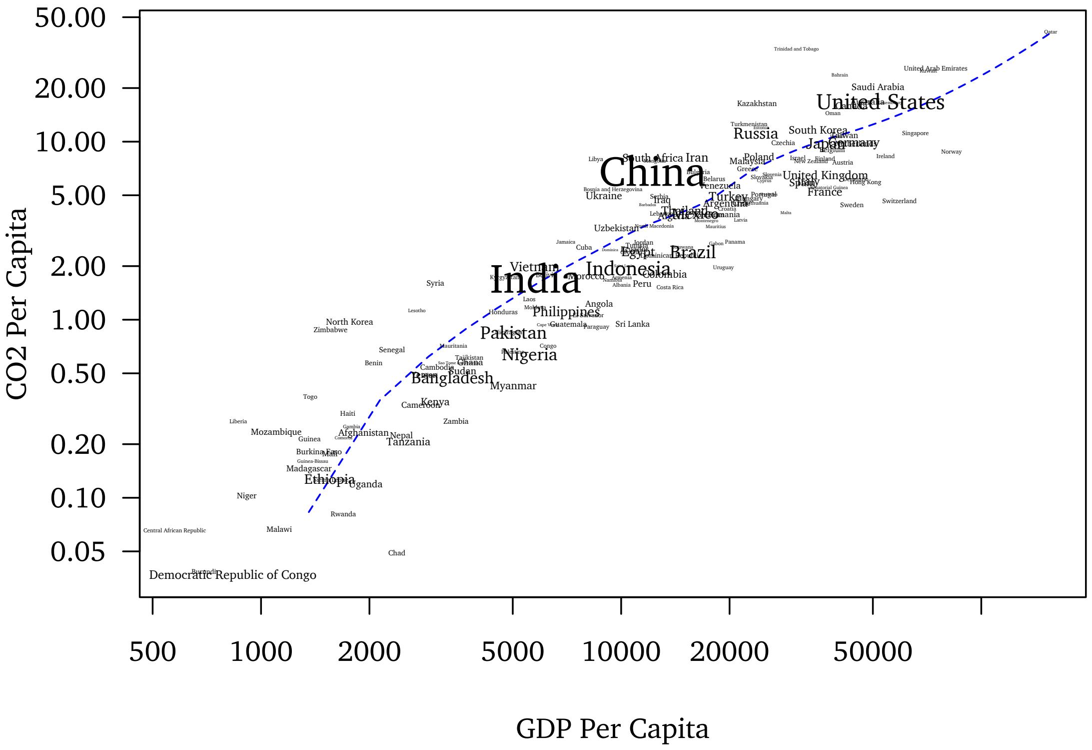
Similarly, as we explained in Chapter 1, the two elephants still hiding in the room now, without which the world cannot curb emissions, are India and Africa. Their energy consumption will continue to grow, though from a low base. This is unavoidable. Thus, to curb emissions, the world must disconnect its energy growth from its emissions growth. The only way this can happen is if developing countries will leapfrog over much of the fossil-fuel stage right into a clean-energy stage. And this will mostly depend on which technology will be cheaper for them to deploy on a large scale.

Emissions Per Capita

As with energy usage, adjusting emissions for population numbers produces a different picture. Figure 2.4 shows that the United States again looms large, with per-capita emissions of about 17 tCO_2 per person per year in 2016. This number was exceeded only by Middle-Eastern countries with cheaper access to fossil fuels. In per-capita terms, China still emitted only about one-third as much as the United States. India's emissions were much lower yet, only about 2 tCO_2 per person per year. The emissions of African countries remained minuscule.

Realistically, the United States will not be able to take a leadership role on global emission reductions until it substantially tackles its own emissions. The rest of the world sees U.S. efforts largely as hypocritical (and fickle). Perhaps the Europeans (with help from the Chinese) could lead, having more aggressively curtailed their own emissions, especially if they were willing to offer fewer appeals but more generous technological help to poorer nations. But poorer countries

Figure 2.4. CO_2 Per-Capita vs GDP, By Country in 2015

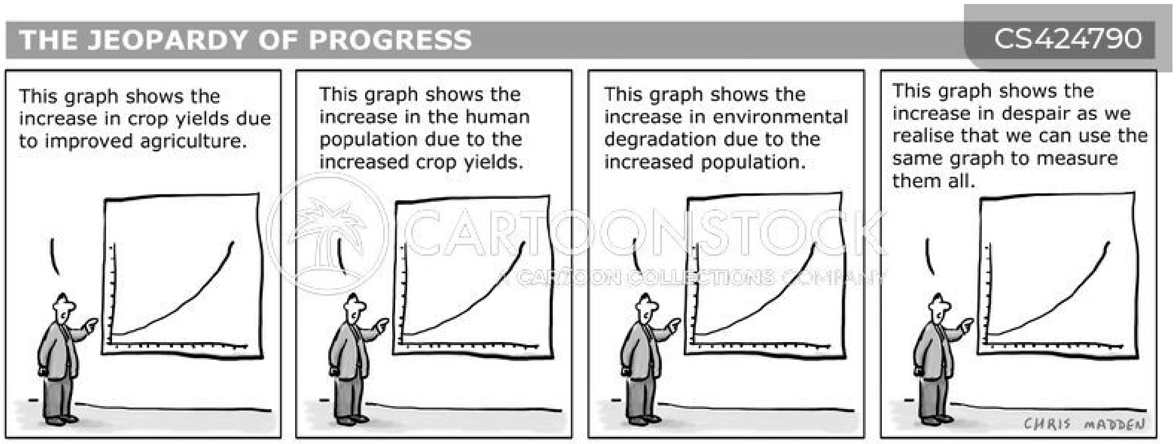


Explanations: The population size is indicated by the size of the text. The relation between GDP and CO_2 is roughly linear. Richer countries use more fossil fuels and thus emit more CO_2.

Source: **Our World in Data**. UPDATE TO 2019.

will always consider themselves not having emitted their "fair shares." They need to come to the conclusion that they will not want to emit.

We will spare you another plot with the trends in per-capita emissions by region. You can just look at the per-capita energy graph from the previous chapter (Figure 1.4) and mentally replace the y-axis label of "per-capita energy" with "per-capita emissions." It looks the same. North America's per-capita emissions are declining, but are still the highest; Europe is next, declining more rapidly; followed by a China with steeply rising per-capita emissions. India and Africa remain tiny.



Emissions Per Productivity

How efficient are different countries with respect to their emissions? Are they emitting pollution frugally or gratuitously? Pollution efficiency is usually measured by the ratio of real GDP to the level of CO_2 emissions. Table 2.3 provides a snapshot of the data. Higher ratios mean more efficiency for the pollution imposed on the world.

Table 2.3. Emissions Efficiency of GDP per kg of CO_2 emissions

Country	2000	2019	
China	\$0.60/kg	\$1.20/kg	Least Efficient
India	\$0.90/kg	\$1.20/kg	
Saudi Arabia	\$1.40/kg	\$1.20/kg	
South Korea	\$1.60/kg	\$2.30/kg	
World	\$2.10/kg	\$2.50/kg	
United States	\$2.20/kg	\$3.70/kg	
West Africa	\$4.00/kg	\$5.20/kg	
Brazil	\$5.10/kg	\$5.30/kg	
Germany	\$3.70/kg	\$5.80/kg	
Sweden	\$6.90/kg	\$12.90/kg	Most Efficient

Source: Brad: The GDP data are from the **World Bank what site** and measured in 2010 inflation-adjusted dollars. The emissions data are from the **Statistical Review of World Energy**, 2020 [often named the Factbook]. They represent CO_2 emissions from the combustion of coal, gas, and oil (omitting other CO_2 sources and the land use charge).

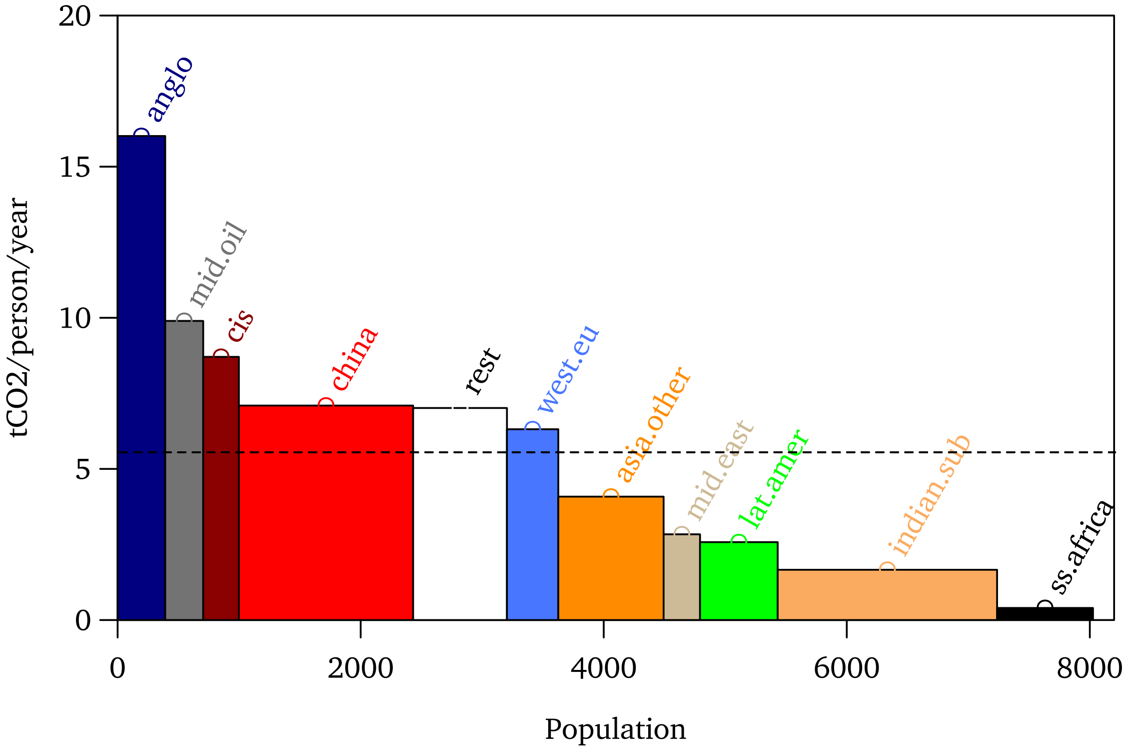
Explanations: The table shows that, in general, European countries tend to be most efficient, Asian countries least efficient.

The most energy-efficient economies are generally in Western Europe. They have also been the most aggressive in taxing fossil fuels. For example, all European countries are levying gasoline taxes of about $2.50 per gallon (€0.55 per liter), compared to about $0.20 per gallon in the USA. Europeans drive smaller cars, live in smaller houses closer to their work, and have more energy-efficient industries than the United States.

In contrast, the least energy-efficient economies are generally in poorer regions and predominantly in Asia. As they become richer, we can predict they will also use energy more efficiently.

The big takeaway in the efficiency data is that most countries and thus the world overall have become more energy-efficient per unit of real GDP as they have become wealthier. However, Figure 2.4 showed that richer countries still emit more per person. The improved efficiency with higher GDP is not enough to outweigh the effect of higher GDP on total emissions. China, India, and African countries will become more frugal per unit of GDP in the future, but they will still emit more net on net when their GDP grows.

Figure 2.5. Per-Capita and Total Emissions, 2019



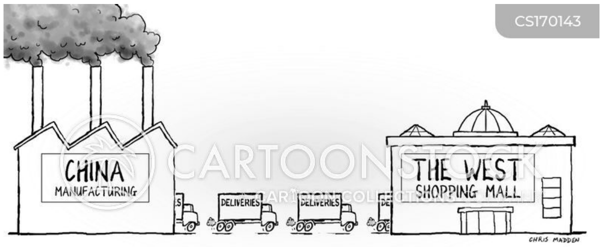
Explanations: The population size (in millions) is on the x axis. The CO_2 emission per person per year is on the y axis. The size of the rectangle is total emissions. The dashed line is the world average. Classification of countries is listed in the appendix to this chapter.

Source: **Our World in Data**. The idea for this graph was borrowed from the original in **MacKay, Chapter 1 (p12f)**.

Recall our statement from Chapter 1 that woe befall us if China were to crank up its *energy consumption per person* to European levels. In terms of *energy consumption per dollar produced*, China is already less efficient than Europe. Its industries are more polluting. Thus, China has already surpassed Europe in terms of *emissions per person*. And, unlike Europe, China is still aspiring to grow energy consumption. Of course, the United States, Canada, and Australia (“Anglo”) have least to brag about: with both prolific consumption and low energy efficiency, they hold the undisputed crowns in terms of emissions per person.

We have not been entirely fair, though. Comparing CO_2 efficiency across countries is naive. It’s a little like comparing apples and oranges.

For one, there is an unequal availability of local non-emitting sources of energy. Hydro-electric power can power Sweden, but it could not power China, India, or Saudi-Arabia. Moreover, if Sweden had to supply energy for 100 times as many people (1.4 billion Indians or Chinese instead of 10 million Swedes), it would also pretty quickly run out of hydro-electric power and resort to fossil fuels. For another, China does much of the world’s manufacturing. Manufacturing requires relatively more power than services (such as banking or tourism).



WHY CHINA’S CARBON FOOTPRINT IS SO LARGE

Nevertheless, it seems plausible that other countries could have manufactured the same goods as China but at a higher price with lower CO_2 emissions — if only because China still relies on coal as its main source of energy. (There are of course other reasons for China’s low manufacturing costs, too, but energy prices matter.)

Thinking that higher-cost countries could have produced the same exportable goods with a little higher cost is an unrealistic dream: industries that make goods that compete in world markets tend to move to where production is least costly. Local industries that do not move to cheaper locales tend to be eliminated by competition.

Thus, country-based emission controls will always be limited in their reach. When Western countries increase their CO_2 taxes or mandate zero net emissions, the unintended consequences are often counterproductive. Factories in Asia would likely appear and produce the same goods with even dirtier energy. This is not a minor theoretical nitpick, but supported by a lot of evidence. When Europe and the United States lost much of their manufacturing base to China over the last two decades, it reduced their own emissions but it did not curb global emissions.

Global Crossroads

Realize this: CO_2 emissions are no longer primarily a Western problem. Even if the United States and Western Europe somehow magically reduced all their emissions to zero, the rest of the world would still emit 30 tCO_2 (though down from 40 tCO_2). Add some more magic (e.g., from charismatic leaders who convince their peoples to fight climate change) and the world might even throttle down to 25 tCO_2. But the world won't be getting anywhere close to zero emissions.

Going back to the two elephants, the critical question to which no one knows the answer is whether the Indian subcontinent and Sub-Saharan Africa — the two regions at the far right in Figure 2.5 and who are still growing population faster than any other region — will manage to leapfrog over fossil-fuel technologies, in the same way they leapfrogged over now-obsolete landline telephones with cellphones.

On the one hand, renewable energy is becoming cheaper than some fossil fuels, so they might leapfrog. On the other hand, these countries cannot afford to pay more for state-of-the-art cleaner installations, and their political instability makes entrepreneurs reluctant to install big-scale clean technology. (Who wants to build a $10 billion nuclear power plant in Congo? Unfortunately, coal plants work at smaller scales than nuclear plants.) Indian and African farmers are not burning wood and bio-waste because they want to, but because they cannot afford electric power.

Moreover, if the Indian subcontinent reached merely the living standards and per-capita emissions of Indonesia, the world would go back to 40 tCO_2 quite quickly. If India and Sub-Saharan Africa start developing (and in the interest of the poor, we have to hope they will), and if they were to go the cheap-and-dirty fossil-fuel route, (regardless of what the rest of the world could realistically ever accomplish in curbing their emissions), and the world could still experience a large increase in future global emissions. At best, aggressive altruistic and self-harming reductions of CO_2 emissions by the West will be able to slow down the growth of Earth's emissions. They can't stop it. The arithmetic is pitiless and inescapable.

It follows that if the West wants to stabilize or reduce the CO_2 in the atmosphere, there is no other way than to get the rest of the world to aggressively curb their emissions, too. Western determination, self-discipline, and sacrifice alone would be futile. It further follows that the only way out is for the world to develop clean and cheap technology — *and* sell it very cheaply especially to poorer countries. For now, it has not been particularly eager to do so.

3 Earth's Natural Carbon Cycle

We have now explained the basics of human emissions. But when our civilization emits greenhouse gases, not all of them accumulate in the atmosphere. Thus we now need to take a brief detour into the earth sciences to explain where they ultimately end up.[2]

Land, Sea, and Air

Carbon in its various forms, including carbon dioxide (CO_2) and methane (CH4), can be found on land (in the ground), in the sea, or in the air. In the ocean, dissolved CO_2 acidifies the water. There is about 50 times more CO_2 (140,000 $GtCO_2$) in the oceans than there is in the atmosphere (3,200 $GtCO_2$). In addition, the oceans also store large amounts of frozen methane at their deepest bottom.[3]

In the ground, carbon is typically no problem, because it is generally bound in stable solid or liquid forms. This carbon and its compounds are stored in biological matter (including not only trees but also you, too), in coal and oil, in weathered rocks, or in the deep underground (where both CO_2 and CH4 become pressurized liquids). In total, the soil holds about 2,500 gigatonnes of carbon, equivalent to about **9,000 $GtCO_2$**.

There is one exception to the general rule that carbon in the ground is no problem. The **Arctic permafrost** is comprised of the regions of northern Canada and Russia where the ground has not melted even in summer for millennia. It now contains a lot of carbon in the form of undecomposed organic matter. If (or better when) the temperature in the high north increases to the point where the permafrost melts, microorganisms will turn this matter into atmospheric carbon-dioxide, or, worse yet, methane. Remarkably, there is more carbon buried in the permafrost (about 3,700 $GtCO_2$) than there is in total in the atmosphere today (about 3,200 $GtCO_2$). From a GHG perspective, the Permafrost is a live time bomb.

Oceans	Atmosphere	Permafrost	Other Terrestrial
140,000 $GtCO_2$	3,200 $GtCO_2$	3,700 $GtCO_2$	5,300 $GtCO_2$

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[2] For a more detailed and yet readable discussion, we recommend David Archer's **The Long Thaw**.

[3] (Unfortunately, we do not know whether it is 1,000 $GtCO_2e$ or 30,000 $GtCO_2e$. Fortunately, it seems highly unlikely that the planet will warm enough to release this Methane during the next few thousand years.)

Carbon Cycle Equilibrium

It is CO_2 and other GHGs in the air that are the sources of humanity's climate-change problem. Their balance in the atmosphere is the main issue of this chapter. (We delay the discussion of *how* the atmosphere raises the planet's temperature through the greenhouse effect to the next chapter.)

Each year, about 1,000 $GtCO_2$ moves naturally into the atmosphere. Common sources are warm ocean surfaces (essentially bubbling out of dissolved CO_2, carbonic acid), fires, and **volcanoes**. Each year, an almost equal amount of 1,000 $GtCO_2$ moves naturally back out of the atmosphere. That is, carbon-dioxide flows out of the atmosphere into "sinks." This circulation is called the "**carbon cycle**."

The most important sink is the ocean. Rain water captures CO_2 and eventually flows into the ocean. This CO_2 is then integrated into plankton (which itself contains large amounts of calcium, Ca), turned into limestone (CaCO3) on the ocean floor, and finally subducted by tectonic forces beneath the ocean into the earth's interior. During this process, the extra CO_2 reduces the ocean's native alkalinity (the opposite of acidity). Over the last 30 years, human CO_2 has increased the ocean acidity from **a ph level of about 8.11 to about 8.08**.[4] Given the giant size of the oceans, this is an impressive change.

Fortunately, there is more than enough calcium in the oceans to absorb all the CO_2 humanity could ever possibly dump into the atmosphere or ocean many times over. Unfortunately, the speed with which the ocean can bring new calcium online (and thus shuttle more CO_2 from the air to the ocean bottom) is (too) slow. Thus, when CO_2 accumulates too quickly in the atmosphere and presses into the ocean, the calcium does not have enough time to react with the CO_2 and pull out more calcite. Therefore, the existing buffer becomes exhausted temporarily, CO_2 becomes carbonic acid, and the ocean alkalinity decreases (i.e., the ocean becomes relatively more acidic). It is this time lag that reduces the ocean's ability to absorb and store CO_2. It is only in the very long-term that the oceans can bring enough calcium back online and expose enough cold ocean surface to the atmosphere to scrub out excess CO_2 and then restore the ocean chemistry to its former alkalinity.

Why does ocean acidity even matter? Human CO_2 emissions will not make the ocean so much less alkaline (more acidic) that it would poison fish. The effect on marine life will be through a different channel. The same calcium that now is pulled into sequestering more CO_2 was previously used by marine life (especially plankton) to build their shells. With less available calcium, many species will no longer be able to build effective shells and will go extinct. In turn, this could percolate up the food chain.

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[4] The level measures alkalinity, of which acidity is the opposite. An acidity level of 1 is battery acid, of 6 is milk, an acidity level of 13 is bleach, an acidity level of 11 is Ammonia. Pure water is a neutral 7. Thus, the oceans are alkaline, but are becoming less so now.

It's **deadly serious**.[5] Some researchers are now investigating whether **lime** ($Ca(OH)_2$) could be added to the ocean in order to help speed up the slow natural calcium cycle *at an affordable cost*. (Yes, it is all about economics.)

The next most important sinks are both terrestrial. The first are minerals that **weather**, i.e., change from one type of rock into another by absorbing CO_2. The most important such mineral is **Olivine**, which constitutes about half of earth's crust. Fortunately, there is enough Olivine around to absorb human emissions a hundred times over. Unfortunately, like the ocean calcium process, the natural weathering process is also very slow, taking many centuries. Some researchers are now investigating whether we can actively coax Olivine to absorb CO_2 faster *at an affordable cost*. (Once again, it is all about economics.)

The second terrestrial sink is life itself. Living organisms are estimated to contain about 550 Gt of carbon, equivalent to about 2,000 $GtCO_2e$. Wood is a particularly good carbon sink, because it is long-lived and decays slowly after death. Young, growing trees are especially efficient in fixing CO_2. Some researchers are now investigating whether planting more trees can sequester CO_2 more quickly *at an affordable cost*. (Economics yet again. Are you detecting a pattern?) However, such schemes will work only if the wood is harvested and used rather than allowed to burn, die, and/or decay. (Incidentally, this will inevitably cause environmental lawsuits to stop the destruction of more forests.)

(We will return to the research underway to capture CO_2, called sequestration, in Chapter 11.)

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[5] We will not realize the extent of this problem for a long time. Ironically, it will be difficult to ascertain humanity's mechanism of influence, because it is doing so much harm on so many fronts at the same time. Humans are simultaneously wiping out fish at an unprecedented rate, changing the ocean currents through global warming, and acidifying the oceans.

4 Accumulated Human Emissions

The carbon cycle is often compared to a giant barrel, with a roughly equal inflow and outflow of water. The flows into and out of the barrel are never perfectly balanced, but small fluctuations do not matter much. It is a big barrel, and it takes large one-sided inflows or outflows to raise or lower the level. However, over long enough time spans, even modest unbalanced excess inflows or outflows can and do accumulate if they occur consistently.

For many millennia, the natural atmospheric inflows and outflows were reasonably well-balanced. Popular belief to the contrary, even large volcanic eruptions have had only temporary influences over the course of millions of years. The giant eruption of Mount Pinatubo in 1991 emitted about 0.05 $GtCO_2$. All global volcanic activity emits about **0.1 to 0.5 $GtCO_2$** per year. Much bigger **supervolcano** eruptions could emit 50–100 $GtCO_2$ or more — but the last such supervolcano eruption (**Lake Taupo**) occurred in New Zealand about **25,000 years ago**. Yellowstone is an even larger supervolcano, but it erupted most recently **about 500,000 years ago**.[6]

By comparison, humans effectively keep pushing an extra 40 $GtCO_2$ per year *every year* into the atmosphere. This is roughly 50–100 times more than what volcanic activity or fires emit in a typical year. Of course, 40 $GtCO_2$ is also much less than the 1,000 $GtCO_2$ that move in and out of the carbon cycle every year or the 140,000 $GtCO_2$ that are already present in the ocean. And if humanity emitted 40 $GtCO_2$ for a year or two, it would not make much difference — the atmosphere is a very big barrel. The problem is that civilization has been emitting 40 $GtCO_2$ every year for many years now *and* it will emit a lot more soon *and* it will do so for many more decades — and this does make a big difference.

Atmospheric Carbon-Dioxide Readjustment Processes

David Archer, who researches the complex long-run and earth-state-specific changes of our atmosphere, characterizes the scrubbing process as it pertains to our human excess CO_2 emissions as follows: about half of our emitted CO_2 is scrubbed immediately (and of this half, equal parts disappear into the ocean and into the soil); another half of the remaining half will disappear within about 30 years; and the remainder will lurk in the atmosphere for **thousands of years or more**. What human civilization does in the 21st century will have long-lasting effects.

The longer description is that the annual absorption of greenhouse gases from the atmosphere into sinks is not directly linked to contemporaneous annual human emissions. Instead, it is determined by the momentary relative balance of CO_2 in its three reservoirs (air, ocean, and land) and influenced by many other aspects relating to the state of the

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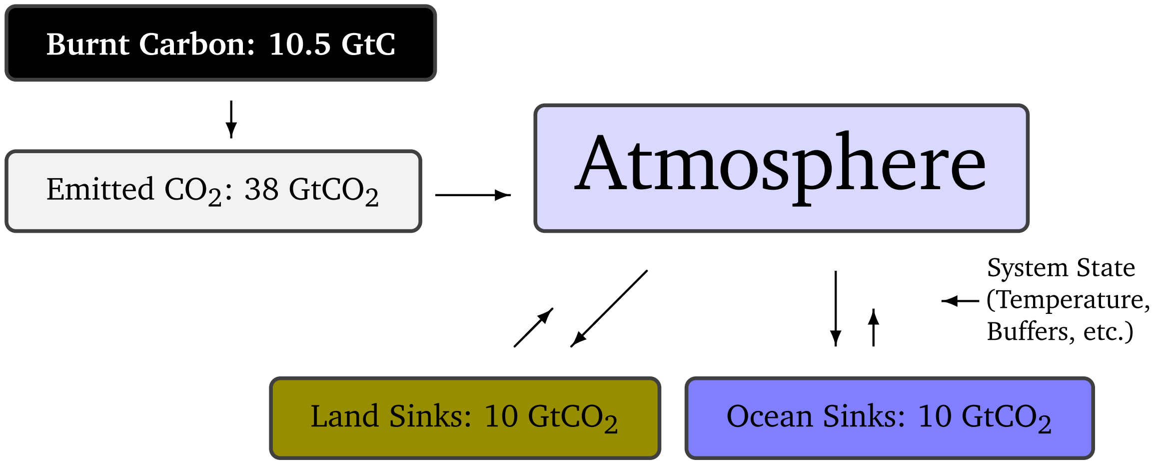
[6] The **Siberian Traps** did emit vastly larger amounts of CO_2 and other gases about 500 million years ago. This probably caused the *Great Dying* in which 97% of all species vanished.

Figure 2.6. Annual Human-Related CO_2 Flows, ca 2018–2022



Explanations: The link between inflows and outflows is weak over human lifespans. If human CO_2 emissions stopped today, it would not change the CO_2 outflow rate from the atmosphere into land and ocean sinks. However, the CO_2 outflow rate would change slowly over time, e.g., based on the (relative) CO_2 in the atmosphere, the planetary temperature, the availability of rocks that can weather, the CO_2 concentration in the ocean, and so on.

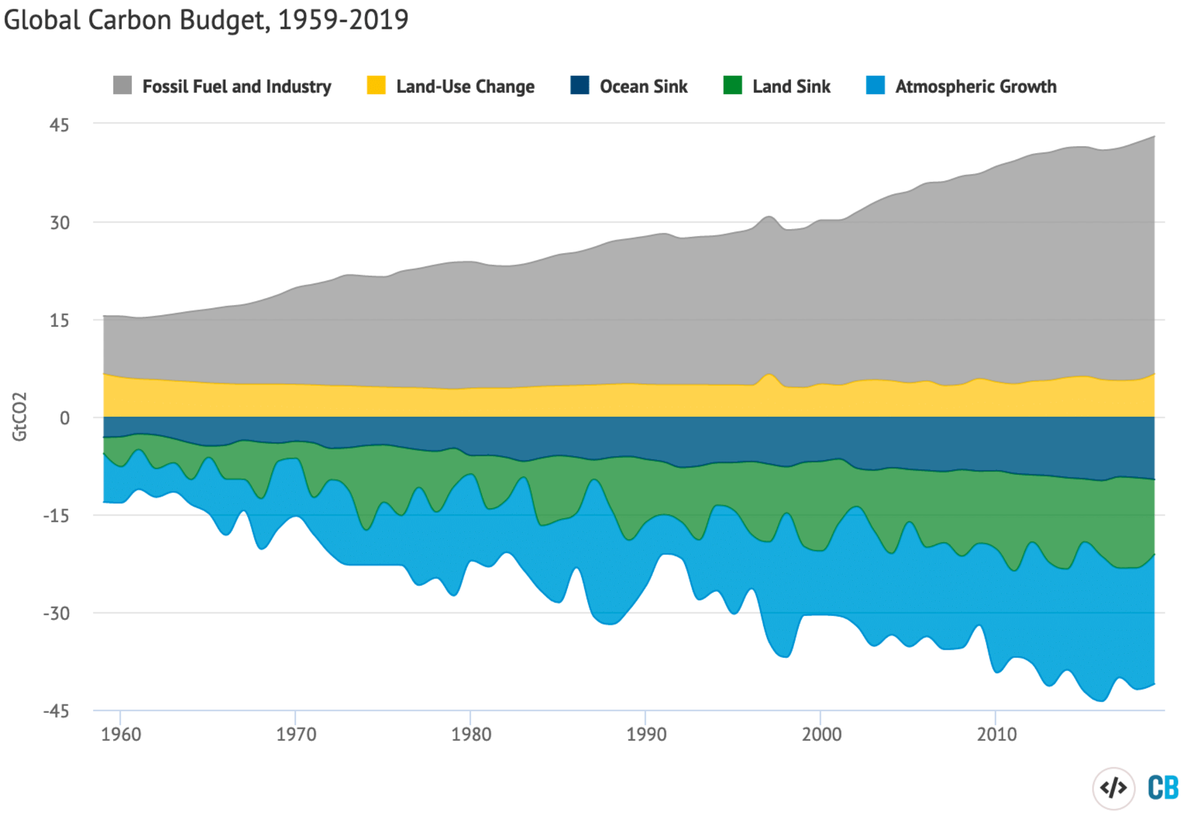
Source: David Archer, The Long Thaw: How Humans Are Changing the Next 100,000 Years of Earth's Climate.

planet — such as the planetary temperature, the current calcite level in the ocean, the availability of olivine on land (plus the rain necessary to allow olivine to weather), and so on.

Figure 2.6 sketches how inflows and outflows were linked (ca 2020). A little more than 10 Gt of carbon from human activity ultimately combined with oxygen to become about 38 $GtCO_2$ of human emissions. We should add a land charge (reduced CO_2 absorption) of about 4 $GtCO_2$, because humans were responsible for tree reductions, too. Call it about 40 $GtCO_2$ over one year. Simultaneously, over the same year, above and beyond the "base sink rate" of about 1,000 $GtCO_2$/year, the planet weathered about an extra 10 $GtCO_2$ into rocks and dissolved about an extra 10 $GtCO_2$ into the ocean due to the differences in the relative CO_2 pressure among the three reservoirs. Even if humanity went cold-turkey and stopped emitting CO_2 altogether, the land and ocean sinks would (likely) still continue to each scrub about 10 $GtCO_2$ per year from the atmosphere for many years. Eventually, these scrubbing processes would then slow down as the CO_2 pressure from the atmosphere into the water would drop.

Figure 2.7. Sources and Sinks Over Time

https://www.carbonbrief.org/analysis-global-fossil-fuel-emissions-up-zero-point-six-per-cent-in-2019-due-to-china



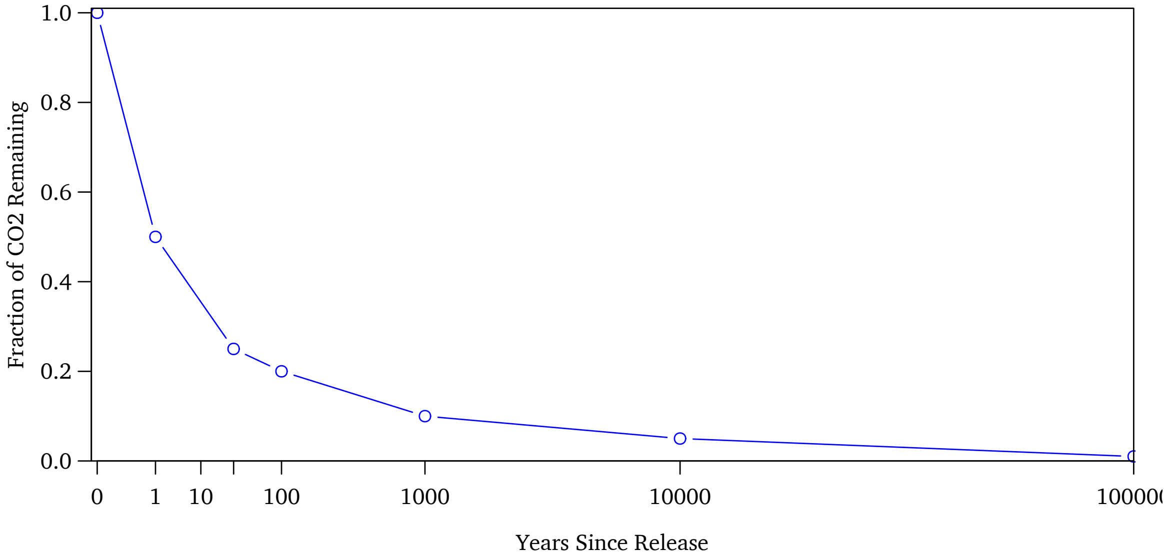
Annual global carbon budget of sources and sinks from 1959-2019. Note that the budget does not fully balance every year due to remaining uncertainties, particularly in sinks. 2019 numbers are preliminary estimates. Data from the Global Carbon Project; chart by Carbon Brief using Highcharts.

Source: The Global Carbon Project and CO2.earth.

Figure 2.7 shows estimates of how the emissions and removal processes have worked year by year over the last 50 years. About 90% of our CO_2 charge were emissions from fossil fuels; the rest was from land use. The oceans have been taking up CO_2 very steadily, while land sinks and the atmosphere have been absorbing CO_2 with much year-to-year variation.

The Half-Life of Human Excess CO_2

Figure 2.8. CO_2 Time to Equilibrium



Source: Interpretation of Archer's Long Thaw.

The dependence of the CO_2 flow process on many other state variables explains why there is no straightforward half-life of CO_2 in the atmosphere. Nevertheless, the concept of a half-life — how long it takes to remove half of any given emission of CO_2 — is still a useful approximation. Figure 2.8 shows current **educated scientific guesses** regarding the removal processes of CO_2.

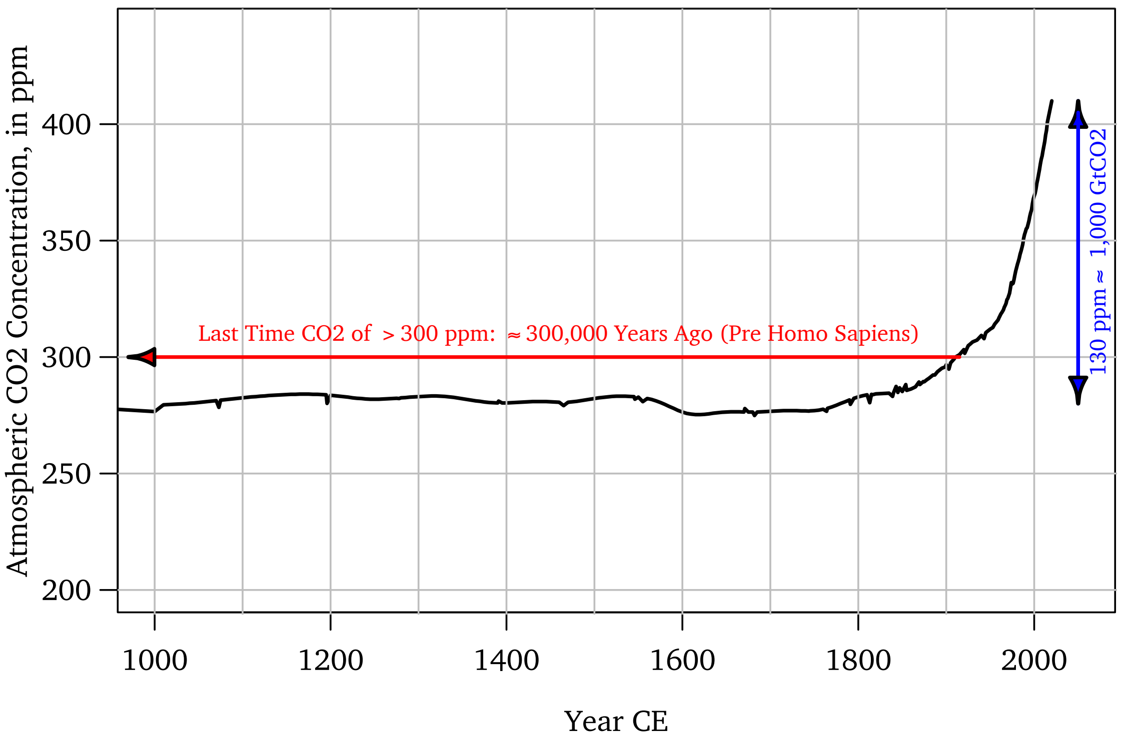
In sum, humans can be held responsible for having added about 20 $GtCO_2$ *net* to our atmosphere in 2020, i.e., CO_2 that the planet did not scrub in the same year. About 5 $GtCO_2$ of this will remain in the atmosphere for one millennium or longer.

Don't worry. The planet will adjust. In the very long term, over a few hundred thousand years, all the human-emitted CO_2 will eventually be scrubbed into sinks, where it will no longer have much impact on the climate. Worry "only" if you are more interested in the next few hundred or thousand years than in the next few hundred-thousand years!

5 The Historical Balance Sheet

You are now armed with enough knowledge to understand the bigger picture.

Figure 2.9. Atmospheric CO_2 Concentration



Source: Pre-1955 values based on smoothed Vostok ice core samples (**ClimateData.Info**). Post-1955 values based on direct **NOAA** CO_2 measurement on Mauna Loa.

Scientists now have reliable measurements of atmospheric CO_2 concentration going back a long time. These measurements are accurate enough to learn how the concentration of CO_2 in the atmosphere changed. On net, before 1900, year-to-year fluctuations in atmospheric CO_2 were determined mostly by natural phenomena, going up in some years, down in others, with little net change over extended periods.

Figure 2.9 plots (smoothed) CO_2 values over just the past 1,000 years. Any CO_2 concentration increases from human emissions prior to 1900 were so small that we cannot know whether observed changes in concentrations could instead have come from slow non-anthropogenic processes not yet fully understood. (And they were mostly scrubbed away by barrel earth within a few years, anyway, though a little residual may have accumulated very slowly since about 1800.) The (smoothed) planetary CO_2 concentration was stable between about 270 and 280 parts-per-million (**ppm**). This was indeed the case not just for a century but for about 300 millennia.

Moreover, simple chemistry and math tells scientists that **1 ppm of CO_2 over the entire planetary atmosphere is the equivalent of about 7.8 $GtCO_2$**. Thus, the increase from the pre-industrial 280 ppm to the 410 ppm today, i.e., 130 ppm, is equivalent to about 1,000 $GtCO_2$ in added CO_2 stored in the atmosphere.

Scientists also know that until about 1800 (or perhaps even 1900), human CO_2 emissions were so small that they could be considered rounding errors. Beginning around 1900, scientists start to have good national accounting estimates for human CO_2-related activities and emissions. In total, humanity has emitted about **1,700 $GtCO_2$** cumulatively since the start of the industrial revolution. Coal was responsible for about 800 $GtCO_2$ (47%), oil for 600 $GtCO_2$ (35%), gas for 250 $GtCO_2$ (15%), and cement for 50 $GtCO_2$ (3%). This sums to about 1,700 $GtCO_2$ in human CO_2 emissions; plus, there is another 600 $GtCO_2e$ for the land charge.

Table 2.4. Human CO_2 Emissions and Atmospheric CO_2

Year ! :	1770	1870	1970	2000	2020
1. Annual Emissions, $GtCO_2$	0.01/y	0.5/y	14.8/y	25.1/y	36.5/y
2. **(Cumulative) Emitted, $GtCO_2$**	0.0	11.5	423	1,040	1,690
3. Change in Atmospheric CO_2 since 1770, $GtCO_2$	0	50	350	850	1,050
4. Atmospheric CO_2 (Total), $GtCO_2$	2,150	2,200	2,500	3,000	3,200
5. **Atmospheric CO_2 ppm**	275	280	320	**380**	410
6. Rate of Change, CO_2 ppm	+0.06/y	+0.14/y	+0.9/y	+2.0/y	+2.2/y

Explanations: [1,2] Human cumulative emitted CO_2 are summed beginning in 1770. The retained change in atmospheric $GtCO_2$ levels since 1770 [3] are net of baseline [4] and obtained via simple translations of atmospheric CO_2 ppm estimates [5]. The rate of change [6] is estimated from single-year changes. This table excludes the land charge, which would add another 600 $GtCO_2e$ for which humanity is responsible. The starting year was chosen because the second agricultural revolution (and with it the industrial revolution and high population growth) began around 1800.

The primary point of this table is to show that planetary changes in CO_2 concentration were determined primarily by non-human sources before 1950 and increasingly by human sources thereafter.

Source: Cumulative and annual human emissions are from **Our World in Data** and NASA. The CO_2 concentrations can be found, e.g., at the **EPA** or **Ahn et al (2012)**.

Table 2.4 puts observed CO_2 concentrations and human emissions together in order to summarize how the world got to where it is today. Because atmospheric CO_2 increased "only" by about 1,000 $GtCO_2$, we can infer that more than 700 $GTCO_2$ of the total cumulative anthropogenic emissions since industrial times (about 1,700 $GtCO_2$) have already been scrubbed from the atmosphere. The 700 $GtCO_2$ emissions that were scrubbed went roughly equally into ocean and land. If we include the land charge, it implies that 1,300 $GtCO_2$ have been scrubbed out of a total of 2,300 $GTCO_2$.

We also have **corroborating chemical evidence** that confirms that most of the atmosphere's increase is due to fossil-fuel- based carbon and not natural sources. Since about 1950, humanity's emissions can account for most of the increase in atmospheric CO_2 concentration — now increasing at a rate of about 2 to 2.5 ppm per year.

6 What Will The Future Hold?

Despite all the clamor about climate activism in the richer countries, the upward trends in atmospheric CO_2 are still not only continuing but accelerating. As we noted at the outset, the world's environmental playbook can best be described as "lament and repeat."

What will happen next? Scientists know how the sinking processes have been working in the past. Fortunately, there has not been any visible deterioration (yet) in the absorbing capabilities of the ocean and land sinks. They are very big sinks!

Scientists also *think* they know how the sinks will work in the future. But they are not certain. Earth is a very complex system and not yet fully understood. The scrubbing processes could hit snags.

This scenario is not entirely implausible, because the carbon sinking processes depend on other aspects such as the planetary temperature. If the planetary temperature were to rise in the future, it could alter or even reverse both the ocean and the soil carbon-dioxide sink rates. The ocean could start bubbling out relatively more CO_2 and absorb relatively less than it does in the cooler waters of today.[7] Similarly, melting permafrost could start releasing more greenhouse gases. And a less reflective ice layer could further heat the planet. But other processes could counterbalance such scary feedback (such as increased plant growth due to higher CO_2 levels).

Frankly, the scientists just do not know for sure what will happen. Many scientists are also loathe to make "worst-case" predictions. The intent of worst-case predictions is that they are not supposed to be likely to come true. Given the politicized "climate around climate change," starker estimates could easily lead to accusations of misrepresentation and unscientific political bias. Who wants to risk this?

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[7] The ocean has already begun to emit more **Ozone** than it absorbs.

How many unknown problems could be out there? Could there be an exhaustion of carbon sinks and could this depletion be dangerous? Given the path that the planet is on at the moment, it looks as if we will find out all too soon.

Further Readings

BOOKS

- **Archer, David**, 2009, **The Long Thaw**, Princeton University Press, Princeton, NJ. Explains the long-term history and effects of CO_2 and global temperature.
- **Gates, Bill**, 2021, **How to Avoid a Climate Disaster**, Knopf, New York. Contains useful emission estimates and calculations.
- **Steven E. Koonin**, 2021, **Unsettled**, BenBella Books. Takes issue with some popular misconceptions.

REPORTS AND ACADEMIC ARTICLES

- OECD, 2017, **Green Growth Indicators**, Country-Based.

SHORTER NEWSPAPER AND MAGAZINE ARTICLES AND CLIPPINGS

- Friedrich, Johannes, Mengpin Ge and Alexander Tankou, 2017, **WRI** on **8 Charts to Understand US State Greenhouse Gas Emissions**, World Resources Institute.
- Mider, Zachary, 2021, **Bloomberg** on **Methane Hunters**, Bloomberg.
- Painting, Rob, 2015, **Why were the ancient oceans favorable to marine life when atmospheric carbon dioxide was higher than today?** (Ocean Acidification), **Skeptical Science**.
- Curtis, Tom, 2012, **Climate Change Cluedo: Anthropogenic CO2** (Attributing atmospheric CO_2 to human emissions), **Skeptical Science**.
- **Carbon Dioxide Information Analysis Center — Conversion Tables**.

WEBSITES

- `https://ourworldindata.org/` curates data on important phenomena.
- `https://skepticalscience.com/` debunks many climate-skeptics’ claims.

COUNTRY CLASSIFICATIONS

West, Europe: Austria, Belgium, Denmark, Finland, France, Germany, Greece, Ireland, Italy, Luxembourg, Netherlands, Norway, Portugal, Spain, Sweden, Switzerland, United Kingdom.

Anglo-American: Australia, Canada, United States.

Latin America: Argentina, Bolivia, Brazil, Chile, Colombia, Costa Rica, Cuba, Dominican Republic, Ecuador, El Salvador, Guatemala, Haiti, Honduras, Jamaica, Mexico, Nicaragua, Panama, Paraguay, Peru, Uruguay, Venezuela.

Indian Subcontinent: Afghanistan, Bangladesh, India, Pakistan, Sri Lanka.

Asia (Other): Cambodia, Hong, Kong, Indonesia, Japan, Laos, Mongolia, Myanmar, North, Korea, Philippines, Singapore, South, Korea, Taiwan, Thailand, Vietnam.

Sub-Saharan, Africa: Angola, Botswana, Burkina, Faso, Burundi, Cameroon, Chad, Congo, Ethiopia, Gabon, Gambia, Ghana, Kenya, Liberia, Madagascar, Malawi, Mali, Mozambique, Namibia, Niger, Nigeria, Rwanda, Senegal, Tanzania, Uganda, Zambia.

Middle East (Oil-Rich): Bahrain, Saudi Arabia, Iran, Iraq, Kuwait, Libya, Oman, Qatar, Syria, Tunisia, Turkey, United, Arab, Emirates.

Middle East (Not Oil-Rich): Egypt, Jordan, Lebanon, Mauritania, Morocco, Syria, Turkey, Tunisia, Yemen.

CIS: Armenia, Azerbaijan, Belarus, Georgia, Kazakhstan, Kyrgyzstan, Moldova, Russia, Tajikistan, Turkmenistan, Ukraine, Uzbekistan.

Compiled: October 20, 2021