Chapter 3

Greenhouse Gases

The previous chapter showed that the combination of population growth and economic development has translated almost one-to-one into increased primary energy consumption. In this chapter, we show that this increase in primary energy use has in turn translated almost one-to-one into increased emissions of greenhouse gases. This is because civilization has relied so strongly on fossil fuels.

As in the previous chapter, we begin with an explanation of the underlying science —- here, the science of greenhouse gases and the planet's carbon cycle. We then describe which regions have been and will continue to be most responsible for their emissions.

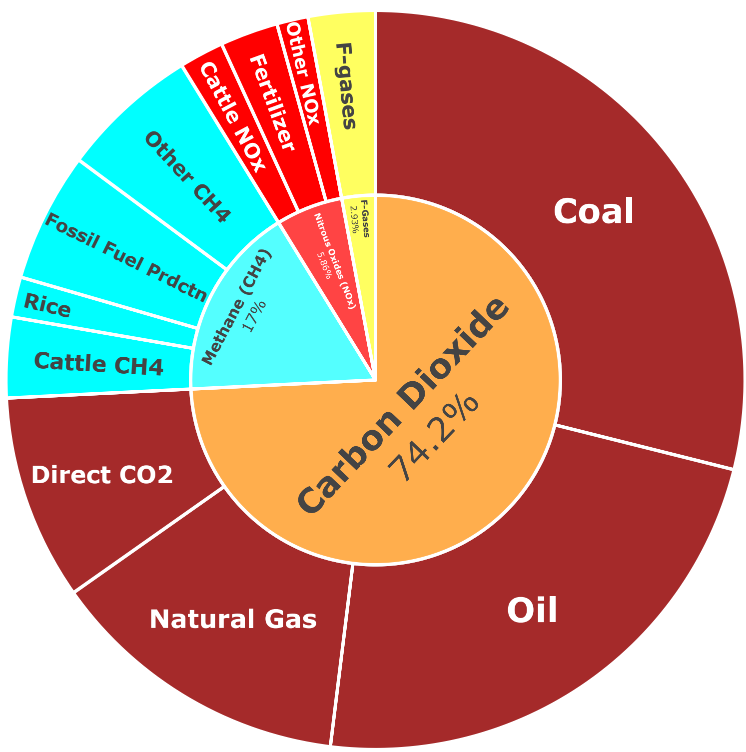
In the next chapter, we will describe the effect of greenhouse gas emissions and concentration in the atmosphere on the planet's climate.

The next decade of indecision could be decisive.

1 Measuring Human Emissions

There are four important long-lived greenhouse gases that scientists have identified as the most troublesome. The most important one by far is carbon-dioxide (CO_2). Methane (CH_4) is a distant second. The other two, nitrous oxide (NO_x) and "F-gases" (containing Fluor), are even less important. We will discuss each gas in turn, but a quick overview makes the abstract more real. Figure 1 shows the main emitters of the different greenhouse gases.

Figure 1. Global Annual Greenhouse Gas (GHG) Emissions



Note: The figure is for emissions around 2020. The detailed explanation is in Table 2.

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 1,540 pounds or 0.70 metric tons (tonne). When burned, the added oxygen transforms it into 2.57 metric tonnes of CO_2. 1 tonne of carbon is therefore equivalent to 3.67 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 scientists also love confusing their audiences 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 emissions in terms of "tonnes of carbon," when they really mean "tonnes of carbon-dioxide."[1] We will try to stick to tonnes of CO_2 in our book *and* spell it out, but 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 8 billion people and 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.[2]

---

[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!

[2] However, most of our breathing is 'just' re-emitting carbon that already was in our food. In some sense, humans were also responsible for removing this CO_2 from the atmosphere by

Table 2. Global Annual Greenhouse Gas (GHG) Emissions (circa 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), 5.9%		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 $GtCO_2e$ (reduction of green land caused by humans, $\approx$ 4 $GtCO_2e$)		55 $GtCO_2e$

Note: 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. 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 vapors 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 will be the subject of the next chapter.

Table 2 (and Figure 1) show the main sources of our CO_2 emissions. (Un-)naturally, our global industrial activities and the burning of fossil fuels (circa 2021) emit a lot more CO_2 than just breathing — about 35 $GtCO_2$ in total.

As with the energy data in the previous chapter, it is common to see different emission estimates quoted. This means estimates are usually perfectly consistent only if you stay within the same data source.[3] For CO_2, there are also more reasons. First, reasonable measurement estimate variations are about ±5%. Second, some sources quote only CO_2 from fossil fuels (such as the Global Carbon Atlas with 34 $GtCO_2$ for 2020), others quote only CO_2 from combustion or emitting agriculture, etc. Thus, it is not uncommon to see CO_2 emission estimates anywhere from 34 $GtCO_2$ to 40 $GtCO_2$. Third, emissions have been increasing. Quoting 2018 gives a lower number than quoting 2021 — and then the Covid year of 2020 has caused all sorts of strange blips, leading some to prefer the earlier 2019 number. (We try to skip straight to 2022 estimates when we can, even though the year is not yet complete.) Usually, the data are not different enough to change the basic points we make.

Furthermore, civilization emits CO_2 not only by burning fossil fuels but also through some agricultural and chemical processes (principally CO_2 outgases in cement production) — roughly accounting for another 5 $GtCO_2$.

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 is accounting 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.

---

growing plants (possibly feeding them to food animals) in the first place. Thus, our breathing "cost" can be viewed as being attributable to our agricultural land-charge.

[3] It can become an issue when one attempts to patch together figures from different sources. For any given table, we try to use the authors' sets rather than patch in figures from other sets in order to continue comparing apples to apples.

The Other Long-Lived Greenhouse Gases

Carbon-dioxide is not the only important greenhouse gas. Table 2 also describes the effects of three other greenhouse gases. The two more important ones are Methane (CH4) and Nitrous Oxides (NOx). Methane is essentially the odorless natural gas that burns easily and runs most stoves and heating systems in the United States today. Nitrous oxide is also called laughing gas and was quite 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. (Therefore, curbing methane — even simply as flaring it off — tends to be more cost-effective than reducing carbon-dioxide.) 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 anthropogenic CO_2 is responsible for about 75% of global warming, Methane for about 15%, and Nitrous oxides (NOx) for about 6%.

In sum, direct human CO_2 emissions now run to about 40 GtCO_2, and greenhouse gas emissions now run at about **50 GtCO_2e per year**. They increase to about **55 GtCO_2e/year** when we add the land charge — the reduction of green land. Reasonable estimates can be 5% higher or lower.

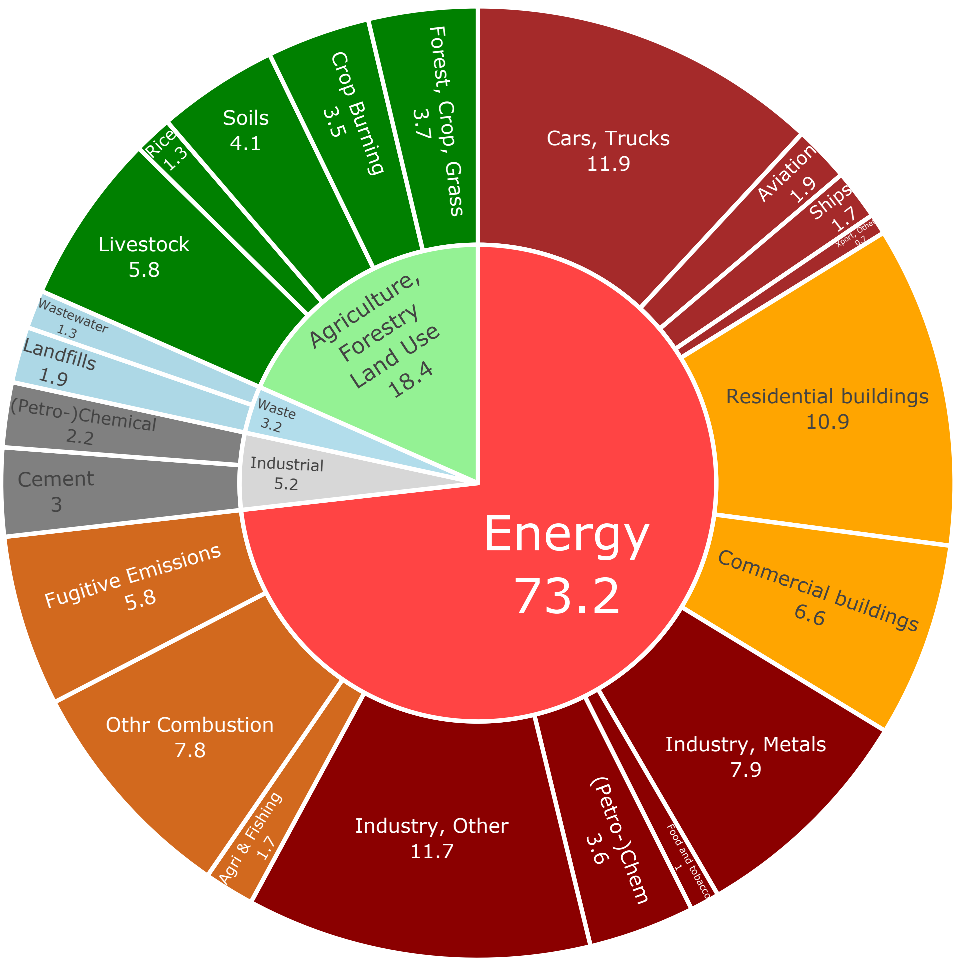
Sources of Greenhouse Gases

Figure 3 provides a breakdown of energy use that is perhaps too detailed but again interesting to gawk at. The two overwhelming emitters are **energy** — the subject of our previous chapter — and **agriculture**.

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 cow 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 4 breaks the sources into broad categories. Unsurprisingly, fossil-fuel

Figure 3. Source of Greenhouse Gases, 2016



Source: Heavily inspired by Hannah Ritchie, 2021, Our World In Data. For energy, the broader categories in clockwise order from the top (and marked in their own hues) are: transportation, heating, industrial uses, and other uses.

Table 4. Annual Emissions, circa 2018–2022

Power, Heat, Agriculture, All GHGs		51 $GtCO_2e$
Agriculture, 19% (of 51 $GtCO_2e$)	9.7 $GtCO_2e$	
Non-Ag Emissions, All GHGs		41 $GtCO_2e$
Combustion, CO_2 Only	33.4 $GtCO_2$	
Combustion, NOx Only	0.5 $GtCO_2e$	
Transport, 16% (of 51 $GtCO_2e$)	8.2 $GtCO_2e$	
Electricity, 27%	13.8 $GtCO_2e$	
Heating, 7%	3.6 $GtCO_2e$	
Industrial, 31%	15.8 $GtCO_2e$	
Reasonably Electrifiable Emissions		25–35 $GtCO_2e$
(Heating=3.6, less fossil-fuel extraction=5, some industrial=5, cars/trucks=5.5.)		
Difficult/Costlier To Electrify		15–25 $GtCO_2e$
(Some high industrial heat and cement=10, agriculture=10, ships/airplanes=1.6.)		

Note: 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 estimates 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.)

combustion looms large. However, agriculture and land use are important non-combustion sources of greenhouse gases as well.

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 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 as well.

Table 4 also 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 electricity generation would 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. Unfortunately, the final third will be much more difficult to decarbonize — agriculture, airplanes, ships, industrial heat, etc. — and perhaps will never rely exclusively on electricity.

And, of course, humanity is still on the move. With continued population growth and economic development, the demand for energy is continuing to increase. As we explained in the previous chapter, humanity will use a lot more energy sooner rather than later, primarily in population-rich developing regions.

Other Fossil-Fuel Pollution

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

Scientists have estimated that without local fossil-fuel pollution, 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). On the high end of death estimates, as many as 5 million to 9 million people may die prematurely every year due to direct pollution caused by fossil-fuel combustion.[4] Between 1-in-5 and 1-in-10 deaths may be hastened by the same fossil-fuel processes that generate our energy and emit our greenhouse gases. Fossil fuels are murderous.

[4] It is not clear whether climate-change itself is already increasing deaths (e.g. through droughts and heat waves). Colder temperatures kill more people than warmer temperatures. For example, the UK Office for National Statistics (ONS) found that more climate change has saved more than 25,000 lives per year between 2001 and 2020. This is not generalizable to the rest of the world.

To be fair, these mortality figures 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 sulfur dioxide (SO_2) aerosol particles — famous for causing acid rain. However, these SO_2 particles are also reflective and thereby enhance the planet's albedo.[5] The burning of dirty coal has therefore probably held down global temperature by about 0.6°C (out of a total of 1.5°C). An ongoing shift towards cleaner coal is about to reduce this cooling effect.

2 Earth's Natural Carbon Cycle

Fortunately, not all human emissions accumulate in the atmosphere. Thus we now take a brief detour into the earth sciences to explain this.[6]

Land, Sea, and Air

Carbon in its various forms, including carbon dioxide (CO_2) and methane (CH4), can be found on land, 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.[7]

In the ground, carbon is typically not a 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 in trees but also in us), 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 big and one small exception to the general rule that carbon in the ground is no problem. The Arctic permafrost is comprised of the regions of

[5]Albedo means literally "whiteness" in Latin. Snow and clouds are the most important sources of planetary albedo.

[6]For a more detailed and yet readable discussion, see David Archer's The Long Thaw.

[7]Scientists 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.

northern Canada and Russia where the ground has not melted even in summer for millennia. It now contains a lot 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 greenhouse perspective, the Permafrost is a live (though probably not a quick-release) time bomb. The smaller exceptions are other non-Permafrost peat lands, which emit CO_2 when they are drying out or being dried out by farmers — still to the tune of about 2 $GtCO_2$ per year.

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

Carbon Cycle Equilibrium

It is the CO_2 and other long-lived 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 what are called "carbon sinks." This circulation is called the "carbon cycle."

The most important carbon sink is the ocean. Rain water captures and dissolves CO_2 and eventually flows into the ocean. This CO_2 is then integrated into plankton (which itself contains large amounts of calcium, Ca). It then turns into limestone (CaCO3) on the ocean floor and is finally subducted by tectonic forces beneath the ocean into the earth's interior.

Fortunately, there is more than enough calcium in the oceans to absorb all the CO_2 that humanity could ever dump into the environment many times over.

Unfortunately, the speed with which the ocean can bring this new calcium online (and thus shuttle more CO_2 from the air to the ocean bottom) is (too) slow. Thus, when CO_2 accumulates in the atmosphere and presses into the ocean, there is not enough calcium to immediately react with the CO_2. The time lag 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 that they can scrub out all excess atmospheric CO_2

When the existing calcium buffers become temporarily exhausted, excess CO_2 turns into increased carbonic acid, and the ocean's native alkalinity decreases.[8] Over the last 30 years, anthropogenic CO_2 has increased the ocean acidity from a ph level of about 8.11 to about 8.08. Given the giant size of the oceans, this is an impressive change.

Why does ocean acidity matter? Human CO_2 emissions will not make the ocean so much less alkaline (relatively more acidic) that it would poison sea creatures. The effect on marine life will work through a different channel. The same calcium that is now pulled out of the solution 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. The effects could be deadly serious far beyond the smallest ocean creatures.[9] Therefore 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, environmentalism is all about economics, too.)

The next two important sinks are 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. It constitutes about half of Earth's crust. Fortunately, there is enough Olivine around to absorb human emissions

[8]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.

[9]Humans will not realize the extent of this problem for a long time. Ironically, it will be difficult to ascertain the mechanism of our destructive influence, because humanity 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 — a veritable trifecta.

a hundred times over. Unfortunately, like the ocean calcium process, the natural weathering process is also very slow, taking many centuries. Therefore other 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 effective and valuable carbon sink, because it is long-lived and decays slowly after death; and young, growing trees are particularly efficient in pulling out CO_2, because they are growing trunks more aggressively. 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 well only if the wood is buried under soil (to become fossil fuel in a few million years) or is harvested and used for lumber. If wood is allowed to burn or die-and-decay, the CO_2 is released back into the atmosphere. (Of course, environmentalists love to sue whenever timber companies are logging forests. They would probably love to sue when fires destroy trees, too, but fire is difficult to drag into court.)

(We will return to research underway to capture CO_2 via enhanced ocean absorption, weathering, or tree planting — called sequestration — in Chapter 12.)

3 Accumulating 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, even modest unbalanced excess inflows or outflows can and do accumulate if they occur consistently over long enough time spans.

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 and small influences over the course of the last few millions of years. The giant eruption of Mount Pinatubo in 1991 emitted about 0.05 $GtCO_2$. All global volcanic activity combined 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 modest supervolcano eruption (Lake Taupo) occurred in New Zealand about 25,000 years ago. It also emitted only about 2–3 times as much as humanity emits each year. Yellowstone is an even larger supervolcano, but it erupted most recently about 500,000 years ago.[10]

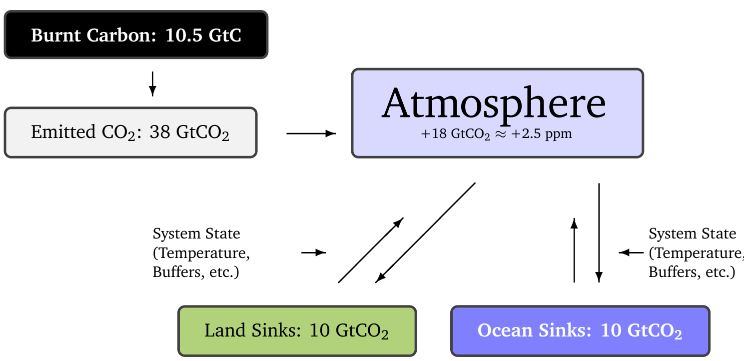
By comparison, humans keep pushing an extra 40 $GtCO_2$ per year *every year* into the atmosphere. This is roughly 50–100 times more than what volcanic activity or fires emit in a typical year. Of course, 40 $GtCO_2$ is also much less than the 1,000 $GtCO_2$ that move in and out of the carbon cycle every 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.

[10] 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.

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.

Figure 5. Annual Human-Related CO_2 Flows, ca 2020



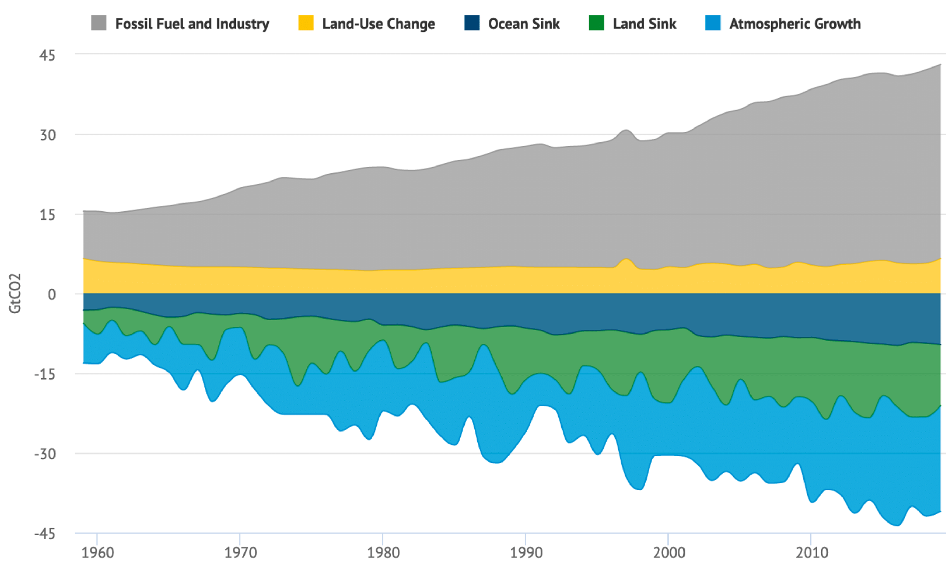
Note: The link between inflows and outflows is weak over human lifespans. Outflows are determined by the system state, not by that year's emissions. If human CO_2 emissions suddenly stopped, it would not instantly reduce the CO_2 outflow rate from the atmosphere into land and ocean sinks. Instead, the outflow rate would slowly start declining, 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.

A 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 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 5 sketches how inflows and outflows were linked (circa 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 6. Sources and Sinks, 1959–2019

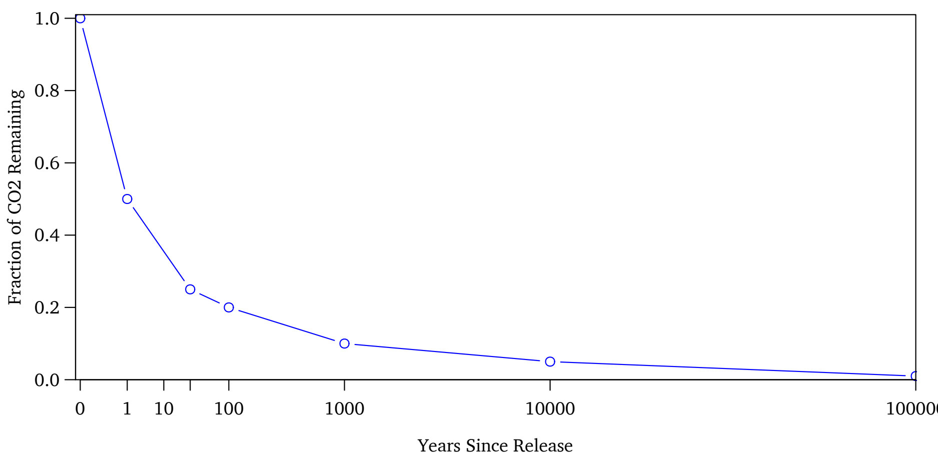


Source: The Global Carbon Project and CO2.earth.

Figure 6 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 7. CO_2 Time to Equilibrium



Source: Our interpretation of David Archer's, Long Thaw.

The dependence of the CO_2 processes 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 — at least at the moment can still be a useful conceptual guide. Figure 7 shows a current educated guess about the speed of the removal processes of extra CO_2 in the atmosphere.

In sum, humans can be held responsible for adding about 20 $GtCO_2$ *net* to our atmosphere every year (ca 2020), i.e., CO_2 that the planet does not scrub away in the same year. About 15 $GtCO_2$ will slowly disappear in a matter of decades or centuries. The final 5 $GtCO_2$ will remain in the atmosphere for a millennium or longer.

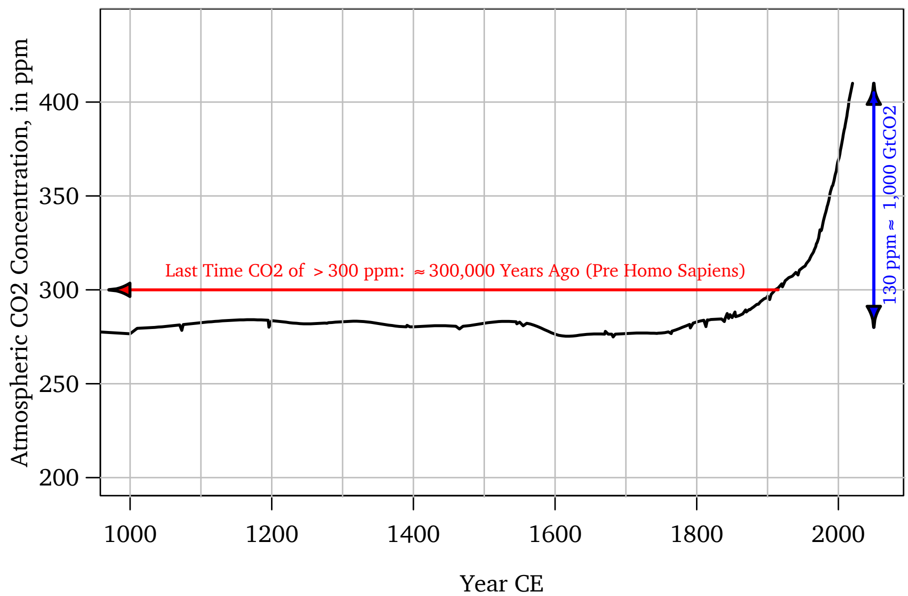
Don't worry. The planet will adjust. In the very long term — over a few hundred thousand years — natural earth processes will eventually scrub all the human-emitted CO_2 into sinks, where this CO_2 will no longer have much impact on the climate. You need to worry "only" if you are more interested in the next few thousand years than in the next few hundred-thousand years!

4 The Balance Sheet

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

The Historical Accumulation

Figure 8. 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 have 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 has changed. Figure 8 plots them over the past 1,000 years.[11] The planetary CO_2 concentration was stable between about 270 and 280 parts-per-million (ppm) until the 19th century. Until the 19th century, atmospheric CO_2 concentration changes due to human emissions

[11] The CO_2 estimates were smoothed to reduce measurement noise. Not shown, the CO_2 concentration over the last 300,000 years was stable. It looks just like the first part of the figure.

were so small, going up or down year by year, that scientists cannot determine reliably whether they came from anthropogenic or natural processes. (And they were mostly scrubbed away by barrel Earth within a few years, anyway, although a little residual may have accumulated very slowly since about 1800.)

Beginning around 1800 but certainly after 1900, scientists observed a steady rise in atmospheric CO_2. They also observed corroborating chemical evidence that most of this CO_2 increase came from burning ancient fossil-fuel-based carbon and not from recent organic carbon or volcanoes. Thus, scientists know that humans are responsible for most or all of the increase in atmospheric CO_2 concentration since 1900.

Moreover, we have confirmation. Simple chemistry and math implies 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 in 2020, i.e., 130 ppm, is equivalent to about 1,000 $GtCO_2$ in added CO_2 stored in the atmosphere. Scientists can compare this to human activities directly. National accounting estimates suggest that humanity ramped up its fossil-fuel based activities beginning with the Industrial Revolution. Adding up national emissions, humans have pushed out a total of about 1,700 $GtCO_2$. 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 $GtCO_2$ of human CO_2 emissions. Another 300 $GtCO_2$ are the land charge. The planet scrubbed a net of about 700 $GtCO_2$ of this; the remaining 1,000 $GtCO_2$ are in the atmosphere. Table 9 puts observed CO_2 concentrations and human emissions together in order to summarize how the world got to where it is today. (The numbers are continuing to change quickly, though. As of 2022, we are about to reach 420 ppm and accelerating.))

The Future

What will happen next? Scientists know how the ocean and land sinking processes have functioned in the past. Fortunately, they have not yet detected any visible deterioration in their absorbing capabilities. (They are very big sinks indeed!) Scientists also *believe* they will continue to function in the future. But they are not certain. Earth is a complex system and not fully understood. The scrubbing processes could hit snags.

A disruption in the carbon sinking processes is not entirely implausible, because these processes depend on other Earth state aspects — such as the

Table 9. Human CO_2 Emissions and Atmospheric CO_2

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

Note: 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).

[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 1770 for the accumulation was chosen because the second agricultural revolution (and with it the industrial revolution and high population growth) began around 1800.

planetary temperature which has not yet increased even half as much as scientists predict it will. Scientists have never observed the state configuration which Earth will soon be experiencing.[12] 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 oceans could start bubbling out relatively more CO_2 and absorb relatively less than they do in the cooler waters of today. Similarly, melting permafrost could start releasing more greenhouse gases. In addition, a less reflective ice layer could further heat the planet. But other processes could counterbalance such scary feedback loops, including increased plant growth due to higher CO_2 levels and increased rainfall.

[12] Scientific Clarification: By state configuration, we do not only mean levels in various inputs but also their direction and rate of change. We are less concerned with 1,000,000 year long-run equilibrium outcome than with short-term 100-year spikes that could "temporarily" devastate the biosphere.

Frankly, scientists cannot know for sure what will happen. They are making "well-educated guesses" — better than those made by pundits and interest groups. But consider this: many scientists are loathe to make "worst-case" predictions. The point of worst-case predictions is that they are not supposed to be likely to come true. Given the politicized "climate around climate change," making starker and more extreme predictions could easily lead to accusations of misrepresentation or even unscientific political bias. What serious scientist wants to risk this?

How many unknown unknowns could be out there? What is the probability that carbon sinks will become exhausted, and how dangerous would this be? Given the path that the planet is on, it looks as if we will find out all too soon.

5 Growth in Human CO_2 Emissions

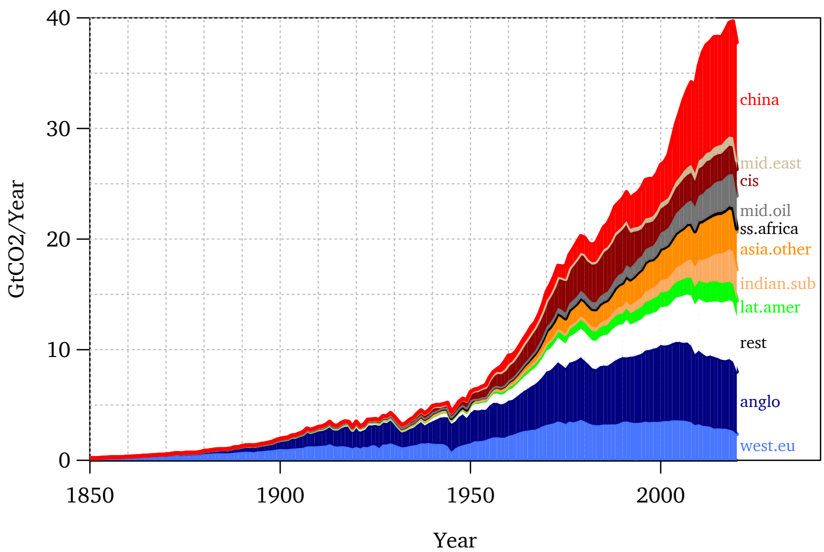
If we want to tackle greenhouse gas emissions, we have to determine where they are originating. We already explained above that 73% of emissions are from energy provision, which are themselves 85% fossil fuels; and that the remaining 27% tend to be highly correlated with energy use, too.

In the previous chapter, we described how different countries and regions consume energy. In the remainder of this chapter, we explain how they have been and will be responsible for emissions.

Figure 10 plots a broad measure of global CO_2 emissions by country/region over the decades. You can see how emissions have grown alarmingly quickly and are still accelerating today. Before 1900, emissions were negligible — just like energy use. 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.

Even by 1950, total 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. By now, civilization emits about 40 $GtCO_2$ per year, 50 $GtCO_2e$ including other greenhouse gases, and 55 $GtCO_2e$ if we add the land charge.

Figure 10. Annual CO_2 Emissions By Area/Country



Note: 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 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.

Our by-now familiar region classification in Table 11 shows that emissions have stabilized in OECD countries (about 12 $GtCO_2$ per year) but continue to grow in non-OECD countries (about 24 $GtCO_2$ per year currently; about 31 $GtCO_2$ within one generation). Without a fundamental change, within our lifetimes, non-OECD countries will emit by themselves what the world emits *in total* today.

The majority of the global growth in emissions over the last 20 years (+10.4 $GtCO_2$) has come from China (+7.8 $GtCO_2$). China alone already emits 11.0 $GtCO_2$ — more than the United States (4.8 $GtCO_2$) and OECD Europe (3.8 $GtCO_2$) combined. It is mostly due to its larger population and its extensive use of coal that it already emits more CO_2 than all rich countries

Table 11. CO_2 Energy-Based Emissions, in $GtCO_2$

	1981	2000	2020	2050e
OECD	11.3	13.6	12.1	12.1
USA	4.6	5.9	4.8	4.8
Europe	4.3	4.4	3.8	3.7
Not OECD	6.8	10.3	24.1	30.8
China	1.2	3.2	11.0	10.5
India	0.2	0.8	2.7	5.8
Other Asia	0.5	1.3	2.8	4.9
Africa	0.5	0.8	1.3	2.0
World	18.1	23.6	34.3	42.8

Source: US EIA International Energy Outlook, Oct 2021. Carbon Dioxide Emissions by Region. Other Asia includes, e.g., Indonesia, Pakistan, and Bangladesh.

combined. It also emits more than the next four biggest country emitters combined.

With a per-capita income of about $20,000 per year, China is also still only about halfway between rich and poor countries. Fortunately, China's emissions are now stable. Unfortunately, they are stable at a very high level. (This is just like the OECD. Remember, these facts are not about finger-pointing or assigning blame.)

The EIA projects that emissions in the next 30 years will grow most in India and other Asian countries. India alone will soon emit more than either the USA or Europe. The same will apply to the rest of Asia (countries other than China and India). That is, each of the three regions — China, India, Other Asia — will soon emit more than either the USA or Europe.

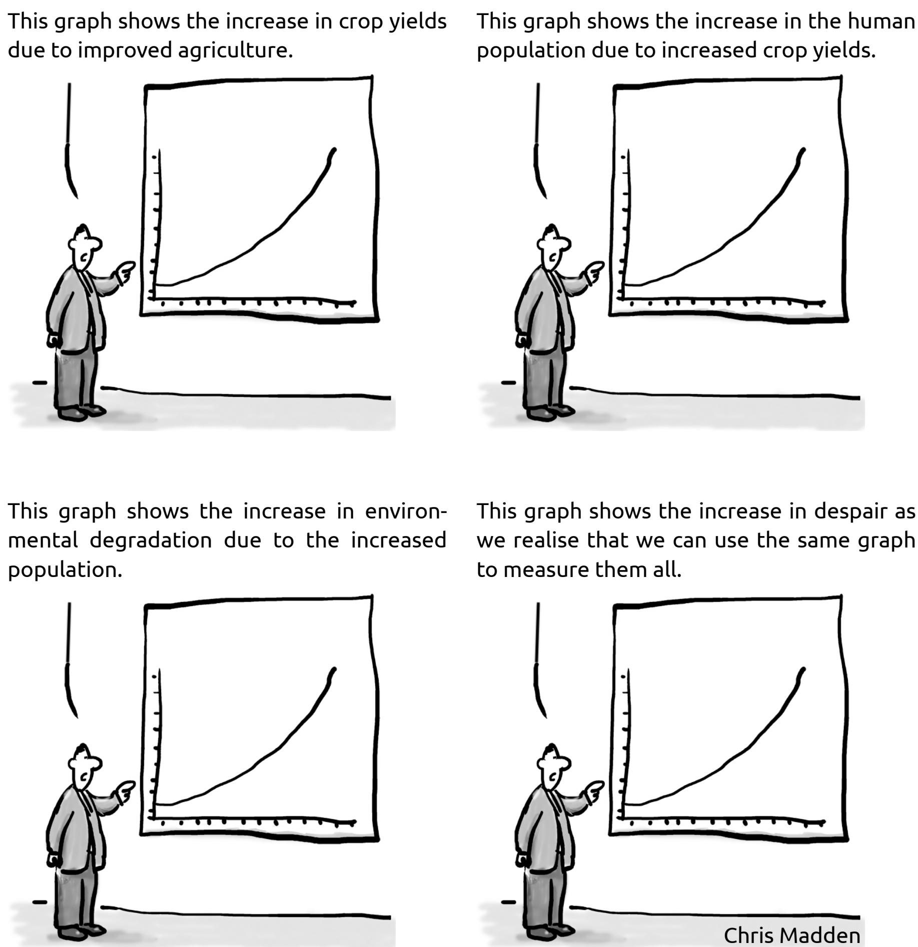
Africa, with its fast-growing population, remains far behind. It emits so little because it uses so little energy because it is so poor. Of course, Africans deserve no less than the humans in the rest of the planet. Contemplate this — how do you imagine will Africans attain reasonable standards of living?

sidenote

A 2021 report by Carbonbrief comes to a surprising conclusion: CO_2 emissions may have already been flat since 2012, because increasing fossil fuel emissions were balanced by a declining land-use charge. Though good news, there is large uncertainty surrounding this estimate and the inference should be confirmed by other scientists.

6 Energy and Emissions

So far, across countries, regions and time, wherever and whenever economic growth has increased, so has primary energy use, so has fossil fuel consumption, and so have greenhouse gas emissions. (Efficiency improvements have mitigated this but not stopped it.)

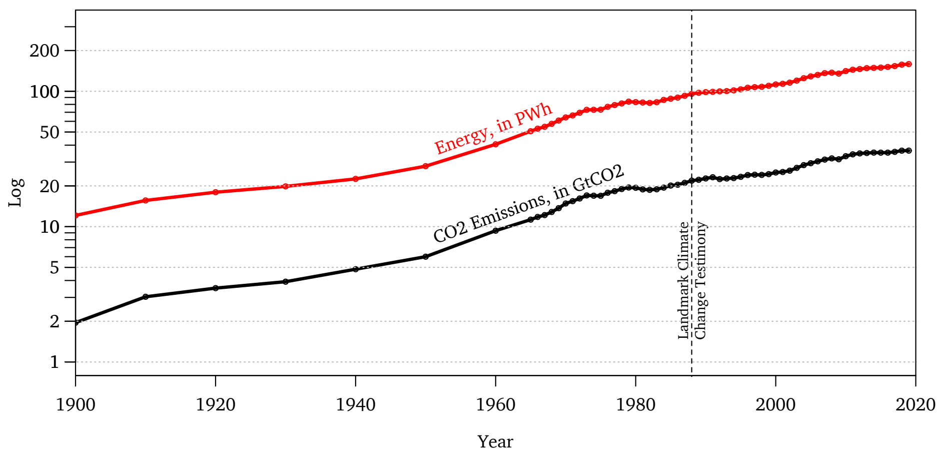


Global Trends

Is it possible to disconnect the world's emission growth from its energy growth (itself caused by population and income growth, especially in non-OECD countries)? Is climate activism an important part of the answer?

We can test this informally. The scientific and popular concern about the cumulative effect of greenhouse gases began only fairly recently. In 1988, global emissions and climate change entered the popular conscience through (bipartisan) landmark testimony by NASA scientist James Hansen to Congress.

Figure 12. Primary Energy Use and CO_2 Emissions



Source: Our World in Energy, global primary energy; and Our World in Data, CO_2 emissions. The numbers are annual measures. The scale is in log, which is visually less alarming. Don't look at the trends. Many variables have upward time trends. Instead look at how deviations from the trend have occured together.

Has the subsequent increased awareness of global warming made much of a difference in reduced economic activity or decoupling CO_2 emissions from economic development? Apparently not yet.

Figure 12 shows how world CO_2 emissions continued to grow in lockstep with energy just as (un-)healthily after 1988 as they did before. The reason is simple: most human emissions of CO_2 were still occurring in the energy provision sector, which was still mostly met by fossil fuels emitting greenhouse gases; and most population and consumption growth occurred in China.

Although the figure is not proof, it does suggest that climate activism has not made a large dent. If you place your faith in more activism, ask yourself this: who needs to become more aware of or concerned about climate change than they are already today? If it has not worked in the past, how exactly will it work in the future? We are not against climate activism. We are just skeptical about whether activism will be more effective in the future.

So what have climate activists *really* accomplished? Pundits have been lamenting year after year that no meaningful progress has been made — today's *Associated Press* headline reads "UN climate report: 'Atlas of human suffering' worse, bigger"). And then the pundits have repeated the same script the following year.

You may or may not agree with Greta Thunberg, but she does have one incontrovertible point: collectively, humanity has not done much so far to curb its emissions. Every year, the world is falling further and further behind on climate activists' aspiration.

Greta is right on her observation, but she is wrong about what the relevant problem is. If she is hoping for collective world action, we are predicting that it will not happen. (We will explain our reasoning in part II of our book.) The world has no central collective decision-maker. Instead, countries and people can only make decisions for themselves. It is not the collective decision problem that matters but the many individual decision problems that do.

Emissions and Emissions Efficiency

The previous chapter explained that primary energy consumption is determined primarily by (a) population, (b) economic activity (income) per capita, and (c) efficiency. It also explained how difficult it would be to tackle population and per-capita income, especially in non-OECD countries which want to escape widespread poverty. Finally, it described how humanity is making good but insufficient progress in energy efficiency all over the globe.

This means that in order to break the link between energy use and emissions, the only remaining lever is working towards higher emission efficiency — less CO_2 emitted for each unit of energy. This means using cleaner energy sources.

Table 13. CO2 Per Unit of Primary Energy, 2022

	CO_2 ($GtCO_2$)	=	Energy (PWh)	×	Energy Efficiency (g/KWh)
OECD	12.1	=	71	×	170
USA	4.8	=	28	×	170
EUR	3.8	=	24	×	160
Not OECD	24.2	=	116	×	209
China	11.0	=	48	×	232
India	2.7	=	12	×	226
Other Asia	2.8	=	14	×	203
Africa	1.3	=	7	×	184
World	36.3	=	187	×	194

Note: Non-OECD countries generally use dirtier energy sources.

Source: US EIA International Energy Outlook, Oct 2021. CO_2 and Primary Energy.

➤ The Current State

Table 13 shows how energy and emissions are related in different regions. OECD countries emit less CO_2 for each unit of energy consumed than non-OECD countries. They rely relatively less on coal and relatively more on natural gas, hydro, nuclear, wind, and solar power. Europe is the most emission-efficient region; China is the least emission-efficient.

Although there are clear differences in the types of energy used and thus their emissions, these differences are not orders of magnitudes. If the goal is to reduce the emissions of CO_2, the efficiency gains need to improve by an order of magnitude. This can only be accomplished by using more clean energy and less fossil fuel.

➤ The Growth

Do trends suggest that the world can reach much greater emissions efficiency anytime soon? Table 14 shows what the EIA reports for historical growth and expects for future growth.

OECD countries have been and are likely to continue covering all their growth in (GDP and) energy use with cleaner energy — although they will remain at their high levels of per-capita emissions. Europe's per-capita emissions are already close to those in non-OECD countries. This is not the case for the United States, whose per-capita emissions run at twice the rate of Europe's. The United States could reasonably and plausibly go quite a bit lower in per-capita emissions with some effort.

Beyond the OECD, the EIA projects that clean energy is not likely to arrest emissions growth, either this coming generation (2050e) or the generation thereafter (2080e). Yes, non-OECD emissions will grow relatively slower in percentage terms than they have in the past, but there is little cause to celebrate. Their base level of emissions is now much higher than it was in 1994, so their growth in emissions is not even slowing down in absolute terms. And unfortunately Earth has not been growing in its ability to absorb more emissions.

China and India had the highest growth in emissions over the last 30 years, relying disproportionately on coal power. India is the only region which did not manage to improve emission efficiency, but its share of global emissions was small in the past.

Looking forward, China will continue to grow its per-capita income growth and energy consumption, but efficiency improvements will be able to cover it. Its population growth has slowed, its emissions efficiency is improving faster than its GDP growth, and it is installing clean energy sources faster than any other country in the world. But not all is well. China's more ambitious public climate-change promises are only set to kick in after 2050 — long after any contemporary promises will still be remembered. Its current policy is still to plan and build new coal plants at a record pace. Like the United States, China could do better on its emissions efficiency — not enough to stop the growth in world-wide emissions but important nevertheless. Currently, it's not happening.

Table 14. CO_2 Growth Per Unit of (Primary) Energy

	CO_2		Energy (E)		Efficiency (CO2/E)	
	94–22	22–50e	94–22	22–50e	94–22	22–50e
OECD	–0.08	–0.01	0.08	0.11	–0.16	–0.12
USA	–0.13	–0.03	0.05	0.16	–0.18	–0.18
EUR	–0.04	0.00	0.13	0.15	–0.16	–0.15
Not OECD	0.96	0.24	1.06	0.43	–0.10	–0.18
China	1.44	–0.05	1.74	0.19	–0.29	–0.24
India	1.51	0.77	1.51	1.08	0.00	–0.31
Other Asia	1.10	0.55	1.28	0.60	–0.18	–0.05
Africa	0.62	0.44	0.76	0.63	–0.14	–0.19
World	0.54	0.17	0.61	0.33	–0.08	–0.16

Note: These should be interpreted as (fractional) changes. However, because they are logged, the components on the right add up to the quantity on the left. The 2050e numbers are quoted in $GtCO_2$ in Appendix Chapter A.

Source: US EIA International Energy Outlook, Oct 2021. CO_2 and Primary Energy.

7 The Kaya Components

Remember that we started the book with the statement that there are only four ways to reduce emissions? The economist Yoichi Kaya first explained why. We can view human emissions through the lens of four components to summarize where we are:

1. We can reduce the number of people on the planet.

   Unfortunately, this is not happening. Human population is not decreasing but increasing. This is especially the case in poorer non-OECD countries — India and Africa, in particular.

2. We can reduce how much energy each of us consumes by reducing our economic activities — for example, by working, producing, and consuming less.

   This is also not happening. People in non-OECD countries want their economies to grow in order to escape poverty. Asian countries are making good progress.

3. We can improve the energy efficiency of our economic activities, reducing how much energy each of us consumes — for example, by insulating our buildings better, or producing and consuming less energy-intensive products.

   This is happening but not fast enough. China and the (much smaller) USA might be able to accelerate their efficiency gains in order to get closer to European standards, but it still won't be fast enough.

4. We can improve the emissions efficiency of our energy use — by switching from fossil fuels to clean energy.

   This is also happening but also not fast enough. Non-OECD countries still use dirtier energy sources than OECD countries. The EIA does not predict that they will be able to leap-frog wholesale over fossil fuels into clean energy.

These facts are collected and put into numbers in Table 15. Over the next generation, expect world emissions to grow as population grows and poor countries escape poverty — despite (insufficient) improvements in energy efficiency and emission efficiency.

Emissions By Population

Our discussion of emission associations is almost done. The last two questions that we want to address quickly are the following: How should we expect per-capita emissions to change with (1) population growth and (2) economic development.

Figure 16 stacks the CO_2 emissions by area. Admittedly, this figure is more tempting for finger-pointing than it is for finding a solution. If fingers are to be pointed, it should be at the countries with the highest bars. Anglo-Americans (USA, Canada, Australia) remain most profligate, followed closely by oil-rich middle-eastern countries and the former Soviet Union.

However, finger-pointing is unproductive. For example, when Wyoming residents emit 100 tCO_2/capita per year, the bar may be high, but it doesn't affect the planet much. It would only matter if there were hundreds of millions of Wyomans. Fortunately for the planet, there are only a few hundred thousand of Wyomans — negligibly few from a planetary perspective.

Table 15. Kaya Decomposition of Emissions, 2022

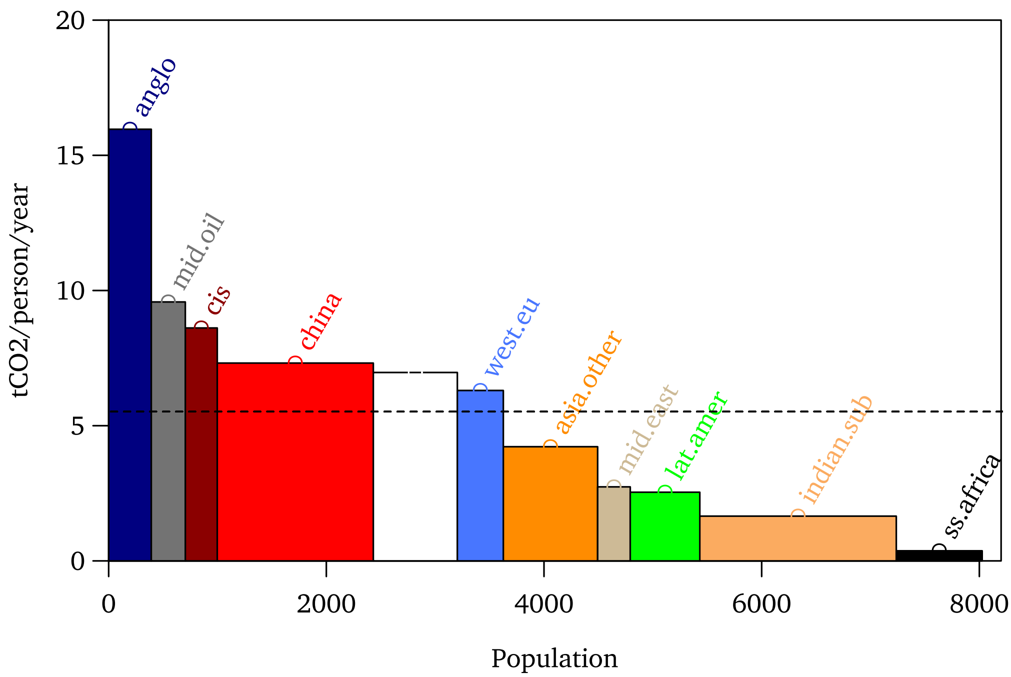
	emissions	=	population	×	income per person	×	energy inefficiency	×	emission inefficiency
	CO_2 ($GtCO_2$)	=	N (million)	×	GDP/N (1,000-$)	×	PE/GDP (KWh/$)	×	CO_2/PE (g/KWh)
OECD	12.1	=	1,380	×	43	×	1.2	×	170
USA	4.8	=	335	×	61	×	1.4	×	170
EUR	3.8	=	593	×	42	×	0.9	×	160
Not OECD	24.2	=	6,502	×	12	×	1.5	×	209
China	11.0	=	1,449	×	19	×	1.8	×	232
India	2.7	=	1,408	×	7	×	1.2	×	226
Other Asia	2.8	=	1,177	×	11	×	1.0	×	203
Africa	1.3	=	1,367	×	5	×	1.1	×	184
World	36.3	=	7,882	×	17	×	1.4	×	194
Forward-Looking Expected Growth Per Year									
2020-2050	+0.7%	=	+0.7%	×	+2.1%	×	–1.5%	×	–0.6%

Source: US EIA International Energy Outlook, Oct 2021: Primary Energy, Population, GDP in purchasing power parity, and CO_2.

If world emissions are to be reduced, it must be via reductions of the large areas. Reductions in thin slivers with higher bars just do not move the needle much. China's area in Figure 16 is already the biggest area. Even its per-person emissions — the height in the figure — are already larger than those in Western Europe. The blocks on the far right — the Indian subcontinent and sub-Saharan Africa — are likely to grow in both directions — in width and height.

Note also that the poorer non-OECD countries will not consent to global limits or shaming. They will always consider themselves not having emitted their "fair shares." The richer countries cannot help this either. Even if the richer countries on the left were to radically reduce their emissions in the future, there would still be their historical emissions to point to. Appealing to the global responsibility of poorer countries seems futile. Instead, for poorer countries not to emit more, they will need to come themselves to the conclusion that it is not in their own interests to emit their fair share.

Figure 16. Per-Capita and Total Emissions, 2019



Note: 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 was borrowed from MacKay, Chapter 1 (p12f).

Although the height of the bar in the graph is not the central concern when it comes to climate change, it does matter for global leadership. Realistically, with this high a bar, the United States will not be able to take on a leadership role. The rest of the world sees U.S. efforts largely as hypocritical — and subject to a "four-year fickle cycle."

The only credible region to lead the world could be the Europeans, having more aggressively curtailed their own emissions than any other region of the world.

No one will take me seriously in these shoes

However, so far, the European efforts have been largely misguided. They have been willing to offer many declarations (mostly about their own CO_2 goals) and too little technology to help poorer nations. That is, to the extent that the Europeans have put skin into the game, it has been the wrong skin. For example, when Germany declares war on global warming by reaching for zero emissions by 2035, it's laughable — not for its aspiration, but for its misunderstanding. Germany emits under 1 $GtCO_2$ per year. Even if Germany eliminates all its emissions, it will still have a negligible effect on world emissions. Germany is simply too small to matter much in itself. Germany could however help far more effectively and cheaply in a different way. It could deploy its advanced science, technology, and industrial base to help figure out how it can make it in the interest of all nations (and especially poorer ones) to reduce their emissions. For instance, it could work on better energy storage solutions. (We will return to this theme in later parts of our book.) Germany's current efforts seem not only wildly expensive, but also rather misguided as far as global warming is concerned. The goal should not be to reduce guilt feelings, but to reduce CO_2 in the atmosphere.

Table 17 summarizes the emissions both in total and per-person for our familiar regional categories. Per capita, Americans emit an embarrassing amount. Europeans emit remarkably little — they are already near the non-OECD average. Ironically, the Chinese are so bad they are now ven "beating" the Europeans as far as emissions per person is concerned — not an accomplishment to be proud of. And there are hundreds of million more Chinese than Europeans!

Table 17. CO2 Per Person, 2022

	CO_2 ($GtCO_2$)	Population (million)	Per-Capita (tCO2/year)
OECD	12.1	1,380	8.8
USA	4.8	335	14.4
EUR	3.8	593	6.4
Not OECD	24.2	6,502	3.7
China	11.0	1,449	7.6
India	2.7	1,408	1.9
Other Asia	2.8	1,177	2.4
Africa	1.3	1,367	1.0
World	36.3	7,882	4.6

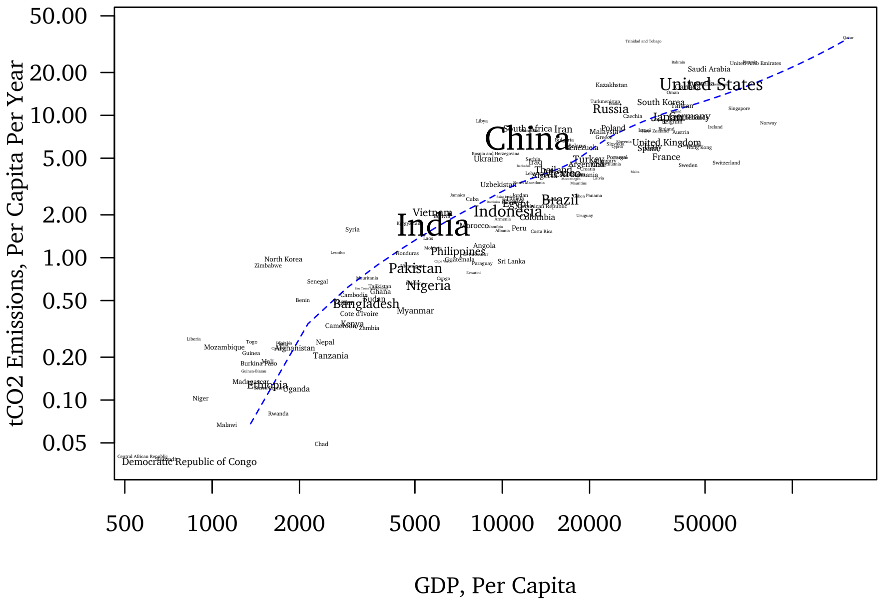
add % change for world expected to 2050e?

Source: US EIA International Energy Outlook, Oct 2021. CO_2 and Population.

Emissions By Economic Development

How do emissions change with economic development? Figure 18 suggests (but does not prove) an interesting association. As countries climb the economic development ladder, per-capita emissions first climb steeply for the very poorest regions. Once countries reach middle-income levels, their per-capita emissions still climb but less steeply. They can afford to become more energy-efficient. Furthermore, not shown in the figure, as countries climb out of the low-income into the middle-income group, they also tend to have fewer children, so their population growth slows. The unabated population growth pattern suggests that allowing subsistence poverty to persist in the lowest-income countries may not just be ethically wrong, but it may ultimately harm the planet's climate as well.

Figure 18. CO_2 Per-Capita vs GDP, By Country in 2018



Note: The population size is indicated by the size of the text. The relation between GDP and CO_2 is roughly linear (both X and Y are in logs), although it is steeper for the poorest countries. Richer countries use more fossil fuels and thus emit more CO_2.

Source: Our World in Data.

Emissions Efficiency by Country

Our last subject is about emissions efficiency. It is the (inverse of the) product of Kaya's two efficiency components: (1) energy use per unit of GDP (energy efficiency) and (2) emissions per unit of energy (emissions efficiency). How efficient are different regions with respect to their per-income emissions? Which regions are emitting pollution frugally vs. gratuitously?

Table 19 provides a snapshot of the 2022 data. Countries can produce a dollar's worth of GDP with about 0.1 KWh (the equivalent of about 1-2 cent in primary energy cost). Energy is an important ingredient into almost every economic activity, but it is a relatively cheap one.

The Europeans are most energy-efficient, followed by other Asian countries and Africa. China is again least efficient. This is not just an accident but

Table 19. Efficiency

	Energy	Emissions	Total
	GDP/Energy ($ / KWh)	Energy/CO_2 (KWh/Kg)	GDP/CO_2 ($/g)
OECD	8.39	5.88	4.94
USA	7.19	5.88	4.23
Europe	10.56	6.24	6.59
Not OECD	6.51	4.79	3.12
China	5.71	4.32	2.47
India	8.49	4.43	3.76
Other Asia	9.63	4.92	4.74
Africa	9.48	5.43	5.15
World	7.22	5.16	3.73
Forward-Looking Expected (Log) Growth			
2020–2050	+41%	+17%	+57%

Note: Higher numbers are better. OECD countries are more efficient than non-OECD countries per GDP. European countries are most efficient, China is least efficient.

Source: US EIA International Energy Outlook, Oct 2021. GDP in purchasing power parity, CO_2 Emissions, and Primary Energy.

policy-based. The Europeans 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.

The Europeans are also most emission-efficient. This is determined primarily by the source of energy. China uses mostly coal for its electricity, which is why its emission-efficiency is so poor. Putting energy and emission efficiency together, Europe is about 2–3 times more efficient in terms of GDP per gram of CO_2 emissions than China and about twice as efficient as non-OECD countries.

The least energy-efficient economies are generally in poorer regions and predominantly in Asia. As they become richer, they will also use energy more efficiently. This seems to be the typical economic dynamic as countries move up the value chain.

Chinese state propaganda often likes to tout improving energy-efficiency per GDP as the country's green commitment to the world. Frankly, this improvement is natural and to be expected. It has been happening almost everywhere. Yet, our dismissal of Chinese propaganda may not be entirely fair to Asian countries and China in particular. Comparing CO_2 efficiency across countries is 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), Sweden would also pretty quickly run out of hydro-electric power and could be forced to 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).

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. Cheap energy is just one input. Cheap labor is even more important.) Yet imagining that higher-cost European 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 could 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, they reduced their own emissions but these losses did not curb global emissions.

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 both over time as they have become wealthier. However, Figure 18 showed that richer countries still emit more per person. The improved efficiency from higher GDP was not enough to outweigh the effect of higher GDP on total emissions in non-OECD regions. 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.

Looking forward to 2050, all regions of the world are expected to be able to produce more GDP with fewer grams of CO_2. Production efficiency will improve even faster than emissions efficiency (clean energy). There are often easy fixes — like better insulation. Nevertheless, efficiency improvements will not be enough to cover the increasing energy needs of the world.

8 Reducing the World's Emissions

There are hard facts of life — facts that acolytes would prefer to ignore. Al Gore was insightful when he called them "inconvenient." The world is warming. The cause is almost surely fossil fuel emissions.

But there are also other hard facts of life that Al Gore and we need to face:

- We in the West are so ethnocentric that we have lost perspective about how much less important we have become — and thus also of what we can accomplish.

  Emissions are no longer primarily an OECD problem. They are primarily a non-OECD problem. By 2050, the OECD will no longer contribute only the minority *one-third* of world emissions that it does today, but only a minority *one-quarter*.

  Even if the OECD could halve its emissions — via efficiency gains or painful forced reductions in economic activity, an unattainable aspiration over the next 30 years absent major scientific breakthroughs — it would reduce global emissions by only 15%. A whole 85% of global emissions (and growing) would still remain.

  If we truly want to reduce (or merely arrest) global emissions, it makes no sense to try to accomplish this primarily via reductions in OECD countries — no matter how appealing this may be to fairness and climate activists. We can do so only via (shared) reductions in non-OECD countries.

  Fighting climate change just in rich countries is like fighting a fire only on one side of the house while letting it expand on the other side.

- CO_2 emissions are not only increasing but still accelerating in absolute terms. Non-OECD regions are responsible. The word "culprit" seems inappropriate, though. The obstacles to slowing down their emissions growths are
  1. widespread poverty (that energy-fueled economic growth can reduce); and
  2. the lack of access to technology that would allow them to leapfrog over fossil fuels.
- We need to find viable solutions to allow poor countries to grow their way out of poverty without increasing their emissions (as much). The United Nations donation box will almost surely not deliver such solutions. Neither does it appear that United Nations climate conferences will deliver global emission cuts.

  The only viable lever to slow worldwide emissions is to break the link between energy consumption and emissions. Poor countries will have to find it in their interests to grow out of poverty with clean energy rather than with fossil fuels. They will have to want to leapfrog over the fossil-fuel stage right into a clean-energy stage — much the same as many of them have leap-frogged over telephone landlines right into cellular mobile phones.

  Whether developing countries will want to go the clean-energy route will mostly depend on which technology will be less expensive on a large scale. Making clean and reliable energy a lot cheaper is the only viable solution.

Western climate activists have had little of real use to offer to the poor countries that are becoming the key to combating climate change. Despite all the publicity that climate activism in the West has been garnering, its results have been mostly mutual accusations and finger-pointing, squabbling among rich countries, and empty declarations of progress. Almost all actual progress in lower emissions has been due to the decline in the cost of clean energy — even in richer countries.

The world's playbook response to bad climate news year after year has always been to "lament and repeat." Then again, there is no world collective that could have had a playbook to begin with. Thinking there could be such a collective in the future is fantasy. Trusting in such a collective to save the world is deluded.

Don't blame the messenger.

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 many useful emission estimates and calculations.
- Kaya, Yoichi; Yokobori, Keiichi (1997). Environment, energy, and economy : strategies for sustainability, United Nations Univ. Press. The Kaya identity expresses the total emissions of CO_2 as the product of four factors: human population (P), GDP per capita (GDP/P), energy intensity (per unit of GDP, E/GDP), and carbon intensity (emissions per unit of energy consumed, $CO2/E$). Our own flavor is a closely related variation. In the previous chapter, we used $E = P \times (E/P) = P \times (E/GDP * GDP/P)$. In this chapter, we used $CO_2 = (CO2/E) \times E$.

Articles

- Colt, Stephen G and , 2016, Economic Effects of an Ocean Acidification Catastrophe argues that the economic harm would be very low — perhaps too low.
- Qiu, Chunjing, et al., 2021, Large historical carbon emissions from cultivated northern peatlands, Science Advances. Northern peatlands converted to croplands from 850 to 1750—i.e., long before the industrial revolution—can account for 120 $GtCO_2$.
- Mooney, Chris, 2021, An enormous missing contribution to global warming may have been right under our feet, Washington Post.
- Union of Concerned Scientists, 2021, Peatlands and Climate Change, Issue Brief. (Peatlands include permafrost and store more CO_2 than forests or the atmosphere.)

Reports

- US EIA International Energy Outlook, Oct 2021, our primary data source.
- OECD, 2017, Green Growth Indicators, Country-Based.

Shorter Newspaper, Magazine Articles, and Clippings

- O'Hara, Fred (ed), 03/2018, Carbon Dioxide Information Analysis Center — Conversion Tables, Carbon Dioxide Information Analysis Center.
- Curtis, Tom, 07/25/2012, Climate Change Cluedo: Anthropogenic CO2 (Attributing atmospheric CO_2 to human emissions), Skeptical Science.
- Friedrich, Johannes, et al., 08/10/2017, 8 Charts to Understand US State Greenhouse Gas Emissions, World Resources Institute.

- Johnson, Scott K., 11/05/2021, Recent CO_2 emissions flattened out by revised forest data, Ars Technica.
- Mider, Zachary, 08/20/2021, The Methane Hunters, Bloomberg.
- Painting, Rob, 11/12/2015, Why were the ancient oceans favorable to marine life when atmospheric carbon dioxide was higher than today?, Skeptical Science.
- Unnamed, 10/24/2021, The Chinese Companies Polluting the World More Than Entire Nations, Bloomberg.

Websites

- `https://www.eia.gov/outlooks/ieo/` is the main source of our information.
- `https://ourworldindata.org/` curates data on important phenomena.
- `https://skepticalscience.com/` debunks many climate-skeptics' claims.
- Global Carbon Atlas, based on Andrew and Peters, 2021.
- `https://www.rff.org/geo/`, *Resources for the Future*, offers a meta outlook based on different projections from different sources.

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.