

EC1340 Topic #1

Introduction and Accounting for Carbon

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Outline

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- 4 Emissions and consumption
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- 9 Conclusion

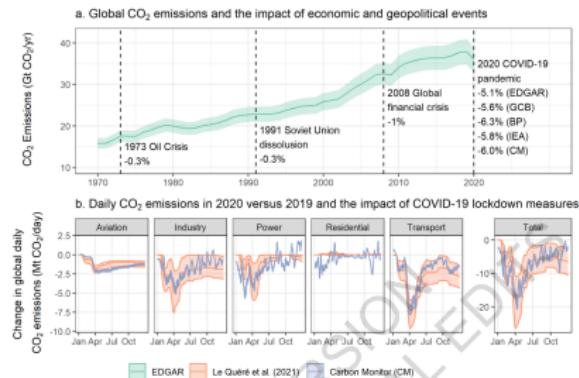
Stabilizing atmospheric CO₂ I

- World emissions of CO₂e in 2019_(2022 IPCC report) were about 59 Gt. Stabilizing atmospheric concentrations (not temp) requires cutting this to about 25Gt.
- There are about 8 bn people in the world as of 2022. Stabilization requires reducing emissions to 25Gt/8bn ≈ 3.0t CO₂e ≈ 1t C emissions per person.
- 2019 per capita CO₂e /incomes are about: US, 18.2t/69,000\$; China is 11.0/12,500\$; India is 2.3/2300\$.
- The US needs between a 50% and 80% reduction if the world is to reach this target.

This appears difficult to accomplish without reducing the number of people, their consumption, or being very clever. Being clever looks attractive here.

Stabilizing atmospheric CO₂ II

To get a sense for how difficult, consider this,



Box TS.1 Figure 1: Global carbon emissions in 2020 and the impact of COVID-19

Box TS.1 Figure 1 legend: Panel a depicts carbon emissions from fossil fuel and industry over the past five decades. The single year declines in emissions following major economic and geopolitical events are shown, as well as the single decline recorded in five different datasets for emissions in 2020 compared to 2019. Panel b depicts the perturbation of daily carbon emissions in 2020 compared to 2019, showing the impact of COVID-19 lockdown policies. (Figure 2.6)

The pandemic reduced 2020 CO₂ emissions by only about 5% from 2019 levels.

Some questions

- The Inflation Reduction Act (the 2022 Manchin-Schumer climate bill) includes about 360 b for clean energy and energy efficiency. Is this a good idea?
- The Green New Deal proposes meeting 100% of US power demand with renewables. Is this a good idea?
- Given that the RGGI (Regional Greenhouse Gas Initiative) is in place, is the state carbon tax Aaron Regunberg proposed a good idea? RGGI website is here, <https://www.rggi.org/>. As of Q1 2022 the allowance auction cleared at \$13.90 per allowance.

An allowance allows emission of 1 short ton of CO₂ by New England power plant > 25MW.(short ton = 2000lb
<2200lb = 1000kg= 1 metric ton).

- How scary is this animation?

<https://matthewturner.org/ec1340/lectures/pnas.1512482112.sm01.avi>

(personal correspondence, Anders Levermann, Sept. 2018).

Contents of the course

We would like to think carefully about the questions that climate change raises. For example,

- How fast should we approach CO₂ stabilization?
- What are the trade-offs between economic welfare and climate?
- What policies should we use to achieve CO₂ reductions?

To think about these questions, it would be helpful to have a model in which the tradeoffs between consumption, emissions and climate at one time and another can be explicitly calculated and examined.

The model developed in ‘A Question of Balance’ does exactly this, and one of the main objectives of the course is to allow you to read this book and to understand what it does.

As a preview, here is some of the Nordhaus, DICE (Dynamic Integrated Climate Economy) model:

$$W = \sum_{t=0}^{24} L(t) \frac{c(t)^{1-\alpha}}{1-\alpha} \left(\frac{1}{1+\rho} \right)^t \quad (1)$$

$$Q(t) = \Omega(t) [1 - \Lambda(t)] A(t) K(t)^\gamma L(t)^{1-\gamma} \quad (2)$$

$$Q(t) = C(t) + I(t) \quad (3)$$

$$K(t) = I(t) + (1 - \delta_K) K(t-1) \quad (4)$$

$$E(t) = \sigma(t) [1 - \mu(t)] A(t) K(t)^\gamma L(t)^{1-\gamma} \quad (5)$$

$$\Lambda(t) = \pi(t) \theta_1(t) \mu(t)^{\theta_2} \quad (6)$$

plus a description of the way climate, carbon, population and technology evolve.

The DICE model has more stuff in it than we need to start thinking about the problem (and it's a bit hard).

What is the minimum amount of hardware that we need to discuss this problem? We need to describe (at least),

- how CO₂ affects climate (a climate model).
- the carbon cycle.
- how CO₂ comes from consumption.
- how climate affects consumption (and/or utility).
- how we can use resources to reduce CO₂, i.e., a mitigation equation.
- how we are willing to make tradeoffs across time.

Notice several of these items describe physical science surrounding climate change. These are covered in the other main reading for the course, 'Storms of my grandchildren'.

Here is the math that goes with the list we just generated. It looks a lot like the ‘consumer problem’ you know, but with more complicated budget constraints. This will help us to organize ideas and keep track of our progress. Once we have worked our way through this problem, we’ll be ready to tackle Nordhaus.

To start, we’ll need some notation,

- c_1, c_2 = per capita consumption now and in 100 years
- W = per capita wealth/income today
- I = investment today
- M = expenditure on mitigation today
- $E_1 = (1 - \rho_4 \frac{M}{W})(\rho_5(c_1 + I))$ = Emission of CO₂ today
increases in I , c_1 and decreases in M
- P_1, P_2 = Atmospheric concentration of CO₂ now and in 100 years
- T_1, T_2 = climate now and in 100 years

Using this notation, we can state the ‘baby DICE’ model (BDICE) as

$$\max_{I,M} u(c_1, c_2) \quad \text{utility} \quad (7)$$

$$\text{s.t. } W = c_1 + I + M \quad \text{budget} \quad (8)$$

$$c_2 = (1+r)I - \gamma(T_2 - T_1)I \quad \text{production} \quad (9)$$

$$E = (1 - \rho_4 \frac{M}{W})(\rho_5(c_1 + I)) \quad \text{emissions} \quad (10)$$

$$P_2 = \rho_0 E + P_1 \quad \text{carbon cycle} \quad (11)$$

$$T_2 = \rho_1(P_2 - P_1) + T_1 \quad \text{climate model} \quad (12)$$

- Choose savings and mitigation to maximizes welfare u . \implies carbon concentration path. These are the IPCC’s ‘Representative Concentration Pathways(s)’
- Physical quantities like climate or the relationship between CO₂ concentration and climate are like prices and endowments.

We're going to work towards an understanding this problem, one parameter and equation at a time. To do this, we'll need to study the following topics

- Emissions and endowment of atmospheric carbon, E , ρ_5 , P_1 and P_2 .
- The endowment of climate, T_1 .
- The link between atmospheric CO_2 and future climate, ρ_1 , T_1 (climate model). ρ_1 is often called 'climate sensitivity', more later.
- The link between emissions and atmospheric CO_2 , ρ_0 (Carbon cycle)
- Cost of climate change, γ .
- Cost of mitigation (reduction of emissions), ρ_4 .
- What should u look like (discounting and uncertainty)

Once we understand this, we'll be able to think about solving the global warming problem, and we'll be ready to tackle the Nordhaus model.

Other things we'll want to think about that aren't in the basic global warming problem (but are in the Nordhaus model)

- Population growth
- Economic growth
- Dynamics – this is a dynamic problem, so c , T are consumption paths and climate paths. A wise regulatory program will reflect the fact that investments in climate and economic growth have different returns at different times. This will turn out to suggest a ‘ramping up’ of mitigation expenditures.
- There is LOTS of uncertainty. This makes everything more difficult.
- There may be ‘thresholds’ that, once crossed, lead to discontinuous changes in the environment.

These are just generalizations of the basic model.

With the model in hand, we'll be able to think about policies to manage CO₂. This will be the last third of the course.

Units for measuring Greenhouse gases(GHG) I

We need to be careful about the units we use to track carbon.

- A Ton is 1000kg(about 2200lb). A Megaton (Mt) is 1,000,000 tons. A Gigaton(Gt) is a billion tons or 1000Mt.
- A molecule of CO₂ , is about 44/12 as heavy as a molecule of C . Each ton of C is 44/12 tons of CO₂ .
- *Hansen and IPCC 2007/2013 Physical Science Basis* measure emissions in terms of Gt C , but *Stern, IPCC 2007/2013 Mitigation of Climate Change* measure emissions in terms of Gt CO₂ .
- Each ppm of atmospheric C is about 2.12 Gt C or $2.12 \times (44/12) = 7.77 \text{ GtCO}_2$. This is a standard conversion factor, both IPCC and Hansen use it. (gigatons = billion tons).

Units for measuring Greenhouse gases(GHG) II

In April 2021, the concentration of co₂ in the atmosphere was 419 ppm. This is equal to 888 Gt c and 3257 Gt co₂ .

CO₂ is not the only GHG I

Table 8.1 Characteristics of Kyoto Greenhouse Gases

Despite the higher GWP of other greenhouse gases over a 100-year time horizon, carbon dioxide constitutes around three-quarters of the total GWP of emissions. This is because the vast majority of emissions, by weight, are carbon dioxide. HFCs and PFCs include many individual gases; the data shown are approximate ranges across these gases.

	Lifetime in the atmosphere (years)	100-year Global Warming Potential (GWP)	Percentage of 2000 emissions in CO ₂ e
Carbon dioxide	5-200	1	77%
Methane	10	23	14%
Nitrous Oxide	115	296	8%
Hydrofluorocarbons (HFCs)	1 – 250	10 – 12,000	0.5%
Perfluorocarbons (PFCs)	>2500	>5,500	0.2%
Sulphur Hexafluoride (SF ₆)	3,200	22,200	1%

Source: Ramaswamy et al. (2001)⁸ and emissions data from the WRI CAIT database⁹.

From Stern 2008, table 8.1

CO₂ is not the only GHG II

- Aggregate all GHGs using conversion factors based on their 'global warming potential(GWP)'. This gives us measurements in terms of 'CO₂ equivalent' (CO₂e).
- April 2021 concentration of CO₂ was 419 ppm. Using the numbers above, current CO₂e is $419\text{ppm}/0.77 = 544\text{ppm CO}_2\text{e}$.
- GWP combines the ability of a molecule to reflect radiation and its lifetime in the atmosphere. More on this later, it's pretty made up.
- Social scientists usually measure Green house gases in terms of CO₂ equivalent emissions:

Units, again

Stern 2007 p193 gives CO₂e emissions for 2000 as 42Gt CO₂e .

Hansen has 8.5 Gt C from fossil fuel.

Can we reconcile these numbers?(Yes)

- About .77 of CO₂e is CO₂ .
- About .18 of CO₂ is non fossil fuel (more on this later)
- Stern reports CO₂ , Hansen C

so, Stern's 42 Gt CO₂e becomes:

$$42 \times (.77(1 - .18)) \times (12/44) = 7.2 \text{ Gt of atmospheric C} .$$

It would be closer, but Stern uses 2000 numbers and Hansen's 8.5 is for about 2008.

Emissions for particular activities I

- CO₂ from gasoline, 2.3 kg/liter = 19.4 pounds/gallon. So, 1000 kg of CO₂ emission results from 435 liters or 114 gallons of gas. (about 1% not burned is mostly N₂O so CO_{2e} is higher).
- CO₂ from diesel 2.7 kg/liter = 22.2 pounds/gallon 1000 kg of CO₂ emission results from 370 liters or 97 gallons of diesel.

<http://www.epa.gov/otaq/climate/420f05001.htm#calculating>

- BBQ propane tank, about 18 pounds propane = 24kg = 53 lb CO₂. (NB Gasoline weighs 6.3 pounds/gallon so 18 pounds of gas gives about 54 pounds CO₂. Propane has more hydrogen per carbon atom than gasoline).

Emissions for particular activities II

- CO₂ sequestration by 1 acre 90 year old pine forest in Southeastern US is about 100 tons C , about 1 ton/acre/year. So burning this acre releases about 100 tons C or 367 tons CO₂ . <http://www.epa.gov/sequestration/faq.html> For tropical forests, about 1.8 times as much not reliable source.
- CO₂ from coal, about 2.00 tons CO₂ per ton (a lot of the stuff in coal is not burned – I think), or 2100lb CO₂ per 1000 KWH from non-baseload coal burning electricity generation. CO_{2e} is higher. Baseload will usually be lower (often nuclear or hydro) <http://www.eia.gov/tools/faqs/faq.cfm?id=74&t=11>.

Emissions for particular activities III

- For natural gas, about 1200lb CO₂ per 1000 KWH. So, fracking is fantastic, unless too much methane leaks before it's burnt. With 1 ton of methane worth 23 tons of CO₂, about 4.3% leakage makes coal and natural gas even (unless there is methane leakage from coal mines). The rate of leakage is contested, 2018 EPA estimate was about 1.4%, best 2013 estimate was 0.5% (Allen et al. PNAS 2013). Some 2020 estimates have the rate around 4%. Distribution technology matters.
- For reference: Avg household in RI = 500KWH/mo; Avg household in TX = 1000KWH/mo.

<https://www.eia.gov/tools/faqs/faq.cfm?id=97&t=3> (Feb 2016). Or, average household in Providence ~ 8000kwh/year in 2001, Dallas ~ 18,500kwh/year (Glaeser and Kahn, JUE 2010).

Emissions for particular activities IV

- For thinking about fracking, also consider the following:



Global emissions per unit of consumption, ca. 2019

Using these sorts of particular numbers, together with information about aggregate consumption, one can calculate world emissions.

- Global annual emissions ca 2019 are about 60Gt CO₂e or $60 \times \frac{12}{44} \sim 16.4$ Gt C (more on this later).
- World GDP in 2019 is about 86 trillion USD. (NB: this is W in our model).
- Dividing, we have $\frac{16.4 \times 10^9 \text{ tons C}}{86 \times 10^{12} \text{ USD}} = \frac{16.4 \text{ ton C}}{8600 \text{ USD}} \sim 0.19 \frac{\text{kg C}}{\text{USD}}$ (1 ton = 1000 kg). Multiply by 44/12 for CO₂ instead of C .

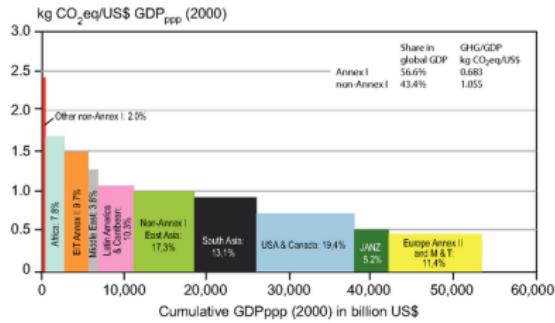
Recall the third equation from our global warming model:

$$E = (1 - \rho_4 \frac{M}{W})(\rho_5(c_1 + I)) \quad (13)$$

We've just calculated ρ_5 . Why is this sloppy?

Emissions per unit of consumption by country

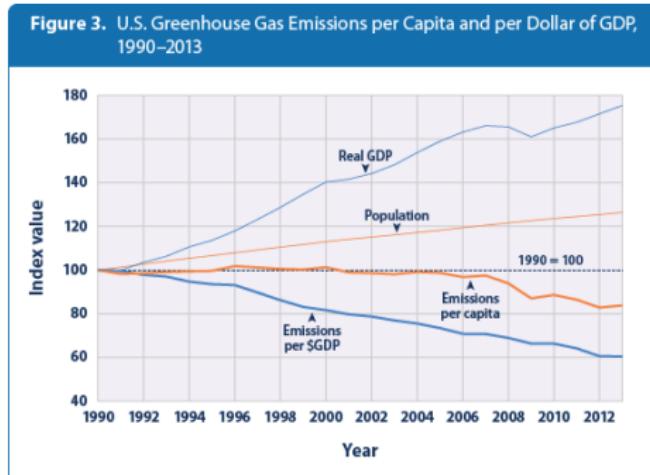
- It's also interesting to look at the country by country breakdown.(ca. 2004) The US and Canada make a lot of stuff per ton of emissions.



IPCC 2007 Mitigation fig SPM.3b

- What if China and Africa made same output at US/CA emission rates? This is why technology transfer is important.
- Compare 0.68 kg CO₂e per dollar ca. 2004 to my calculation of 0.19 kg C per dollar 2019. How important is technical progress?

Technological progress I



<http://www3.epa.gov/climatechange/science/indicators/ghg/us-ghg-emissions.html>, January 2016

Technological progress II

Nordhaus does this calculation every year, country by country

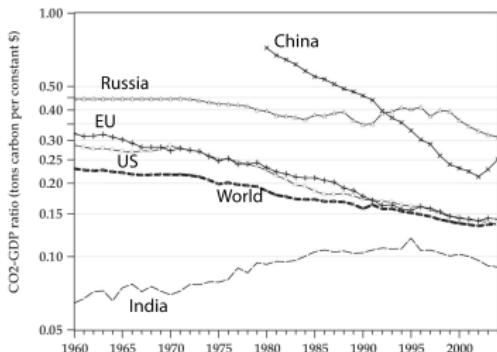


Figure 3-1. Historical ratios of CO₂ emissions to GDP for major regions and globe, 1960–2004. Trends in the ratio of CO₂ emissions to GDP for five major regions and the global total. We call the decline in this rate “decarbonization.” Most major economies have had significant decarbonization since 1960. The rates of decarbonization have slowed or reversed in the last few years and appear to have reversed for China. With the changing composition of output by region, the world CO₂-GDP ratio has remained stable since 2000. Note that “W C Eur” is Western and central Europe and includes several formerly centrally planned countries with high CO₂-GDP ratios.

Emissions - Summary I

- We've now calculated ρ_5 , emissions per GDP at about 0.19kg c per dollar ca. 2019.
- Looking at the data a little more carefully highlights two deficiencies on our model:
 - Technological progress is at work, so this ratio changes over time.
 - There are huge difference across places in this ratio

This highlights the importance of technological progress and technology transfer in solving the problem of climate change.

- We'll address this when we get to the Nordhaus model.

Emissions - Summary II

Recall,

$$\max_{I,M} u(c_1, c_2) \quad (14)$$

$$\text{s.t. } W = c_1 + I + M \quad (15)$$

$$c_2 = (1+r)I - \gamma(T_2 - T_1)I \quad (16)$$

$$E = (1 - \rho_4 \frac{M}{W})(\rho_5(c_1 + I)) \quad (17)$$

$$P_2 = \rho_0 E + P_1 \quad (18)$$

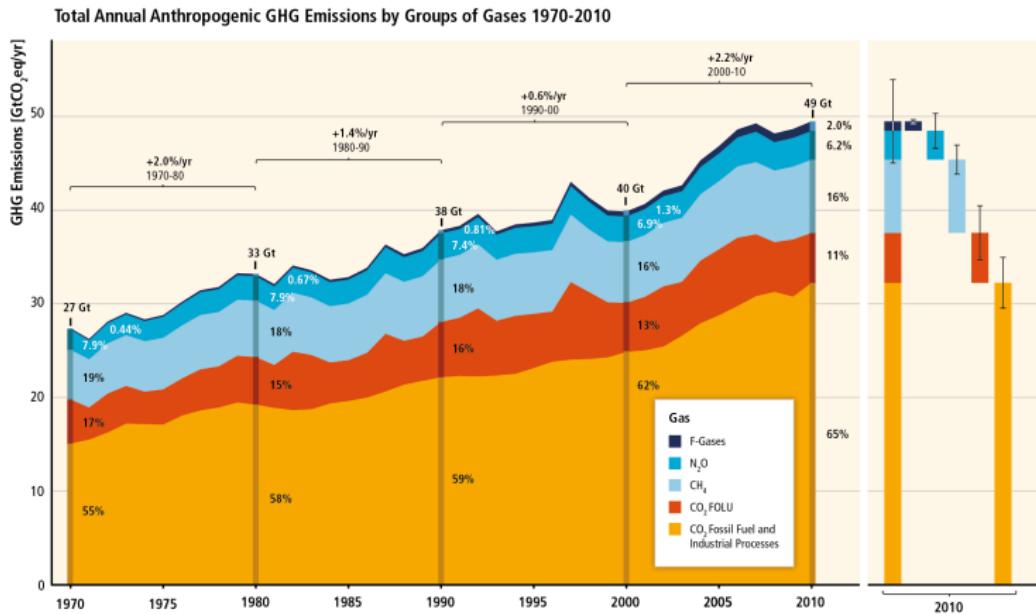
$$T_2 = \rho_1(P_2 - P_1) + T_1 \quad (19)$$

We've filled in $\rho_5 = 0.19 \text{kg}/\$$. W is world GDP. If $M \approx 0$ then $W = c + I$. We actually know $E \approx 13 \text{GtC/year}$ (just fossil C, not C_{org})

Emissions - Summary III

equivalent), but it's important enough to learn a little more about – coming up.

CO₂e 1970-2010



IPCC 2013 WG3 fig TS.1

Right panel gives confidence bounds for 2010. 49Gt CO₂e in 2010.

Emissions levels and trends

CO₂e 1990-2019

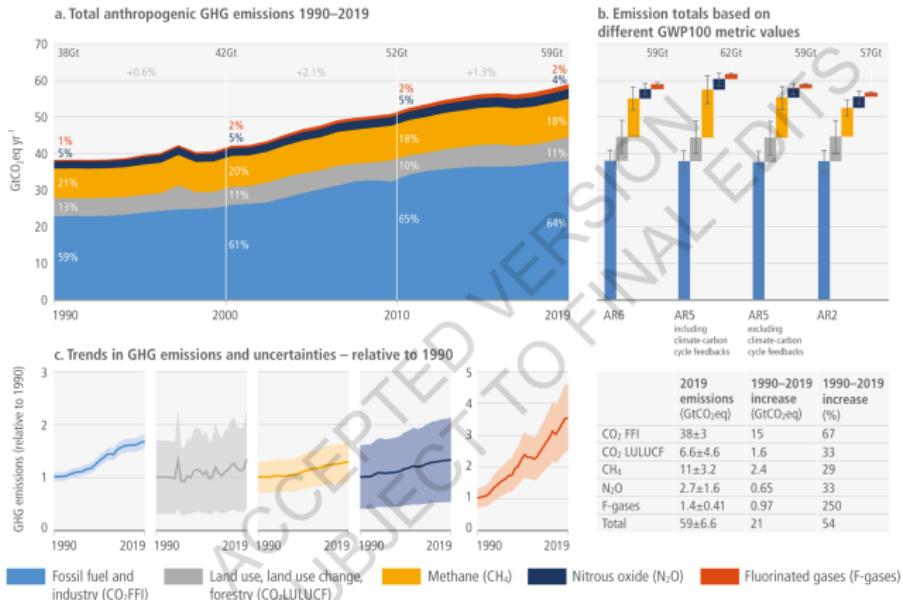
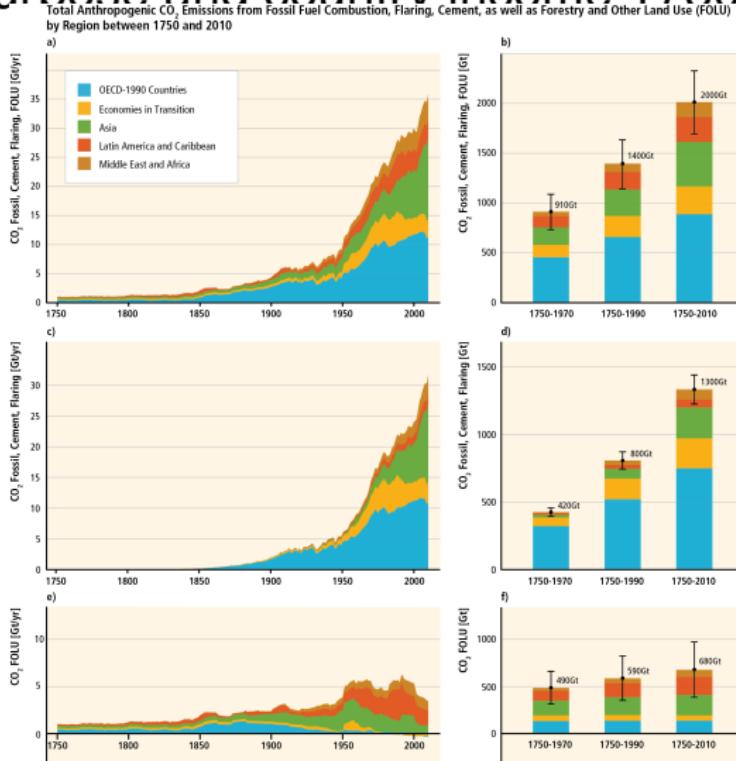


Figure TS.2: Global anthropogenic emissions have continued to rise across all major groups of greenhouse gases (GtCO₂-eq yr⁻¹) 1990–2019

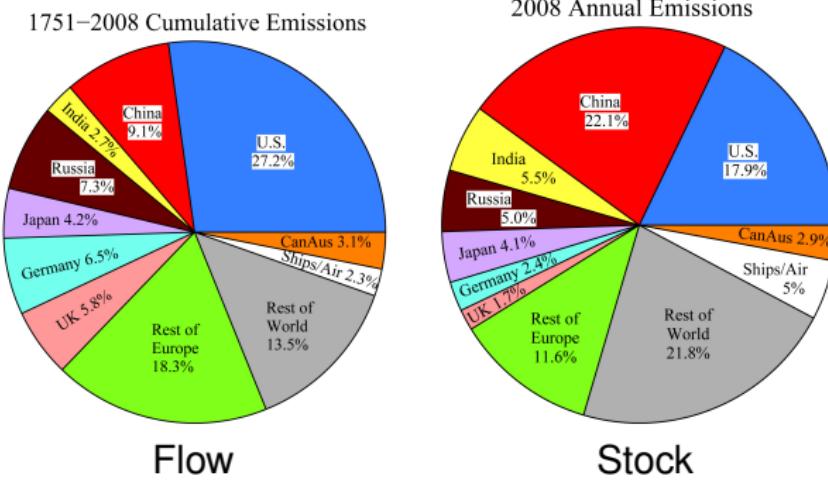
IPCC 2022 WG3 fig TS.2

CO₂ by purpose and country income 1750-2010



IPCC 2013 WG3 fig TS.2

Hansen's version of the same thing...

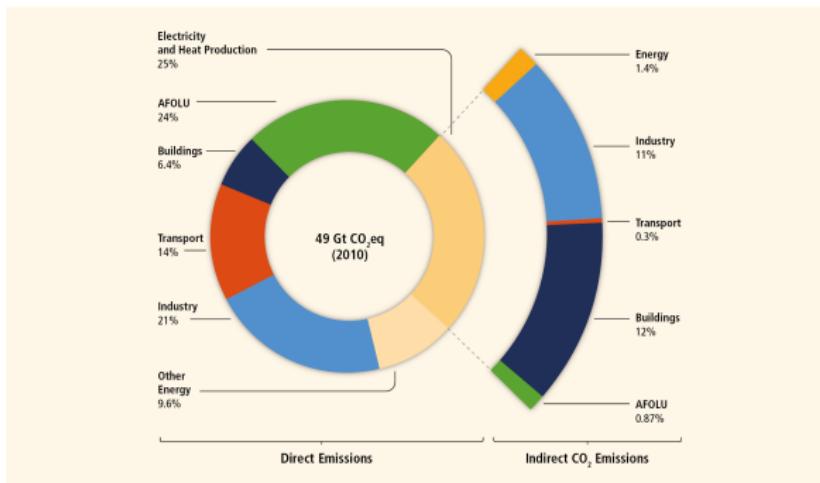


Hansen 2009 fig 27

Contributions to stock and flow are very different. At the negotiating table, developing countries want the right to emit, since everyone else had their turn.

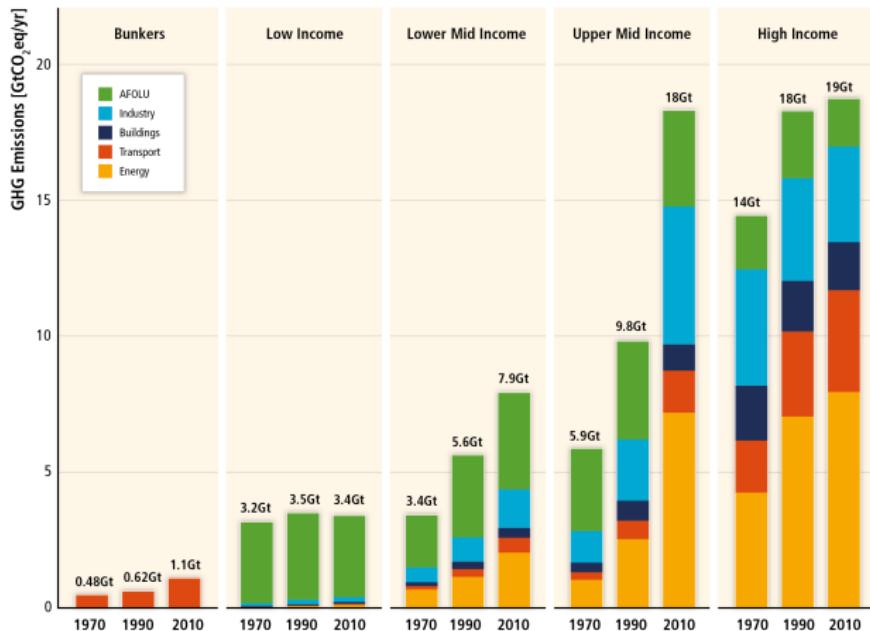
2010 CO₂e by purpose

Greenhouse Gas Emissions by Economic Sectors



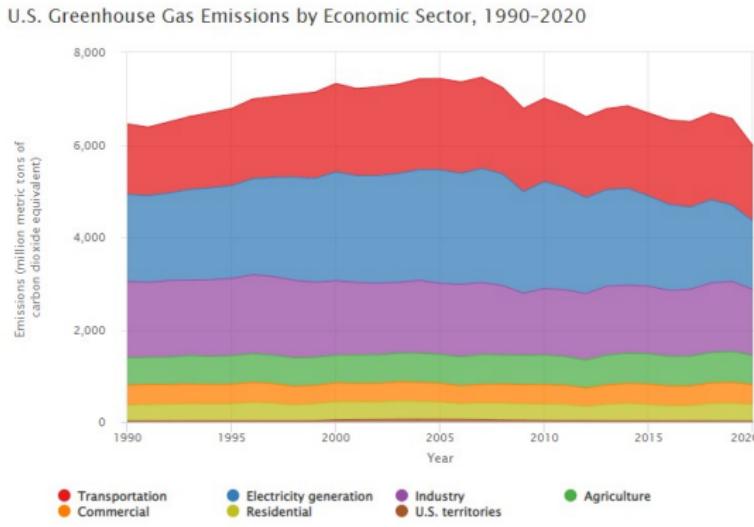
IPCC 2013 WG3 fig TS.3

2010 CO₂e by purpose and country income



IPCC 2013 WG3 fig TS.3

US 1990-2019 CO₂e

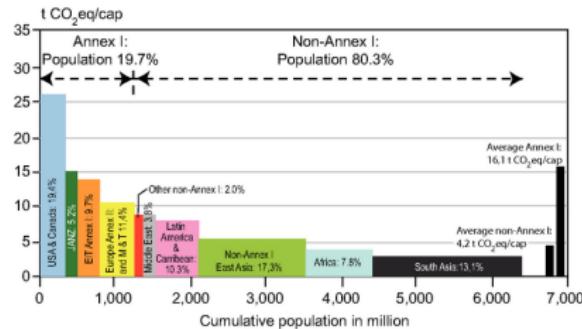
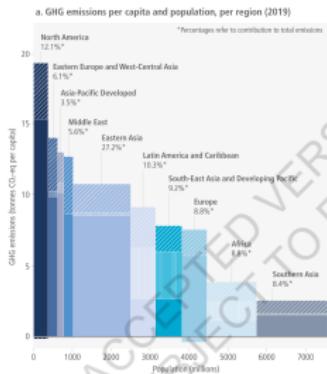


https://www.epa.gov/system/files/images/2022-04/emissions_econsector_1990-2020.jpg, July 2022

This reflects: fracking, recession, technical progress, off-shoring of manufacturing.

Emissions per person I

It's also interesting to look at the country by country breakdown in terms of emissions per capita. This is for 2019 and 2006:



IPCC 2022 WGIII TS 22

IPCC 2007 Mitigation fig SPM.3a

Emissions per person II

As of 2012(2019) US had 4.54(4.20) tons C /person and for India, this number was 0.46(0.50). China was 1.8(2.1). (<http://cdiac.ornl.gov/trends/emis/top2011.cap>(2012) and World Bank (2019)). Note that C /pp in developed countries is decreasing and increasing in less developed countries.

Summary

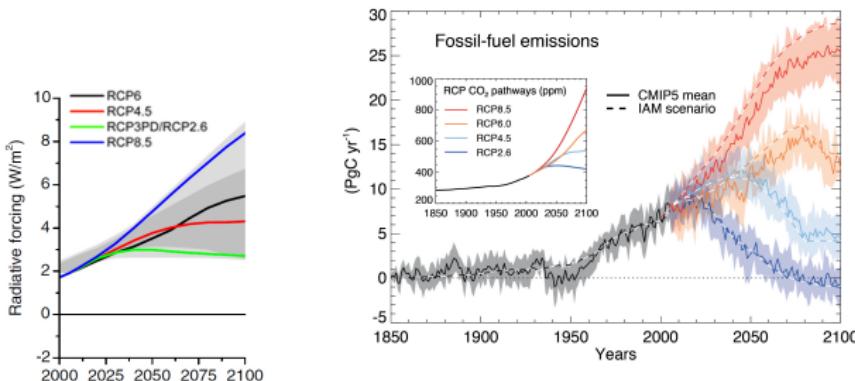
- 2019 emissions of CO₂e were about 59Gt. Of this, 45Gt was CO₂, and of this, about 38Gt from fossil fuels and 7Gt from land use change and agriculture. This is E in our model.
- Emissions are growing rapidly, about 2%/year between 2000 and 2019. 1970 CO₂e was 30Gt.
- 2010 CO₂e : 14% transport, 18% buildings, 21% industry 24% AFOLU. We could use this to calculate refinements of ρ_5 .
- The countries responsible for most of the stock are not the countries responsible for most of the flow.
- Per capita emissions vary by a factor of about 10 between rich and poor countries.
- There has been an absolute decline in US emissions since 2008 due to; fracking, recession, technical progress, off shoring. We are now below 1990 levels.

Future emissions/concentration I

What we really care about is the path of emissions going forward in time, not backwards. This is what we get to choose and this is a better match for E or P_2 in DICE/BDICE. The IPCC has two ways of talking about future emissions and concentrations; RCPs(old) and SSPs(new for 2022).

Future emissions/concentration II

The IPCC fifth assessment report is organized around RCPs.
These are hypothetical future levels of CO₂.



RCP 8.5 is ‘business as usual’ and involves CO₂ concentrations reaching 850 ppm within 100 years. Other RCPs involve varying degrees of mitigation. In the right panel, Pg is ‘petagram’, the same thing as Gigaton.

Future emissions/concentration III

The IPCC AR6 is organized around SSP's. These are hypothetical future levels of CO₂ and greenhouse gases. They are a more detailed version of RCPs. (This is too much detail for us.)

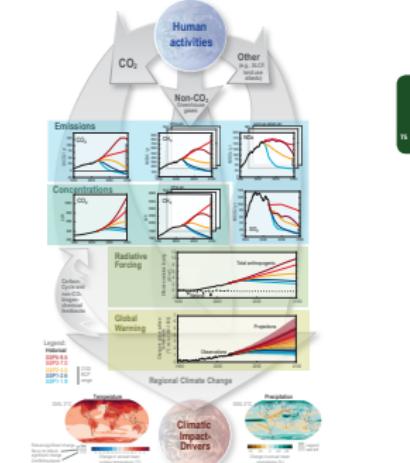


Figure T.16 | The climate change cause-effect chain. The intent of this figure is to illustrate the process chain starting from anthropogenic emissions, to changes in climate system components, to changes in global climate and ultimately to climate impact drivers. Issues in the context of this figure include: (i) the role of the climate system in determining the magnitude of climate change; (ii) the role of the climate system in determining the magnitude of climate impacts; and (iii) the role of the climate system in determining the magnitude of adaptation and mitigation responses. In changes in direct energy demand ('Warming'), no changes in global climate and ultimate climate impact drivers. Issues in the context of this figure include: (i) the role of the climate system in determining the magnitude of climate change; (ii) the role of the climate system in determining the magnitude of climate impacts; and (iii) the role of the climate system in determining the magnitude of adaptation and mitigation responses. In changes in direct energy demand ('Warming'), no changes in global climate and ultimate climate impact drivers. Issues in the context of this figure include: (i) the role of the climate system in determining the magnitude of climate change; (ii) the role of the climate system in determining the magnitude of climate impacts; and (iii) the role of the climate system in determining the magnitude of adaptation and mitigation responses. In changes in direct energy demand ('Warming'), no changes in global climate and ultimate climate impact drivers. Issues in the context of this figure include: (i) the role of the climate system in determining the magnitude of climate change; (ii) the role of the climate system in determining the magnitude of climate impacts; and (iii) the role of the climate system in determining the magnitude of adaptation and mitigation responses. In changes in direct energy demand ('Warming'), no changes in global climate and ultimate climate impact drivers. Issues in the context of this figure include: (i) the role of the climate system in determining the magnitude of climate change; (ii) the role of the climate system in determining the magnitude of climate impacts; and (iii) the role of the climate system in determining the magnitude of adaptation and mitigation responses.

Future emissions/concentration IV

SSP labelling about matches RCP labelling.

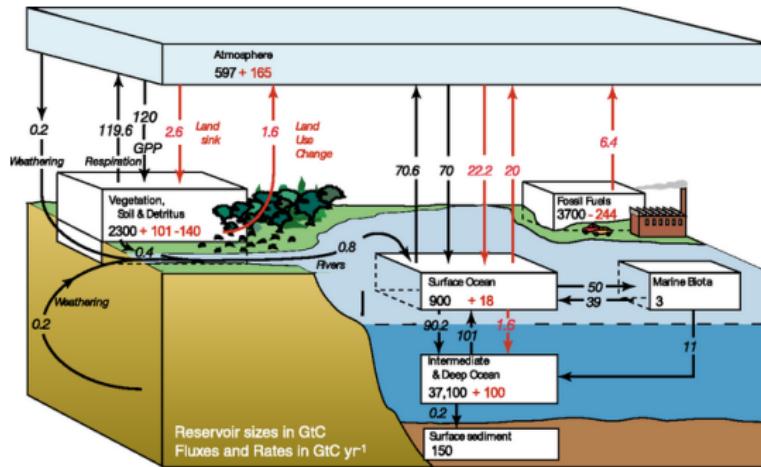
For the purposes of BDICE, SSPs/RCPs are just E . SSPs plan emissions for 250+ / – years, we just need one period for BDICE.

Carbon cycle

Carbon is cycled back and forth between the atmosphere, ocean and land by biological and chemical processes. This means that emissions don't translate immediately into atmospheric concentrations. Stocks/annual flows of C (not CO₂) are:

- Atmosphere 800/+4.5Gt
- Ocean 40,000/+3Gt
- Volcanos -/-0.1Gt
- Forests 600/-1.6 Gt
- Fossil fuels 5000/-8.5
- Sediments -/-1Gt

Fossil fuel emissions and deforestation put about 10Gt c in the atmosphere (ca. 2007). Atmospheric c increased by about 4.5Gt. About 3Gt are absorbed by the ocean. The remaining 2.5Gt are thought to be absorbed by plants (N.B: old numbers to go with figure). Numbers from Hansen 2009, about the same as in Jacob 1999



Black = natural, Red=Anthropogenic. AOGCM models of carbon cycle are complicated. IPCC 2007 Physical Science basis

figure 7.3

Basic atmospheric chemistry

- Nitrogen 78%, 780,000 ppm
- Oxygen 21%, 210,000 ppm
- Argon 0.93% 930 ppm
- CO₂ 0.0365% , 365 ppm
- Methane (CH₄) 1.7 ppm

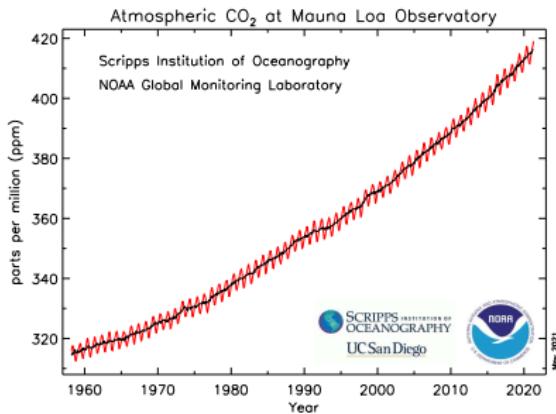
and lots of other trace gases. From: Introduction to Atmospheric Chemistry, D. J. Jacob, Princeton University press, 1999.

CO₂ concentration = 409ppm in July 2018. 412ppm in July 2019.
419ppm in April 2021.

Pre-industrial norm is 280ppm. This will be P_1 .

Atmospheric Carbon Measurements

Since 1959, the Mauna Loa observatory in Hawaii has measured atmospheric concentration of CO₂ daily. CO₂ disperses rapidly through the atmosphere, so a single observatory gives a good description of the whole world.



Atmospheric CO₂ cycle, data I

We can compare emissions data and concentration data for a purely empirical approach to the carbon cycle.

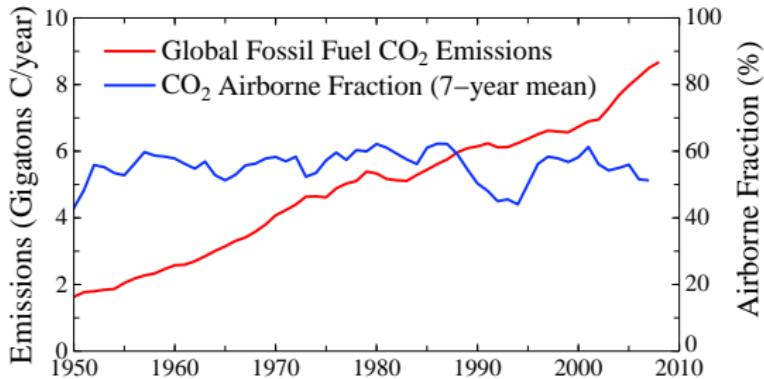
- Calculate annual change in c ppm from Mauna Loa (e.g.)
- Calculate annual emissions using emissions rates and consumption data (more below).
- Calculate ratio $\frac{\Delta \text{CO}_2 \text{ppm}}{\text{CO}_2 \text{ emissions}}$ = concentration yield of emissions.

Example:

- In 2020, Emissions were about 60Gt CO₂e .
- This is about $\frac{12}{44} \times 0.77 \times 60 = 12.6 \text{Gt c}$.
- At 2.12 Gt c per ppm, this is $\frac{12.6}{2.12} = 6 \text{ppm}$ of concentration.
- But Mauna Loa shows that concentration increases by only about 3ppm in 2020.

Atmospheric CO₂ cycle, data II

- About half of emissions, somehow, fall out of the atmosphere in 2020.
- Hansen does this calculation every year from 1950 to 2008...



Atmospheric CO₂ cycle, data III

Hansen 2009 figure 16

Atmospheric CO₂ cycle, data IV

So, concentration yield of emissions is about .55. Thus,

- $(1/0.55) = 1.8 \text{ Gt c}$ emissions gives 1 Gt ton of atmospheric C.
- 2.12 Gt atmospheric C to gives 1 ppm atmospheric C (or CO₂).
- Multiplying, $1.8 \times 2.12 = 3.8 \text{ Gt c}$ of emissions to get 1 ppm of atmospheric concentration.

Recall the carbon cycle equation from our model:

$$P_2 = \rho_0 E + P_1.$$

We have just calculated that $\rho_0 = \frac{1}{3.8} = 0.26 \frac{\text{ppm C (or CO}_2\text{)}}{\text{Gt C}}$.

What is ρ_0 if we denominate emissions in terms of CO₂?

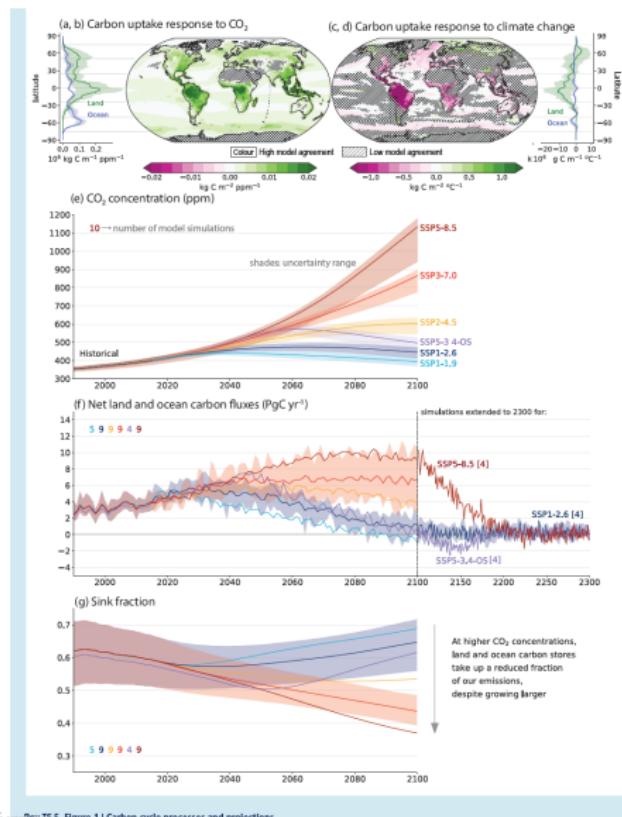
Atmospheric CO₂ cycle, data V

In Hansen's graph, the fraction of emissions retained in the atmosphere is CONSTANT as emissions are increasing. This is thought to reflect increased absorbtion by plant, 'carbon fertilization' or increased 'net primary productivity'.

In AOGCM's the carbon cycle is modelled very carefully. We really want to deal with the possibility that absorbtion varies with temperature or CO₂ (it probably does) and there is a lot of uncertainty about this relationship.

AR6 tries to analyze it more carefully ...

Atmospheric CO₂ cycle, data VI



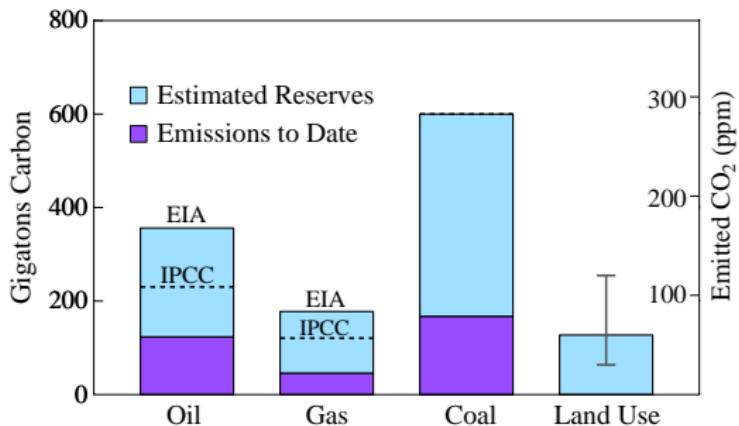
The problem of stabilizing atmospheric CO₂

- CO₂ Emissions are about 45Gt CO₂ \approx 13Gt C per year for 2019.
- The ocean and biosphere absorb about 45% of emissions (so far – this will probably fall over time).
- This means the ocean and biosphere absorb $13 \times 0.45 \approx 6$ Gt C per year.
- As a rough guess, this means that reducing emissions to 6Gt C per year will stabilize atmospheric CO₂e (but not climate).
- This involves a 55% decrease in CO₂ and a larger decrease in CO₂e (about 63%). For an average American this means this means reducing emissions from 18.2 t CO₂e per year to about 6.8 if US share of total emissions stays constant. If emissions are allocated equally to each of the world's 8b people, then each of us gets 6Gt C /8b people or about 0.75 t C \approx 3.6t CO₂e . This is an 82% decrease for the average American. It is also about twice the level of the average Indian and one third that of the average Chinese (in 2021).

Will we run out of fossil fuel? (aside)

Will we run out of fossil fuel? I

Not soon enough to matter:

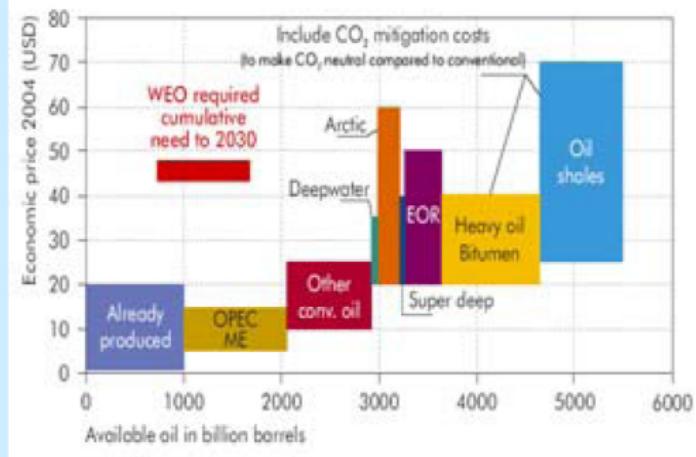


We have oceans of coal and lots of oil, and these figures predate US fracking.

Will we run out of fossil fuel? (aside)

Will we run out of fossil fuel? II

Figure 7.6 Availability of oil by price⁴⁸



Source: International Energy Agency

Conclusion I

Here is where we stand with our model:

$$\max_{I,M} u(c_1, c_2) \quad (20)$$

$$\text{s.t. } W = c_1 + I + M \quad (21)$$

$$c_2 = (1 + r)I - \gamma(T_2 - T_1)I \quad (22)$$

$$E = (1 - \rho_4 \frac{M}{W})(\rho_5(c_1 + I)) \quad (23)$$

$$P_2 = \rho_0 E + P_1 \quad (24)$$

$$T_2 = \rho_1(P_2 - P_1) + T_1 \quad (25)$$

We've filled in a little more. We know E and how E is converted into P , that is ρ_0 . We also know P_2 . This is a policy for future concentration, or an RCP – it's something we get to choose.

Conclusion II

- Each ppm of atmospheric CO₂ corresponds to about 2.12 Gt C and 7.78 Gt of CO₂. Pay attention to units.
- Not all gases are equal in their green house potential. CO₂ is most common and most important, but other gases are more important per unit of emissions.
- Over the past 50 years, about 55% of each emitted Gt of C has stayed in the atmosphere. The rest has been absorbed by land or oceans. Thus, it takes about 3.8 Gt C emissions per 1ppm of atmospheric CO₂.

Conclusion III

- Emissions are about 50Gt CO₂e for 2019. The rate at which atmospheric CO₂ is increasing has risen from about 1ppm/yr 1960s to 2ppm for 2000's. Since there is lots of fuel, we should expect atmospheric CO₂ to continue to increase and at an increasing rate. 'business as usual' RCPs call for atmospheric CO₂e > 800 within 100 years.
- Not all countries are the same. They are responsible for different current and historical shares, have different per capita emissions, use emissions more or less efficiently. These factors are obstacles to international agreements, and suggest the need for a richer model.

Conclusion IV

- Steady state CO₂ emissions are probably very small, Stern suggests less than 1/3 of current. Our calculations suggest (1-0.55)=45%.