

# EC1340 Topic #1

## **Introduction *and* Accounting for Carbon**

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# Outline

- 1 Course administration and expectations
- 2 Introduction
- 3 Units for measuring CO<sub>2</sub>
- 4 Emissions and consumption
- 5 Emissions levels and trends
- 6 RCPs
- 7 Carbon Cycle
- 8 Will we run out of fossil fuel? (aside)
- 9 Conclusion

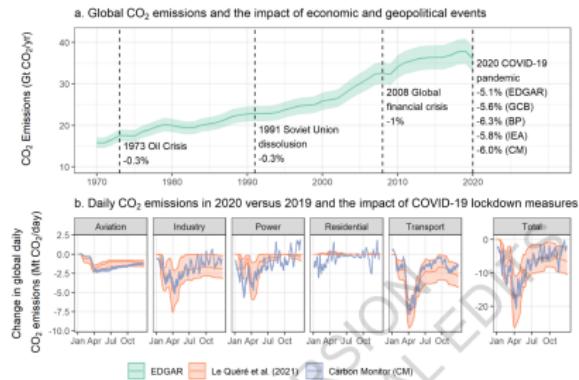
## Stabilizing atmospheric CO<sub>2</sub> I

- World emissions of CO<sub>2</sub>e in 2019<sub>(2022 IPCC report)</sub> 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  
 $\approx 3.0\text{Gt CO}_2\text{e} \approx 1\text{Gt c emissions per person}$ .
- 2019 per capita CO<sub>2</sub>e /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 CO<sub>2</sub> 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<sup>1</sup> 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 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 c 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 CO<sub>2</sub> 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 CO<sub>2</sub> stabilization?
- What are the trade-offs between economic welfare and climate?
- What policies should we use to achieve CO<sub>2</sub> 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 CO<sub>2</sub> affects climate (a climate model).
- the carbon cycle.
- how CO<sub>2</sub> comes from consumption.
- how climate affects consumption (and/or utility).
- how we can use resources to reduce CO<sub>2</sub>, 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 CO<sub>2</sub> today  
increases in  $I$ ,  $c_1$  and decreases in  $M$
- $P_1, P_2$  = Atmospheric concentration of CO<sub>2</sub> 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(RCPs)’
- Physical quantities like climate or the relationship between CO<sub>2</sub> 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,  $E$ ,  $\rho_5$ ,  $P_1$  and  $P_2$ .
- The endowment of climate,  $T_1$ .
- The link between atmospheric  $\text{CO}_2$  and future climate,  $\rho_1$ ,  $T_1$  (climate model).  $\rho_1$  is often called 'climate sensitivity', more later.
- The link between emissions and atmospheric  $\text{CO}_2$ ,  $\rho_0$  (Carbon cycle)
- Cost of climate change,  $\gamma$ .
- Cost of mitigation (reduction of emissions),  $\rho_4$ .
- 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 CO<sub>2</sub>. 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 CO<sub>2</sub> is about 44/12 as heavy as a molecule of C. Each ton of C is 44/12 tons of CO<sub>2</sub>.
- 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 CO<sub>2</sub>.
- 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 co<sub>2</sub> in the atmosphere was 419 ppm. This is equal to 888 Gt c and 3257 Gt co<sub>2</sub> .

# CO<sub>2</sub> 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 <sub>2</sub> 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 <sub>6</sub> )	3,200	22,200	1%

Source: Ramaswamy et al. (2001)<sup>8</sup> and emissions data from the WRI CAIT database<sup>9</sup>.

From Stern 2008, table 8.1

## CO<sub>2</sub> 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 'CO<sub>2</sub> equivalent' (CO<sub>2</sub>e ).
- April 2021 concentration of CO<sub>2</sub> was 419 ppm. Using the numbers above, current CO<sub>2</sub>e 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 CO<sub>2</sub> equivalent emissions:

## Units, again

Stern 2007 p193 gives CO<sub>2e</sub> emissions for 2000 as 42Gt CO<sub>2e</sub> .

Hansen has 8.5 Gt C from fossil fuel.

Can we reconcile these numbers?(Yes)

- About .77 of CO<sub>2e</sub> is CO<sub>2</sub> .
- About .18 of CO<sub>2</sub> is non fossil fuel (more on this later)
- Stern reports CO<sub>2</sub> , Hansen C

so, Stern's 42 Gt CO<sub>2e</sub> 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

- CO<sub>2</sub> from gasoline, 2.3 kg/liter = 19.4 pounds/gallon. So, 1000 kg of CO<sub>2</sub> emission results from 435 liters or 114 gallons of gas. (about 1% not burned is mostly N<sub>2</sub>O so CO<sub>2e</sub> is higher).
- CO<sub>2</sub> from diesel 2.7 kg/liter = 22.2 pounds/gallon 1000 kg of CO<sub>2</sub> 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 CO<sub>2</sub>. (NB Gasoline weighs 6.3 pounds/gallon so 18 pounds of gas gives about 54 pounds CO<sub>2</sub>. Propane has more hydrogen per carbon atom than gasoline).

## Emissions for particular activities II

- CO<sub>2</sub> 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 CO<sub>2</sub> . <http://www.epa.gov/sequestration/faq.html> For tropical forests, about 1.8 times as much not reliable source.
- CO<sub>2</sub> from coal, about 2.00 tons CO<sub>2</sub> per ton (a lot of the stuff in coal is not burned – I think), or 2100lb CO<sub>2</sub> per 1000 KWH from non-baseload coal burning electricity generation. CO<sub>2e</sub> 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 CO<sub>2</sub> 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 CO<sub>2</sub>, 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 CO<sub>2</sub>e 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 CO<sub>2</sub> instead of c .

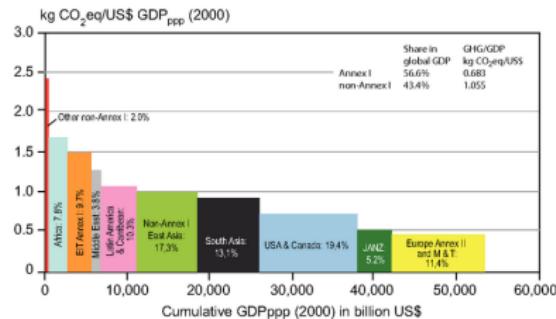
Recall the third equation from our global warming model:

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

We've just calculated  $\rho_5$ . 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.

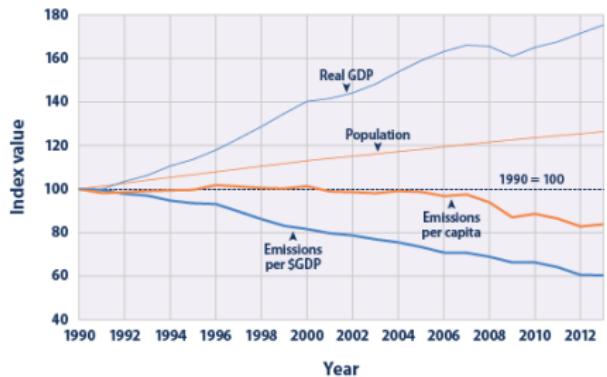


IPCC 2007 Mitigation fig SPM.3b

- What if China and Africa made same output at US/CA emission rates? This is why technology transfer is important.
- Compare 0.68 kg CO<sub>2</sub>e per dollar ca. 2004 to my calculation of 0.19 kg C per dollar 2019. How important is technical progress?

# Technological progress I

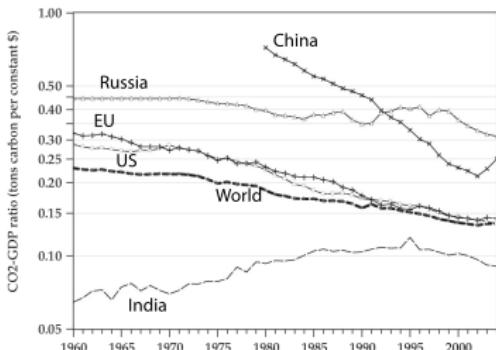
Figure 3. U.S. Greenhouse Gas Emissions per Capita and per Dollar of GDP, 1990–2013



<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  $\text{CO}_2$  emissions to GDP for major regions and globe, 1960–2004. Trends in the ratio of  $\text{CO}_2$  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  $\text{CO}_2$ -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  $\text{CO}_2$ -GDP ratios.

## Emissions - Summary I

- We've now calculated  $\rho_5$ , 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,

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

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

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

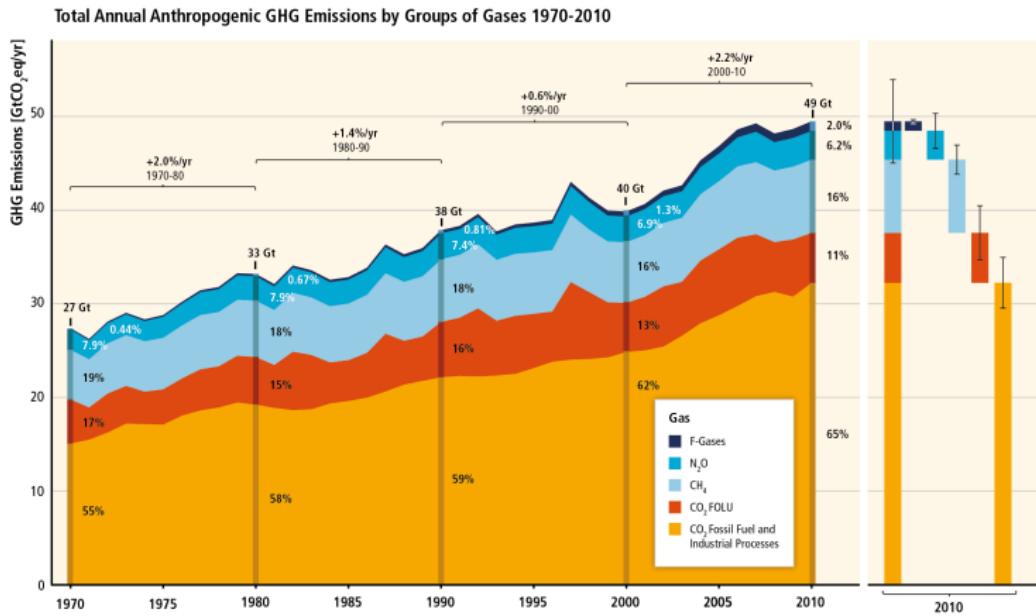
$$E = (1 - \rho_4 \frac{M}{W})(\rho_5(c_1 + I)) \quad (17)$$

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

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

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  $E \approx 13 \text{GtC/year}$ , but it's important enough to learn a little more about – coming up.

# CO<sub>2</sub>e 1970-2010



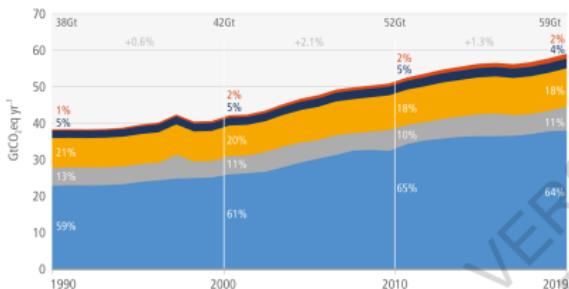
IPCC 2013 WG3 fig TS.1

Right panel gives confidence bounds for 2010. 49Gt CO<sub>2</sub>e in 2010.

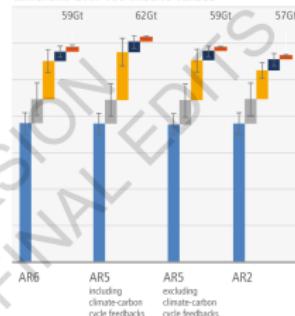
## Emissions levels and trends

# CO<sub>2</sub>e 1990-2019

a. Total anthropogenic GHG emissions 1990–2019



b. Emission totals based on different GWP100 metric values



c. Trends in GHG emissions and uncertainties – relative to 1990

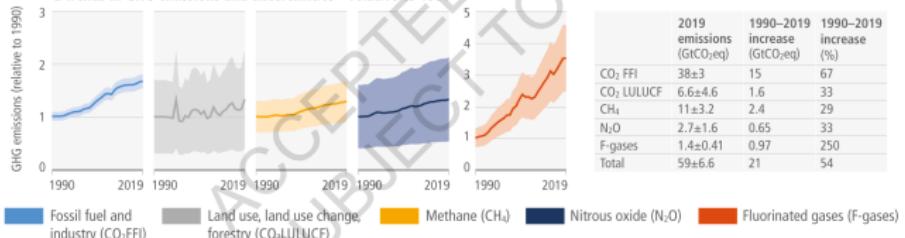
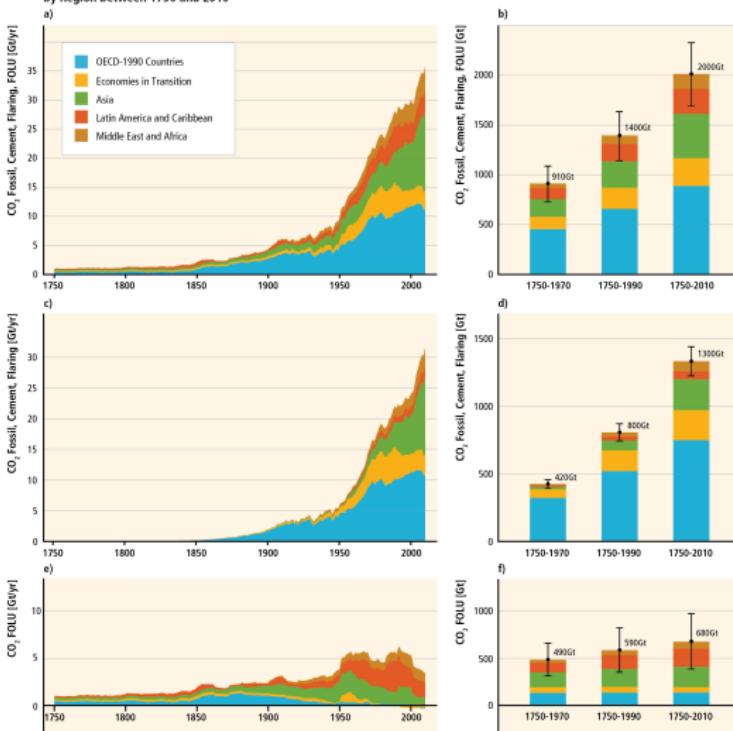


Figure TS.2: Global anthropogenic emissions have continued to rise across all major groups of greenhouse gases (GtCO<sub>2</sub>-eq yr<sup>-1</sup>) 1990–2019

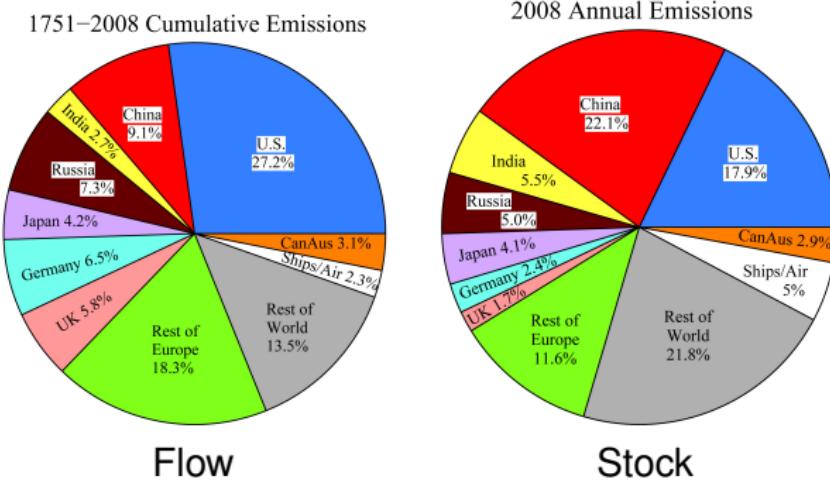
IPCC 2022 WG3 fig TS.2

# CO<sub>2</sub> by purpose and country income 1750-2010

Total Anthropogenic CO<sub>2</sub> Emissions from Fossil Fuel Combustion, Flaring, Cement, as well as Forestry and Other Land Use (FOLU) by Region between 1750 and 2010



# Hansen's version of the same thing...

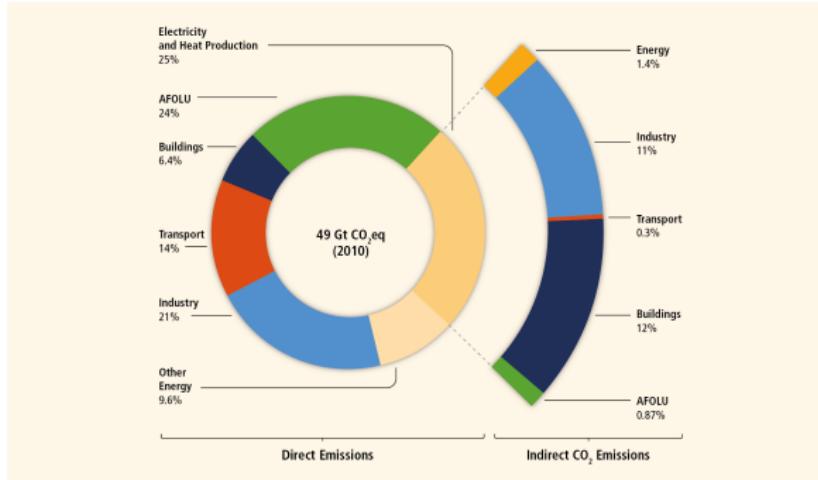


Hansen 2009 fig 27

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.

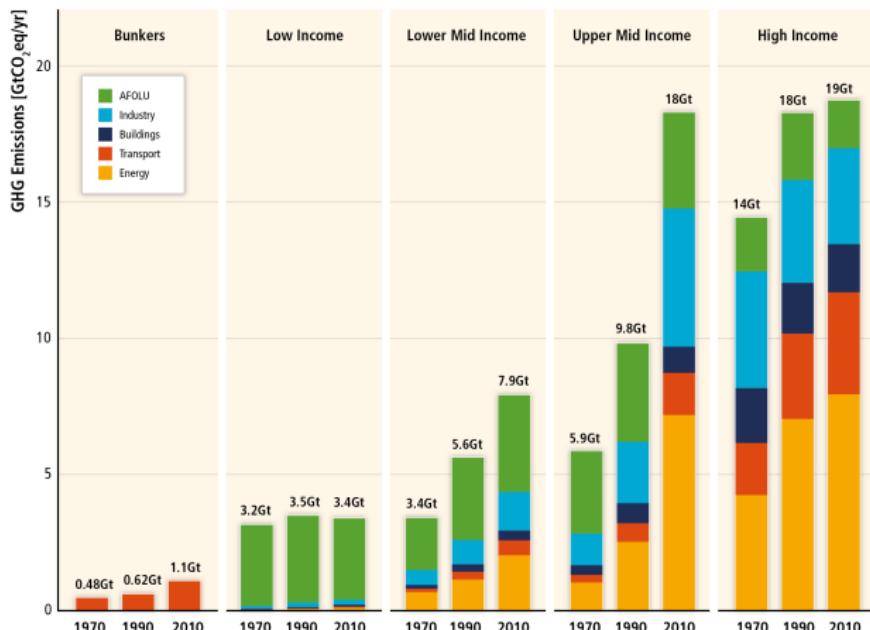
# 2010 CO<sub>2</sub>e by purpose

Greenhouse Gas Emissions by Economic Sectors



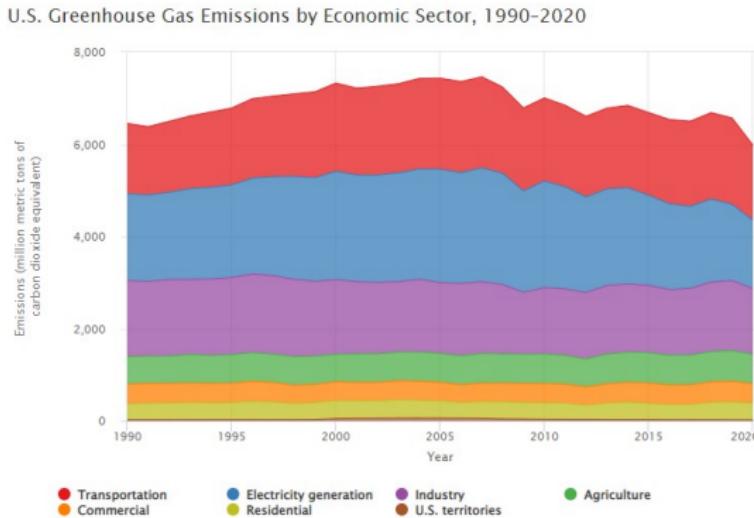
IPCC 2013 WG3 fig TS.3

# 2010 CO<sub>2</sub>e by purpose and country income



IPCC 2013 WG3 fig TS.3

# US 1990-2019 CO<sub>2</sub>e



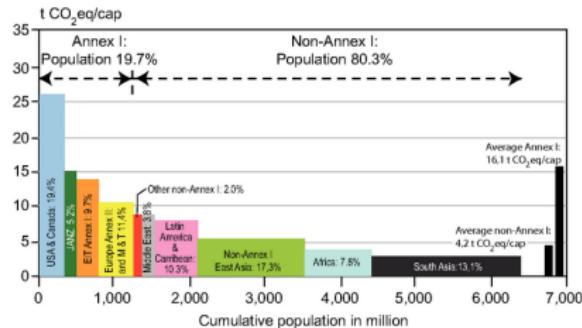
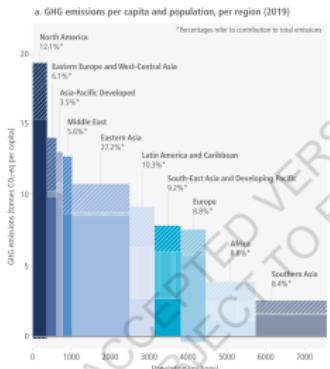
Source: U.S. EPA's Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2020.  
<https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks>

[https://www.epa.gov/system/files/images/2022-04/emissions\\_econsector\\_1990-2020.jpg](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.

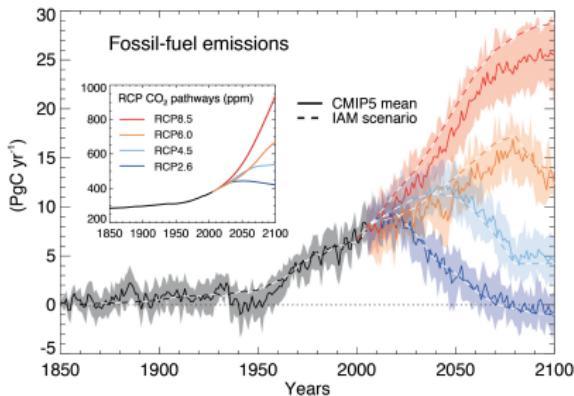
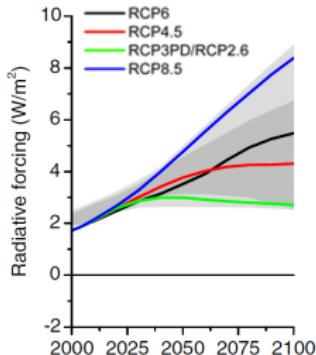
## Summary

- 2019 emissions of CO<sub>2</sub>e were about 59Gt. Of this, 45Gt was CO<sub>2</sub>, 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 CO<sub>2</sub>e was 30Gt.
- 2010 CO<sub>2</sub>e : 14% transport, 18% buildings, 21% industry 24% AFOLU. We could use this to calculate refinements of  $\rho_5$ .
- 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.

# Representative Concentration Pathways (RCPs)

The IPCC fifth assessment report is organized around RCP's.

These are hypothetical future levels of  $\text{CO}_2$ . This is what we get to choose. In BDICE, and RCP is just the future level of concentration,  $P_2$ .

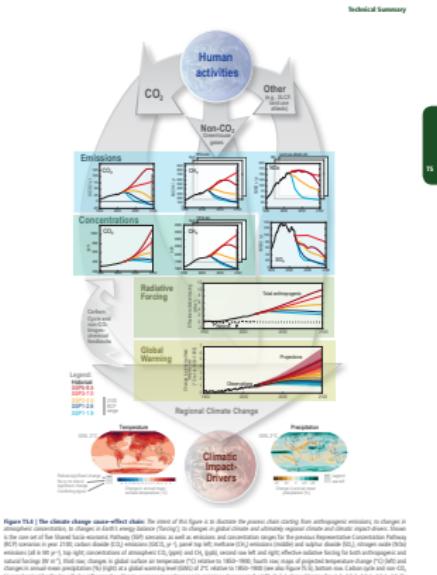


RCP 8.5 is 'business as usual' and involves  $\text{CO}_2$  concentrations reaching 850ppm within 100 years. Other RCPs involve varying degrees of mitigation. In the right panel, Pg is 'petagram', the same thing as Gigaton.

# Shared Socio-economic Pathways (SSPs)

The IPCC sixth assessment report is organized around SSP's.

These are hypothetical future levels of CO<sub>2</sub> and other things that affect climate. This is just a fancier/more detailed version of RCPs.  
(This is too much detail for us.)

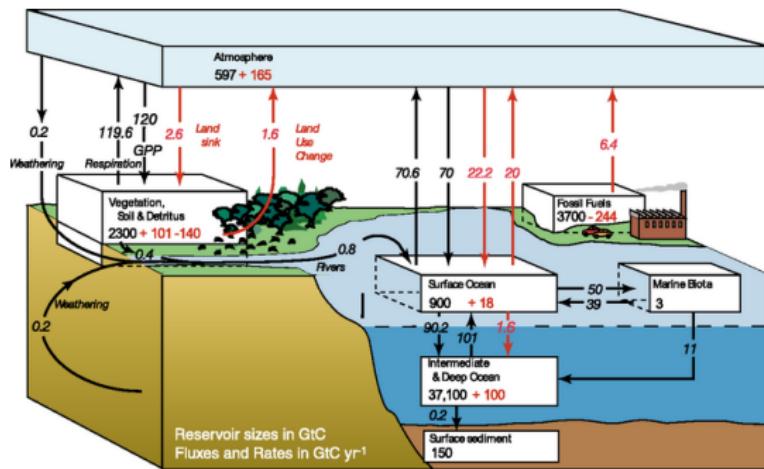


## Carbon cycle

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 CO<sub>2</sub>) 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
- CO<sub>2</sub> 0.0365% , 365 ppm
- Methane (CH<sub>4</sub>) 1.7 ppm

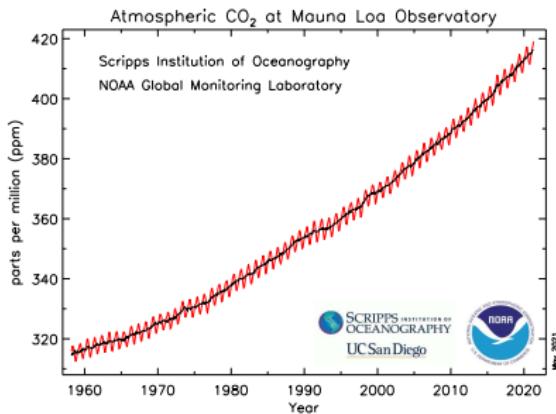
and lots of other trace gases. From: Introduction to Atmospheric Chemistry, D. J. Jacob, Princeton University press, 1999.

CO<sub>2</sub> 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 CO<sub>2</sub> daily. CO<sub>2</sub> disperses rapidly through the atmosphere, so a single observatory gives a good description of the whole world.



## Atmospheric CO<sub>2</sub> cycle, data I

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

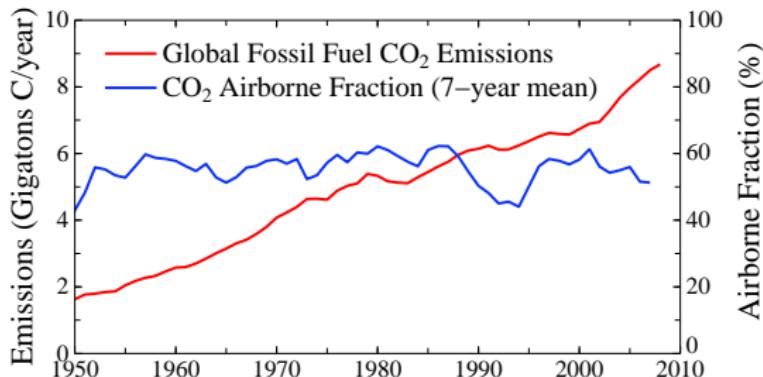
- Calculate annual change in c ppm from Mauna Loa (e.g.)
- Calculate annual emissions using emissions rates and consumption data (more below).
- Calculate ratio  $\frac{\Delta \text{CO}_2 \text{ ppm}}{\text{CO}_2 \text{ emissions}}$  = concentration yield of emissions.

Example:

- In 2020, Emissions were about 60Gt CO<sub>2</sub>e .
- 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 CO<sub>2</sub> 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 CO<sub>2</sub> cycle, data III

Hansen 2009 figure 16

## Atmospheric CO<sub>2</sub> 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 CO<sub>2</sub>).
- 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  $\rho_0$  if we denominate emissions in terms of CO<sub>2</sub>?

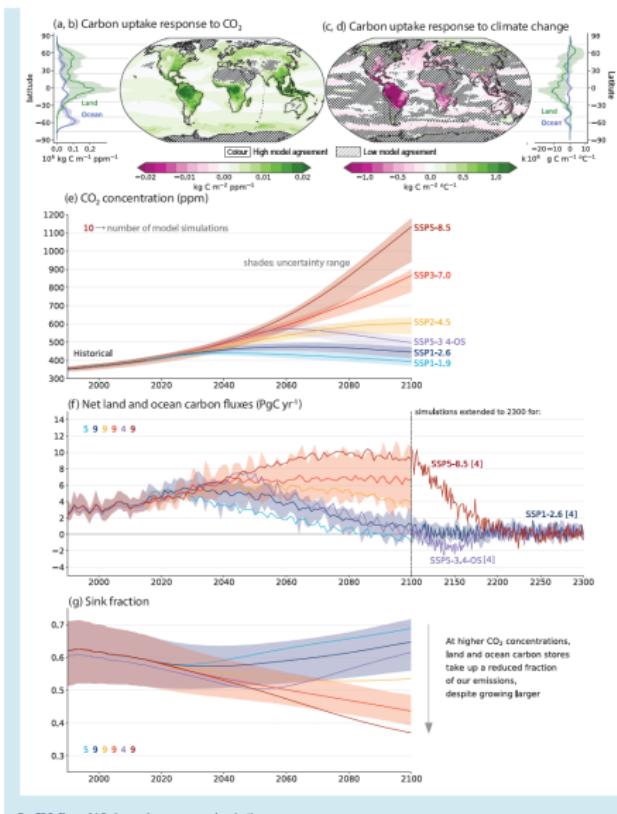
## Atmospheric CO<sub>2</sub> cycle, data V

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 CO<sub>2</sub> (it probably does) and there is a lot of uncertainty about this relationship.

AR6 tries to analyze it more carefully ...

# Atmospheric CO<sub>2</sub> cycle, data VI



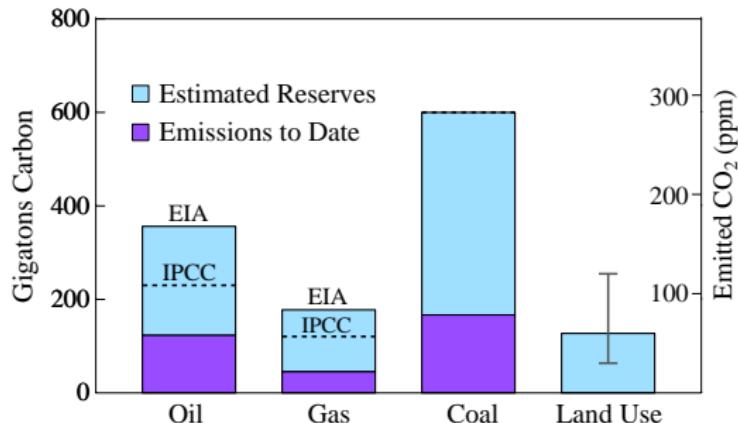
## The problem of stabilizing atmospheric CO<sub>2</sub>

- CO<sub>2</sub> Emissions are about 45Gt CO<sub>2</sub> ≈ 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 CO<sub>2</sub>e (but not climate).
- This involves a 55% decrease in CO<sub>2</sub> and a larger decrease in CO<sub>2</sub>e (about 63%). For an average American this means this means reducing emissions from 18.2 t CO<sub>2</sub>e 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 ≈ 3.6t CO<sub>2</sub>e . 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:

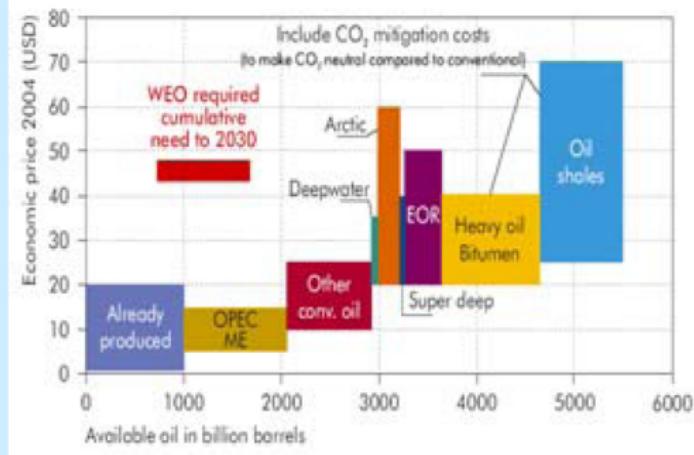


We have oceans of coal and lots of oil, and these figures predate US fracking.

Will we run out of fossil fuel? (aside)

## Will we run out of fossil fuel? II

Figure 7.6 Availability of oil by price<sup>48</sup>



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  $\rho_0$ . 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 CO<sub>2</sub> corresponds to about 2.12 Gt C and 7.78 Gt of CO<sub>2</sub>. Pay attention to units.
- Not all gases are equal in their green house potential. CO<sub>2</sub> 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 CO<sub>2</sub>.

## Conclusion III

- Emissions are about 13Gt c for 2013. The rate at which atmospheric CO<sub>2</sub> is increasing has risen from about 1ppm/yr 1960s to 2ppm for 2000's. Since there is lots of fuel, we should expect atmospheric CO<sub>2</sub> to continue to increase and at an increasing rate. 'business as usual' RCPs call for atmospheric CO<sub>2</sub>e > 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 CO<sub>2</sub> emissions are probably very small, Stern suggests less than 1/3 of current. Our calculations suggest (1-0.55)=45%.