Decarbonising the global economic system

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Climate macroeconomics & finance 2024/25 - Lecture 3

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Some relevant upcoming events

- Christopher Hambel (Tillburg)
  - Field seminar: Thursday 14 November 2024, 2.30pm (DSE seminar room)
- Lint Barrage (ETH)
  - Seminar: Tuesday 3 December 2024, 1.00pm (DSE Auditorium)
- Ulrich Wagner (Mannheim)
  - Seminar: Tuesday 10 December 2024, 12.00pm (DSE Auditorium)

In the last lectures

- Climate change threat
  - Climate is changing very rapidly..
  - .. and it's definitely us
  - Climate risks for humans, firms, financial system
- $\rightarrow$ Transition away from GHGs
  - Our global production/consumption system based on fossils
  - How do we make the transition happen?
  - Today: mitigation options and attached risks
  - Next lecture: mitigation policies/strategies

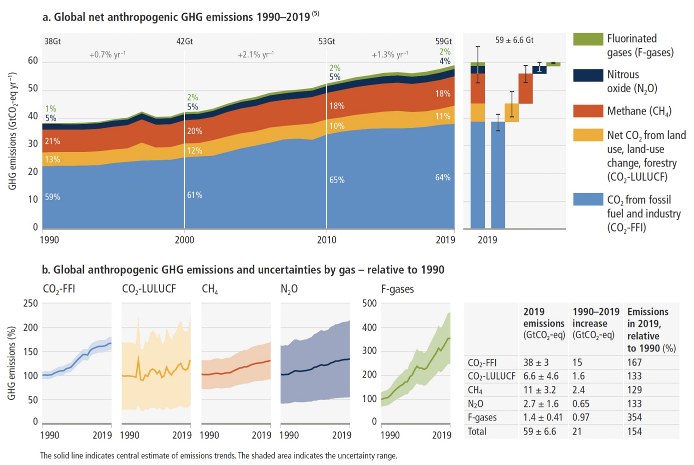
Outline of today's lecture

- Where do GHG emissions come from?
  - Key source: combustion of fossil fuels
  - Electricity, transport, industry, agriculture, buildings..
- How much should they reduced?
  - Carbon budget
  - Emission reduction pathways
- Climate mitigation
  - Emission accounting: Kaya identity
  - Technological options
- Abatement costs
  - Marginal abatement cost curve: theory and empirical evidence
- Mitigation macroeconomic requirements
  - Physical and financial investment needs

Where do GHG emissions come from?

Recent trends in emissions

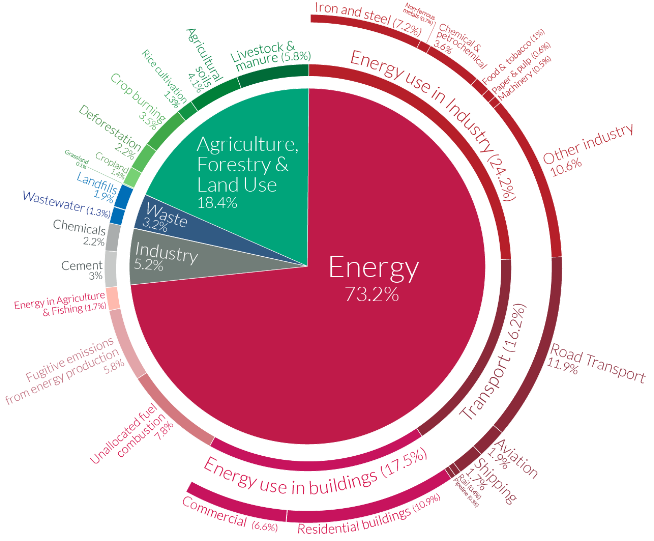
- 2019 GHG emission level: 59±6.6 GtCO2-eq



	2019 emissions ($GtCO_2$-eq)	1990–2019 increase ($GtCO_2$-eq)	Emissions in 2019, relative to 1990 (%)
CO_2-FFI	38 ± 3	15	167
CO_2-LULUCF	6.6 ± 4.6	1.6	133
CH_4	11 ± 3.2	2.4	129
N_2O	2.7 ± 1.6	0.65	133
F-gases	1.4 ± 0.41	0.97	354
Total	59 ± 6.6	21	154

Global net anthropogenic GHG emissions (GtCO2-eq yr–1) 1990–2019. Source: IPCC WGIII, SPM (2022)

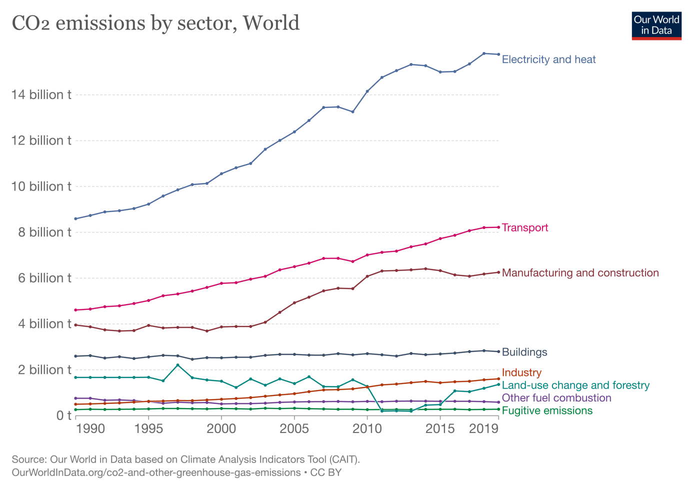
Where do emissions come from now?



Global GHG emissions by sector in 2016. Source: Our World in Data

CO2 emissions by sector

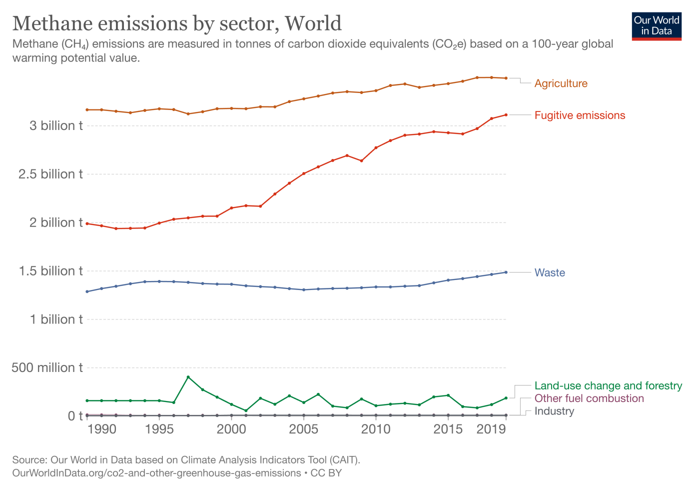
- Main driver: combustion of fossil fuels



CO2 emissions by sector. Source: Our World in Data

CH4 emissions by sector

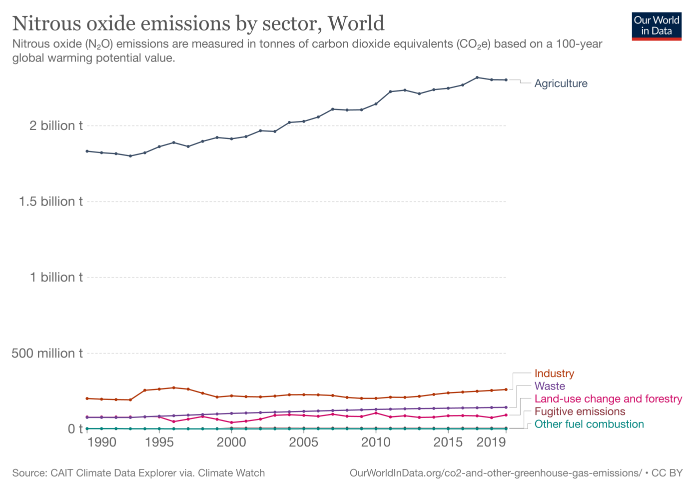
- Main sources: livestock and rice production; gas leaks; landfills



CH4 emissions by sector. Source: Our World in Data

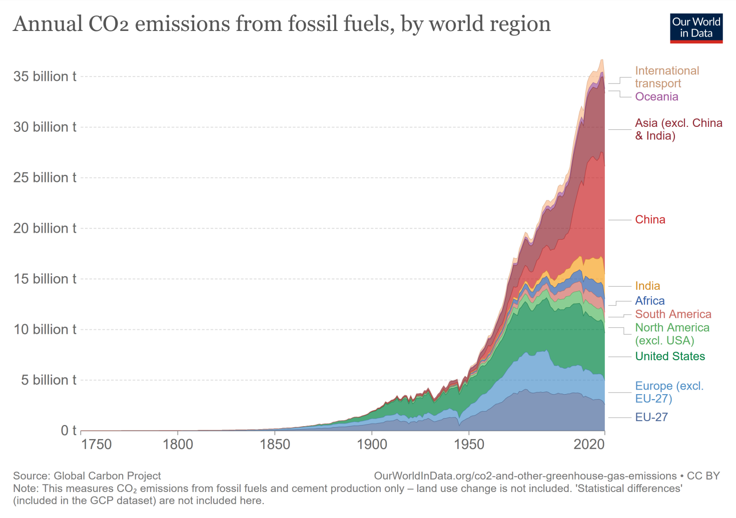
N2O emissions by sector

- Most of N2O linked to use of nitrogen fertilizers



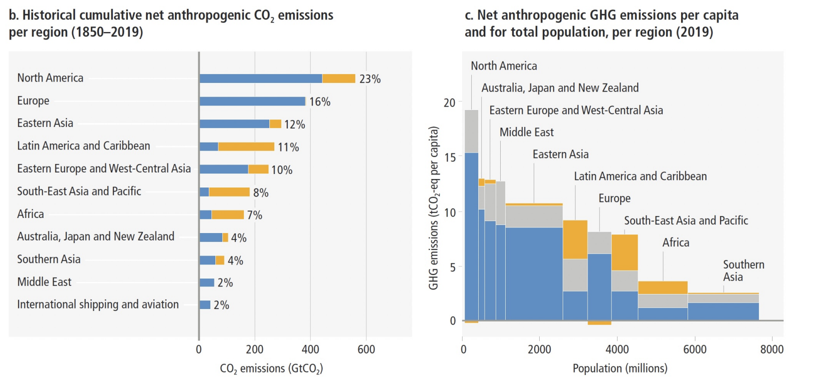
N2O emissions by sector. Source: Our World in Data

Regional differences



CO_2 emissions from fossils and cement. Source: Our World in Data

Regional differences

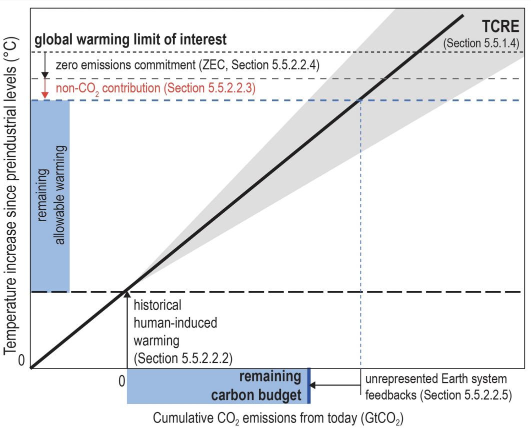


Regional distribution of GHG emissions (light blue: CO2-FFI; yellow: CO2-LULUCF; grey: other GHGs). Source: IPCC WGIII, SPM (2022)

How much should GHG emissions be reduced?

The carbon budget concept

- TCRE: linear relation between cum CO2 emissions and ΔT
  $\rightarrow$ Carbon budget



Stylised representation of carbon budget assessment. Source: IPCC 2021 WGI, Ch. 5. See also Rogelj et al (2019)

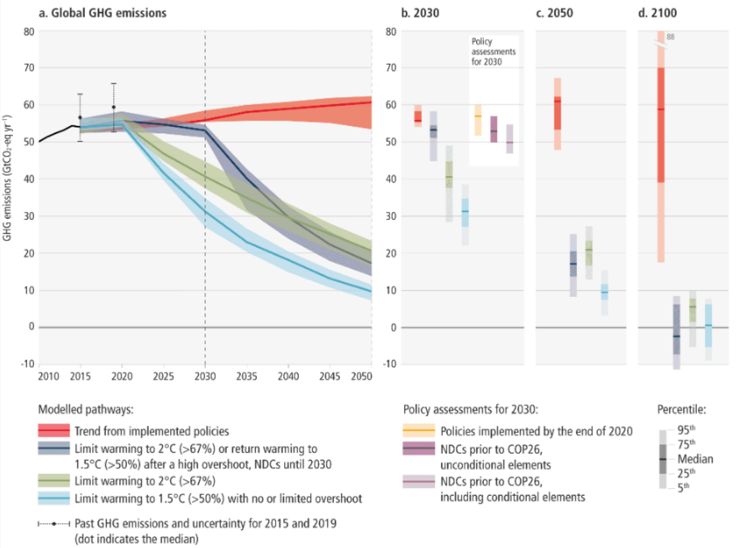
Carbon budget estimates

- Headline figures (WGIII)
  - 1.5°C with 50% probability: 500GtCO2
  - 2°C with 67% probability: 1150GtCO2

Additional Warming Since 2010–2019[a]	Warming Since 1850–1900[a]	Remaining Carbon Budget[b] starting from 1 January 2020 and subject to variations and uncertainties quantified in the columns on the right					Scenario Variation	Geophysical Uncertainties			
°C	°C	Percentiles of TCRE[c,d] PgC ($GtCO_2$)					Non-CO_2 scenario variation[e]	Non-CO_2 forcing and response uncertainty[f]	Historical temperature uncertainty[a]	Zero emissions commitment (ZEC) uncertainty[g]	Recent emissions uncertainty[h]
		17th	33rd	50th	67th	83rd	PgC ($GtCO_2$)	PgC ($GtCO_2$)	PgC ($GtCO_2$)	PgC ($GtCO_2$)	PgC ($GtCO_2$)
0.23	1.3	100 (400)	60 (250)	40 (150)	30 (100)	10 (50)	Values can vary by at least ±60 PgC (±220 $GtCO_2$) due to choices related to non-CO_2 emissions mitigation	Values can vary by at least ±60 PgC (±220 $GtCO_2$) due to uncertainty in the warming reponse to future non-CO_2 emissions	±150 PgC (±550 $GtCO_2$)	±115 PgC (±420 $GtCO_2$)	±6 PgC (±20 $GtCO_2$)
0.33	1.4	180 (650)	120 (450)	90 (350)	70 (250)	50 (200)					
0.43	1.5	250 (900)	180 (650)	140 (500)	110 (400)	80 (300)					
0.53	1.6	330 (1200)	230 (850)	180 (650)	150 (550)	110 (400)					
0.63	1.7	400 (1450)	290 (1050)	230 (850)	190 (700)	150 (550)					
0.73	1.8	470 (1750)	350 (1250)	280 (1000)	230 (850)	180 (650)					
0.83	1.9	550 (2000)	400 (1450)	320 (1200)	270 (1000)	210 (800)					
0.93	2	620 (2300)	460 (1700)	370 (1350)	310 (1150)	250 (900)					
1.03	2.1	700 (2550)	510 (1900)	420 (1500)	350 (1250)	280 (1050)					
1.13	2.2	770 (2850)	570 (2100)	460 (1700)	390 (1400)	310 (1150)					

Assessment of remaining carbon budget. Source: IPCC 2021 WGI, Ch. 5

Emission reduction pathways



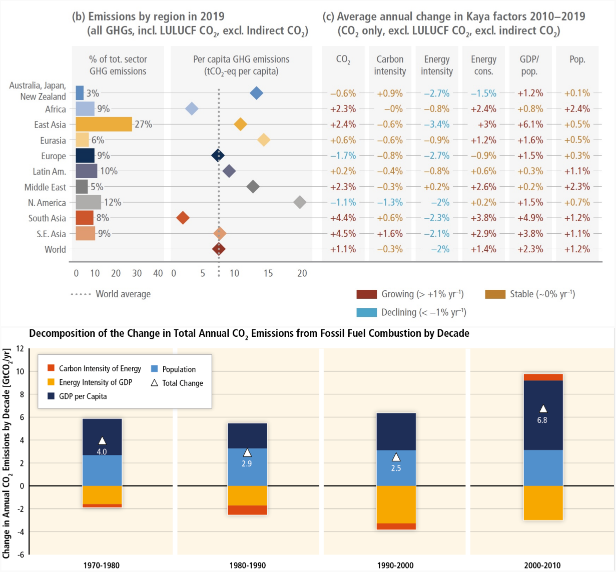
Global GHG pathways. Source: IPCC 2021 WGIII, SPM

How do we decarbonise? The Kaya identity

GHG Emission drivers

- IPAT identity: $I \equiv P \cdot A \cdot T$, where
    - I: Impact; P: population; A: affluence; T: technology
    - Taking logs: $\hat{I} \approx \hat{P} + \hat{A} + \hat{T}$
- Kaya identity $CO_2 \equiv P \cdot \frac{Y}{P} \cdot \frac{E}{Y} \cdot \frac{CO_2}{E}$, where:
    - CO_2: emissions
    - P: population
    - Y/P: income per capita
    - E/Y: energy intensity of GDP
    - CO2/E: carbon intensity of energy
    - $\rightarrow \hat{CO_2} \approx \hat{P} + \left(\hat{\frac{Y}{P}}\right) + \left(\hat{\frac{E}{Y}}\right) + \left(\hat{\frac{CO_2}{E}}\right)$

Kaya CO2 emission decomposition



Decomposition of fossil fuel CO2 emission drivers. Source: IPCC AR6 WGIII, Ch.2

Kaya decomposition results

- In most regions and the world as a whole:
  - Carbon/energy intensity decreased (efficiency improvements!)..
  - ..but pop. and income growth more than compensated them..
  - ..leading to an overall increase in emissions
- This is called *relative* decoupling
  - We are detaching income and emission dynamics, but emissions are still rising
  - *Absolute* decoupling: income grows, emissions decline
- Strong regional differences
  - Europe and North America seem in absolute decoupling..
  - .. while parts of Asia showed increasing carbon intensity

Emission reduction immediate drivers

- Reduce population
  - Population control measures, but very slow
  - Ethical and freedom issues (eg. one child policy in China)
- Reduce income
  - Degrowth; discussion on income-welfare links
  - Politically unpalatable and only applicable to high-income countries
- Improve production processes
  - Technological/process advancements to reduce energy/carbon intensities
  - 'Green growth': grow by getting green

Is green growth feasible?

- The needed intensity reductions to reduce emissions only through technological progress are historically unprecedented

Table 1. A Kaya identity decomposition of global CO_2 emissions, 1971–2017 and 2017–2050.

	Actual change			Projection
	1971–1990	1991–2017	1971–2017	85% Reduction in CO_2 emissions 2017–2050
Global CO_2 emissions	2.05	1.80	1.88	−6.92
World population	1.81	1.30	1.52	0.79
Real GDP per capita	1.52	1.54	1.49	−1.34
Energy intensity (TPES/GDP)	−0.86	−1.05	−0.96	−2.69
Carbon intensity (CO_2/TPES)	−0.41	0.01	−0.17	−3.68

A Kaya identity decomposition of global CO2 emissions, 1971–2017 and 2017–2050.
Source: Schröder and Storm (2020)

How do we decarbonise?
Technological options

Main categories

- Decarbonise vs sequester
  - Main goal: reduce (control?) GHG atmospheric concentration
  - Either we reduce emissions (so to respect carbon budget)..
  - .. or we directly sequester GHGs from the atmosphere
- Supply- vs demand-side
  - Supply-side: e.g. produce clean electricity
  - Demand-side: e.g. reduce energy consumption
- Sector/gas-specific
  - Energy, AFOLU, buildings, transport, industry,..
  - CO2, CH4, N20, etc.
- Most common in economics
  - Emission reduction, supply-side, CO2

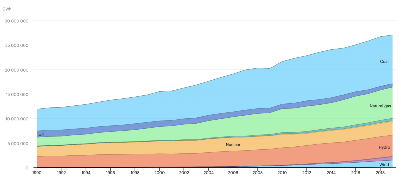
Electricity: main power-generating technologies

- Fossils
  - Burn coal, gas, oil $\rightarrow$ turbines spin generating electricity
  - Large emissions of CO_2 and pollutants
- Nuclear:
  - Nuclear fission using uranium
  - Low-carbon, but not renewable and safety issues (eg. waste)
- Hydropower
  - Involves building dam and reservoir (land use)
  - Also useful for pumped storage
  - Limited number of places to make hydro plants
- Non-hydro renewables:
  - Solar, wind, geothermal, etc.

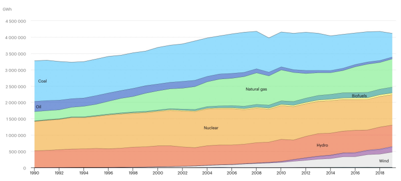
Electricity from renewable sources

- Solar
  - Exposure to light: photovoltaic (PV) panels - large or small
  - Concentrated Solar Power (CSP)
- Wind
  - Rotation of wind turbines
  - Onshore vs offshore
- Other clean renewables
  - Geothermal, tidal, biomass,..
- Issues:
  - Intermittent $\rightarrow$ Energy storage issue
  - High demand of critical minerals $\rightarrow$ geopolitical implications
  - Land/sea use, visual impacts
  - Competitiveness!

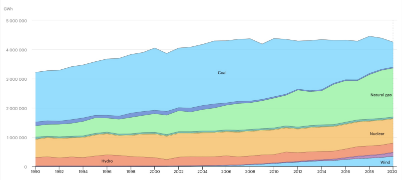
Electricity production by source



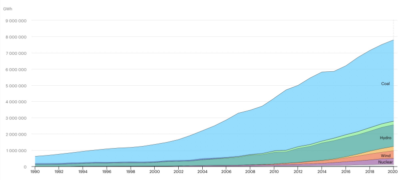
(a) World



(b) Europe



(c) USA



(d) China

Electricity production by source. Source: IEA (2022)

Electrification

- Main idea
  - Electrify everything you can (with clean electricity of course)
- Electric transport
  - Diffusion of electric vehicles
  - High-speed trains for long-distance
  - International transport (shipping, air travel)?
- Electric heating
  - For households e.g. heat pumps
  - For industry e.g. electric arc furnaces

The demand side

- Main idea
  - Reduce use of energy and materials
- Two main options
  - Improve efficiency (the T in the IPAT identity: E/Y)
  - Reduce overall demand (P or Y/P down)
- Several ways to improve efficiency
  - Buildings: heat insulation, lighting efficiency
  - Industry: energy management systems; automation
  - Transport: more efficient engines
  - Reduce overall demand (P or Y/P down)
- Demand reduction
  - Lifestyle (e.g. transport mode switch, diet change, water use)
  - Use behaviours (e.g. smart meters)

Industry

- Several industries with large emissions
  - Fossils for heat (steel, paper, etc.)
  - Fossils as raw material (plastic, chemicals)
  - Fossils as fuel (Shipping, aviation)
  - CO2 as side-product of production process (cement)
- Hard-to-abate sectors
  - Limited alternative technologies
  - E.g electric arc furnaces; bio-plastics
  - Economic feasibility? $\rightarrow$ R&D

LULUCF: Land use, land-use change and forestry

- Historical land-use change
  - Transform forests into crop fields or farming
- Impact on emissions
  - Sink removal: diminished CO2 absorption by vegetation
  - Emission of CH4 from rice fields and livestock
  - Emission of N20 from fertilizer use
- Mitigation strategies?
  - Reduced deforestation, afforestation
  - New agricultural/farming techniques (e.g. nitrogen-fixing rotations)

Carbon capture and storage

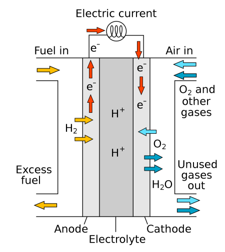
- Main idea:
    - Capture CO_2 emissions at their source (e.g. coal plants)
    - Store it somewhere safe, or use it
- Can we capture carbon?
    - Technologically doable, but very expensive
    - Pilot project stage $\rightarrow$ more R&D investment needed
- What to do with it?
    - Store in geological formations or oceans: safe?
    - Recycle in industry (e.g. carbonated drinks)
- BECCS concept
    - Bioenergy + CCS = BECCS (Negative emissions)

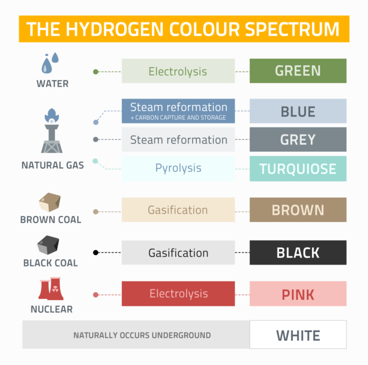
Carbon dioxide removal

- Main idea
  - Remove GHGs already in the atmosphere
- Direct air capture
  - Several techs, but based on air contact with chemicals
  - Economic feasibility? DAC 1 coming
- Ocean fertilization
  - Introduce nutrients in the ocean (e.g. iron) $\rightarrow$ increase in phytoplankton activity $\rightarrow$ increase in CO_2 absorption capacity of oceans
  - Concerns about efficacy and side-effects
- Sequestration by trees
  - Preserve/enhance CO_2 absorption capacity of vegetation
  - Strategies: halt to deforestation, reforestation, afforestation

Hydrogen

- Hydrogen can be used as a fuel
    - Fuel cells
- The colours of hydrogen production
- Issues
    - Hard to transport
    - Safety concerns?
    - Technological competition





Source: Wikipedia (left). What's Watt (above).

Radical breakthroughs?

- Solar radiation management (‘geoengineering’)
  - Reflect solar radiations back to decrease incoming energy
  - Injection of aerosols and atmospheric methods
  - Increase surface albedo (e.g. roofs)
  - Space mirrors?
  - Concerns: side effects, geopolitical, safety
- Nuclear fusion
  - The International Thermonuclear Experimental Reactor (ITER) project
  - Available (maybe) only in the long term

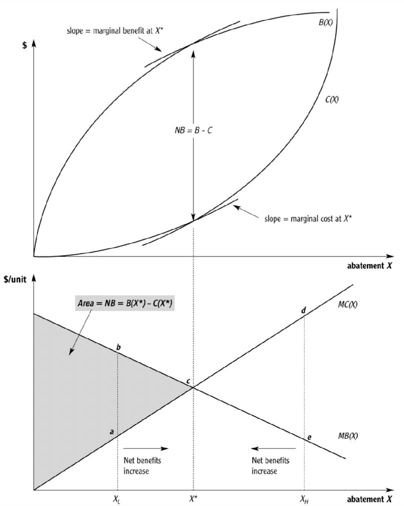
Abatement costs

Absolute and marginal abatement costs

- Reduction ('abatement') of emissions
  - How is it best to abate?
  - Economic theory: equate marginal cost and marginal benefit
- Benefits of abating
  - Avoiding emission damages
  - Market/non-market impacts on health, labour, crops..
  - Assumed to be concave in abatement
- Costs of abating
  - Additional expense compared to a no-abatement case
  - e.g. move to less convenient tech, with related investments
  - e.g. reduce production (and consequent sales/revenues)
  - Assumed to be convex in abatement

Finding the optimal level of abatement

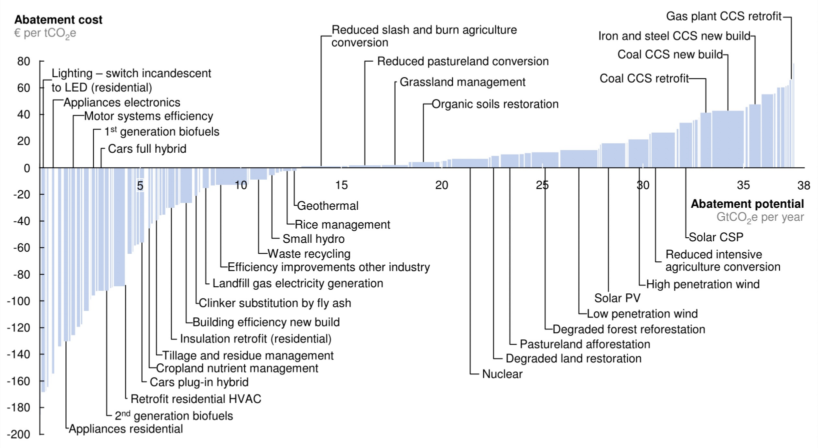
- Marginalist thinking
  - Should I emit the next ('marginal') unit of GHGs?
  - MBA>MAC $\rightarrow$ it makes sense to abate
  - MAC>MBA $\rightarrow$ it makes sense to emit
- Optimal state: MAC=MBA



Source: Keohane and Olmstead (2016)

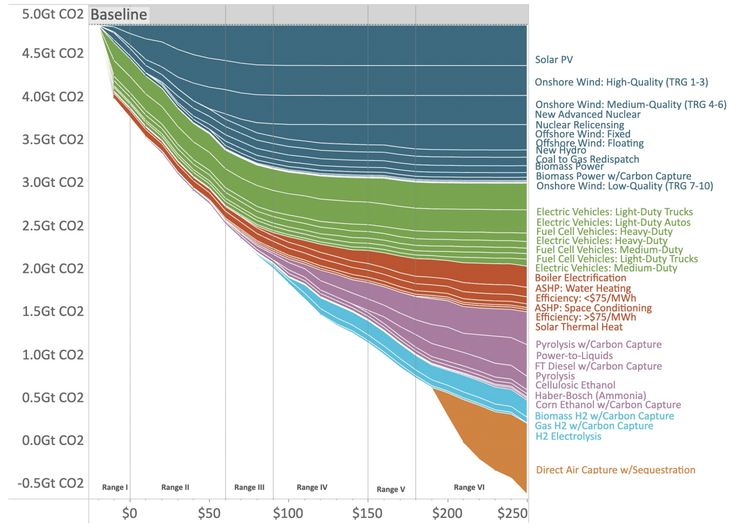
Empirical MAC curves

- The original McKinsey abatement cost curve



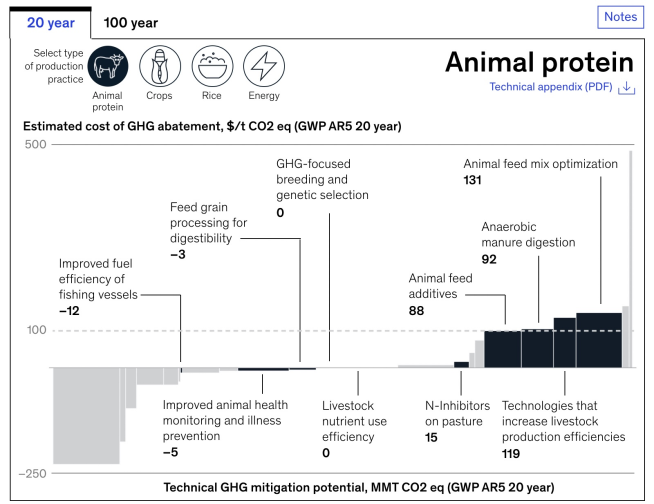
GHG abatement cost curve v2.1 (vs 2030 BAU). Source: McKinsey (2010)

A more recent MAC curve for the US



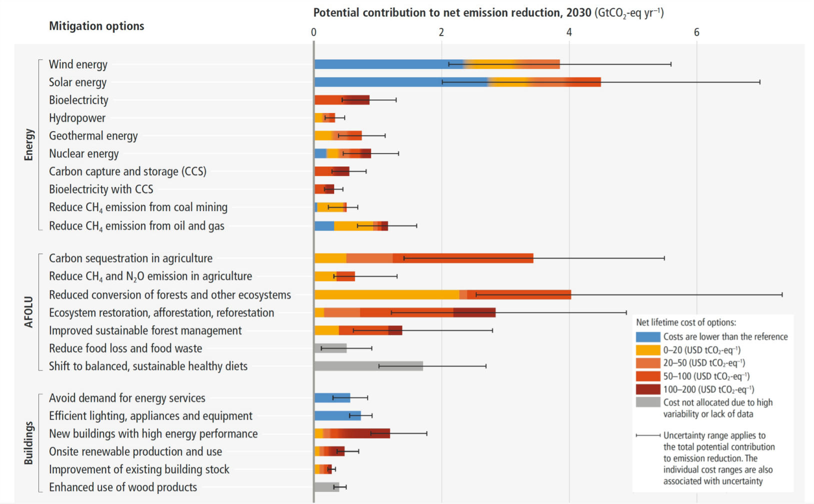
2050 MAC curve for US energy and industry CO2. Source: EDF (2021)

A MAC curve for agriculture



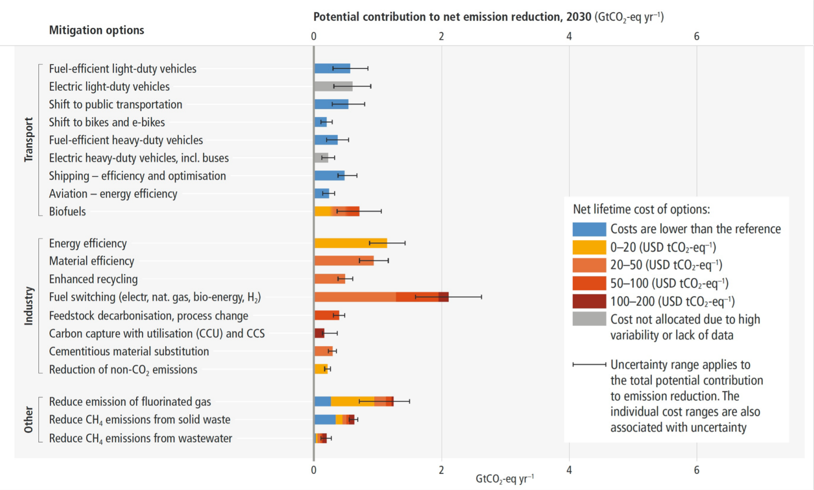
Agriculture abatement cost curve. Source: McKinsey (2020)

IPCC AR6 abatement tech potential and cost (i)



Overview of mitigation options and their estimated ranges of costs and potentials in 2030. Source: IPCC AR6 WGIII, SPM (2022)

IPCC AR6 abatement tech potential and cost (ii)



Overview of mitigation options and their estimated ranges of costs and potentials in 2030. Source: IPCC AR6 WGIII, SPM (2022)

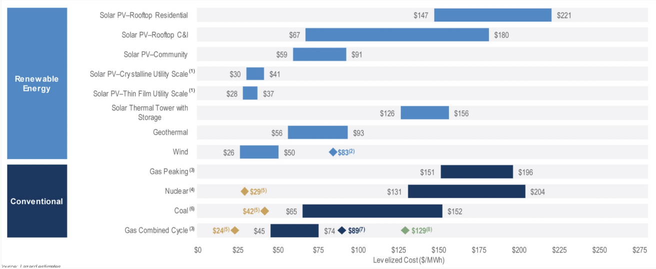
Innovation

- Technological costs can decrease!
- R&D investments
  - Private (e.g. large corporate, VC) vs public funding (e.g. development banks)
- Learning-by-doing; experience effects
  - Wright's law: costs function of cumulative production
- Innovation spillovers
  - lithium-ion battery research for smartphone $\rightarrow$ electric mobility
  - thin-layer nanotechnology $\rightarrow$ photo-voltaic energy on plastics

Note for electricity: the LCOE

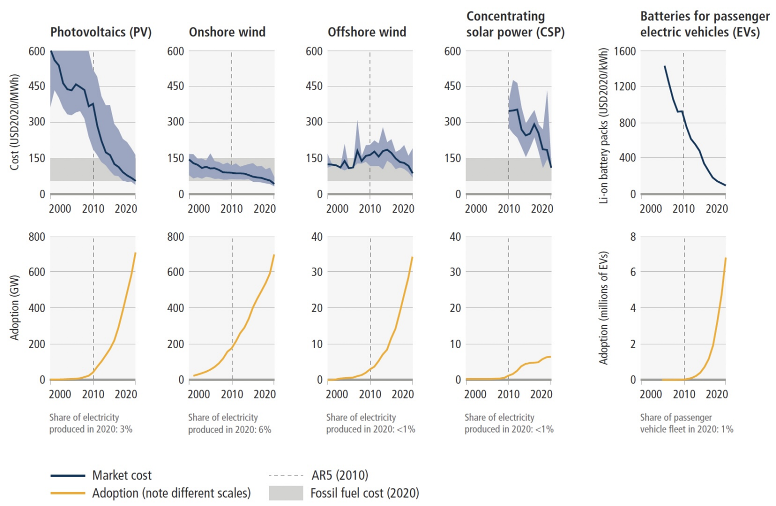
- Levelised cost of energy/electricity
  - Discounted life-time cost of producing electricity ($/MWh)
  - Renewables: high CAPEX but no fuel costs
  - Fossil-fueled: lower CAPEX but volatile fuel costs

$$LCOE = \frac{\left[CAPEX_0 + \sum_{t=0}^{T}(O\&M + fuel)\right](1+r)^{-t}}{\left[\sum_{t=0}^{T} MWh\right](1+r)^{-t}}$$



Levelised cost of energy estimates. Source: Lazard (2021)

Evolution of electricity costs

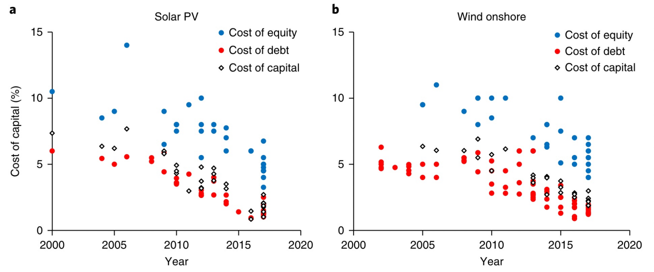


Evolution of costs and adoption dynamics. Source: IPCC 2021 WGIII, SPM

Cost of capital

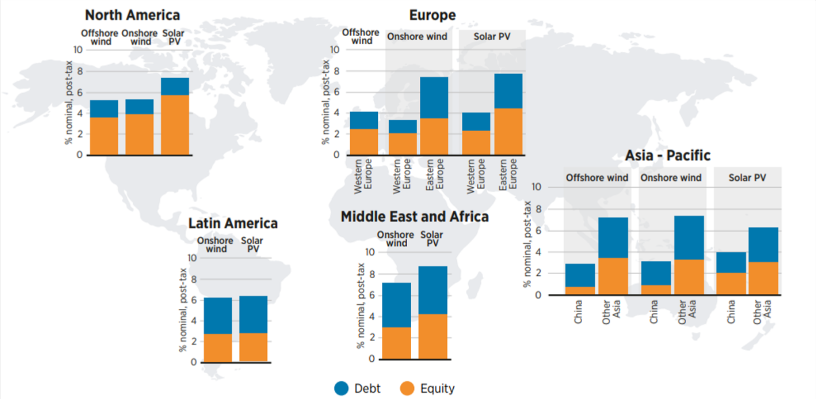
- Two main sources of finance
  - Equity (ownership) $\rightarrow$ Cost of equity (CoE)
  - Debt (lender) $\rightarrow$ Cost of debt (Cod)
  - Variable shares (common: 60% debt, 40% equity $\rightarrow d = 0.6$)
- Weighted average cost of capital (WACC)

$$WACC = d(1-\tau)CoD + (1-d)CoE$$



Levelised cost of energy estimates. Source: Egli et al. (2018)

Regional CoC differences



Debt and equity contribution to the total weighted average cost of capital. Source: IRENA (2023)

Conclusions

Conclusions

- Main strategy to reduce emissions: decarbonise
  - Use technology, rather than population or income
- Main abatement strategies
  - Clean power
  - Electrification
  - Efficiency
  - Clean industries
  - Land-use change
- Problem: costs
  - Some tech might be convenient in the long-term
  - Others need to be incentivised
- Next lecture: policies for a rapid low-carbon transition