

Decarbonising the global economic system

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Climate macroeconomics & finance 2024/25 - Lecture 3

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In the last lectures

- Climate change threat
 - Climate is changing very rapidly..
 - .. and it's definitely us
 - Climate risks for humans, firms, financial system
- → 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

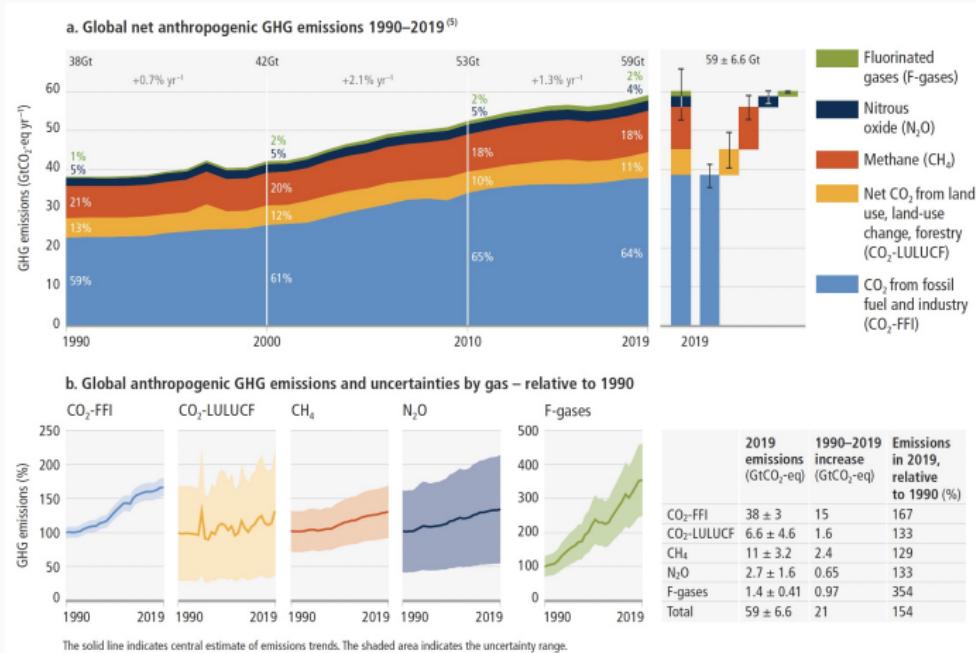
Outline of today's lecture

- 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?

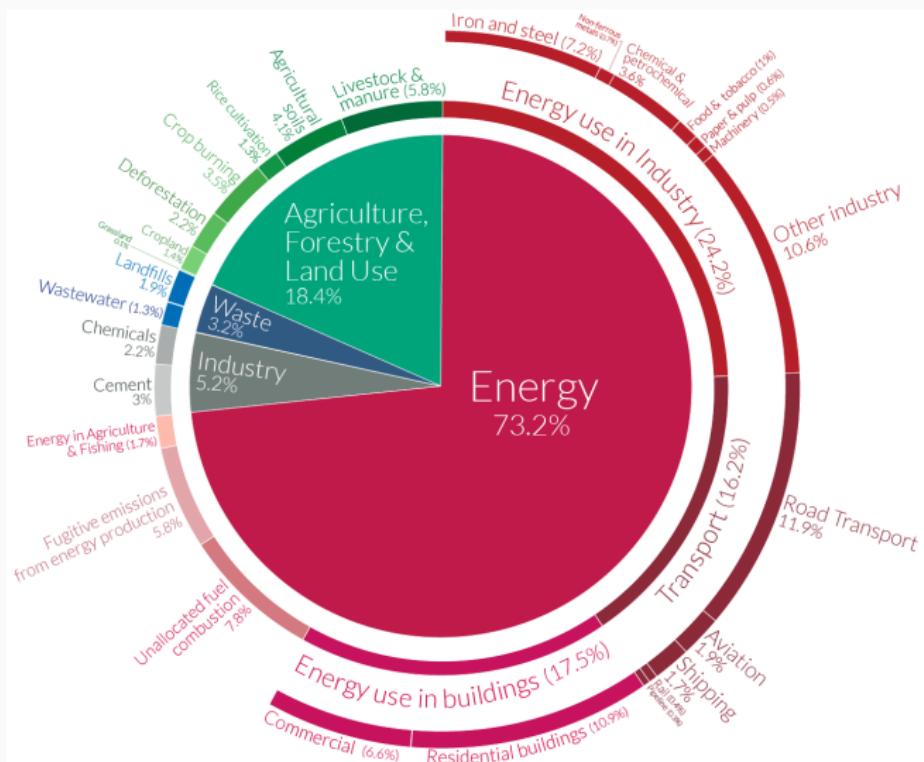
Recent trends in emissions

- 2019 GHG emission level: $59 \pm 6.6 \text{ GtCO}_2\text{-eq}$



Global net anthropogenic GHG emissions ($\text{GtCO}_2\text{-eq yr}^{-1}$) 1990–2019. Source: [IPCC WGIII, SPM \(2022\)](#)

Where do emissions come from now?



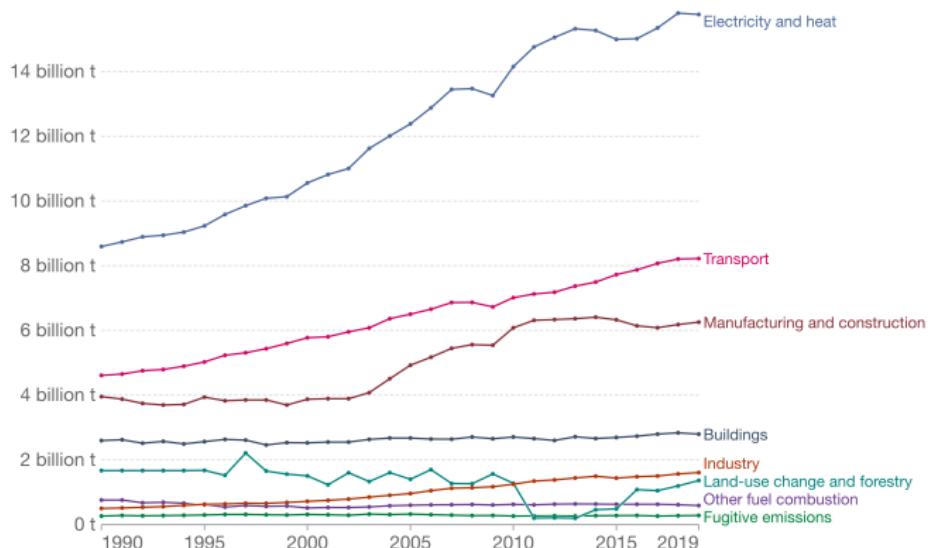
Global GHG emissions by sector in 2016. Source: Our World in Data

CO2 emissions by sector

- Main driver: combustion of fossil fuels

CO2 emissions by sector, World

Our World
in Data



Source: Our World in Data based on Climate Analysis Indicators Tool (CAIT).
OurWorldInData.org/co2-and-other-greenhouse-gas-emissions • CC BY

CO2 emissions by sector. Source: Our World in Data

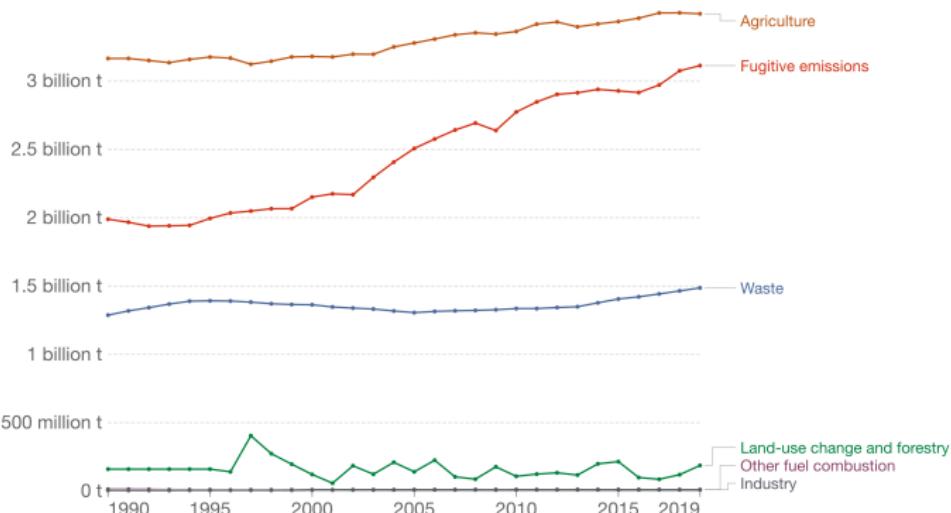
CH4 emissions by sector

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

Methane emissions by sector, World

Our World
in Data

Methane (CH_4) emissions are measured in tonnes of carbon dioxide equivalents (CO_2e) based on a 100-year global warming potential value.



Source: Our World in Data based on Climate Analysis Indicators Tool (CAIT).
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CH4 emissions by sector. Source: Our World in Data

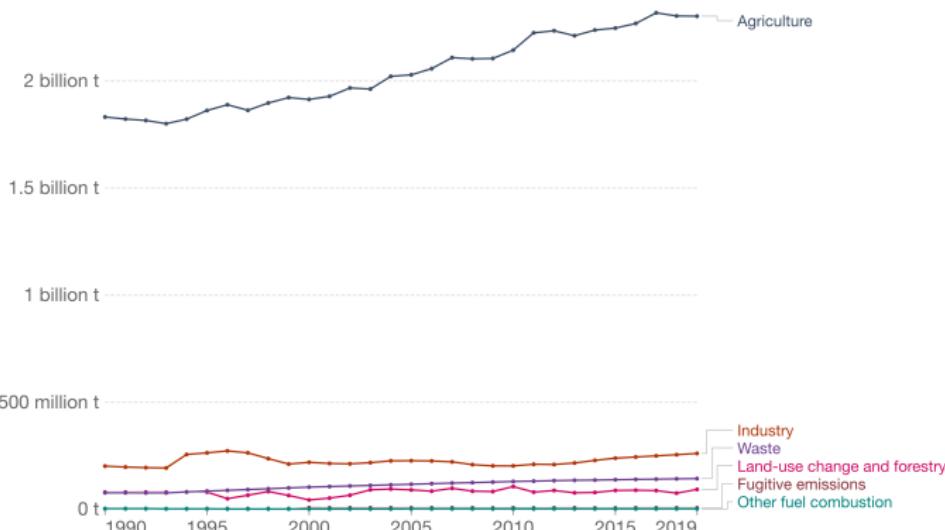
N₂O emissions by sector

- Most of N₂O linked to use of nitrogen fertilizers

Nitrous oxide emissions by sector, World

Nitrous oxide (N₂O) emissions are measured in tonnes of carbon dioxide equivalents (CO₂e) based on a 100-year global warming potential value.

Our World
in Data



Source: CAIT Climate Data Explorer via. Climate Watch

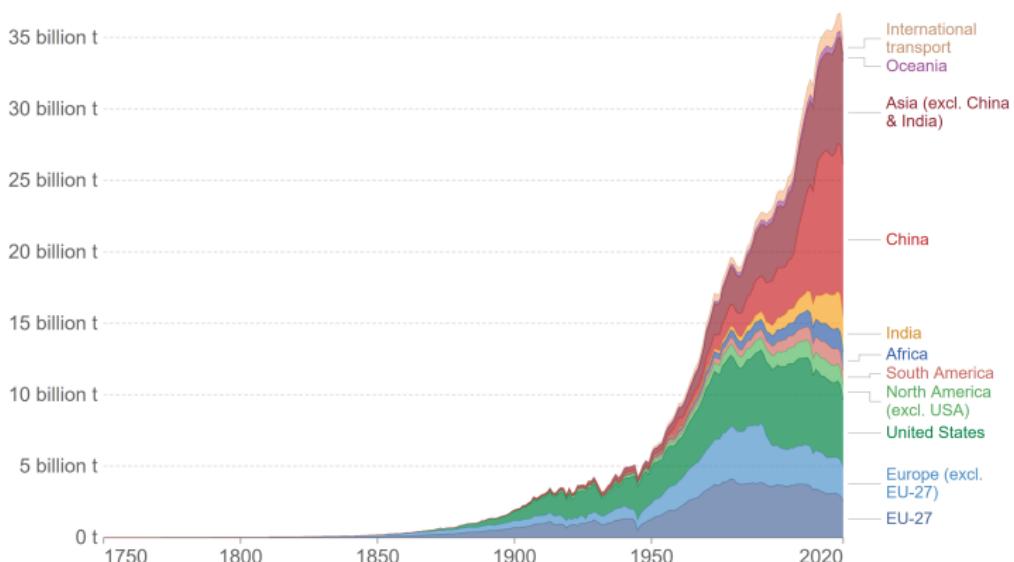
OurWorldInData.org/co2-and-other-greenhouse-gas-emissions/ • CC BY

N₂O emissions by sector. Source: Our World in Data

Regional differences

Annual CO₂ emissions from fossil fuels, by world region

Our World
in Data



Source: Global Carbon Project

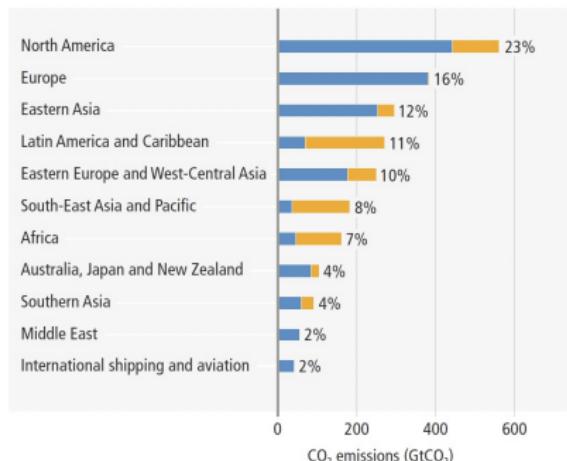
Note: This measures CO₂ emissions from fossil fuels and cement production only – land use change is not included. 'Statistical differences' (included in the GCP dataset) are not included here.

OurWorldInData.org/co2-and-other-greenhouse-gas-emissions • CC BY

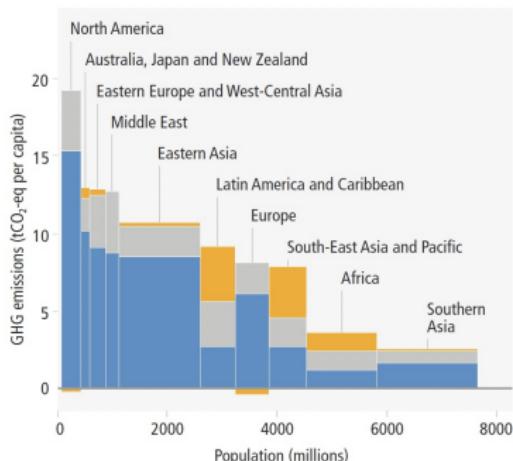
CO₂ emissions from fossils and cement. Source: [Our World in Data](#)

Regional differences

b. Historical cumulative net anthropogenic CO₂ emissions per region (1850–2019)



c. Net anthropogenic GHG emissions per capita and for total population, per region (2019)

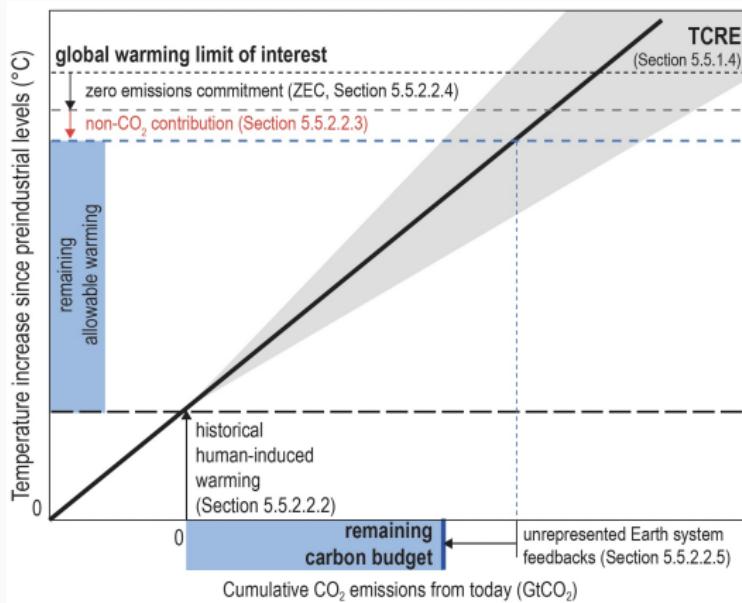


Regional distribution of GHG emissions (light blue: CO₂-FFI; yellow: CO₂-LULUCF; grey: other GHGs). Source: [IPCC WGIII, SPM \(2022\)](#)

**How much should GHG emissions
be reduced?**

The carbon budget concept

- TCRE: linear relation between cum CO₂ emissions and ΔT
→ 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

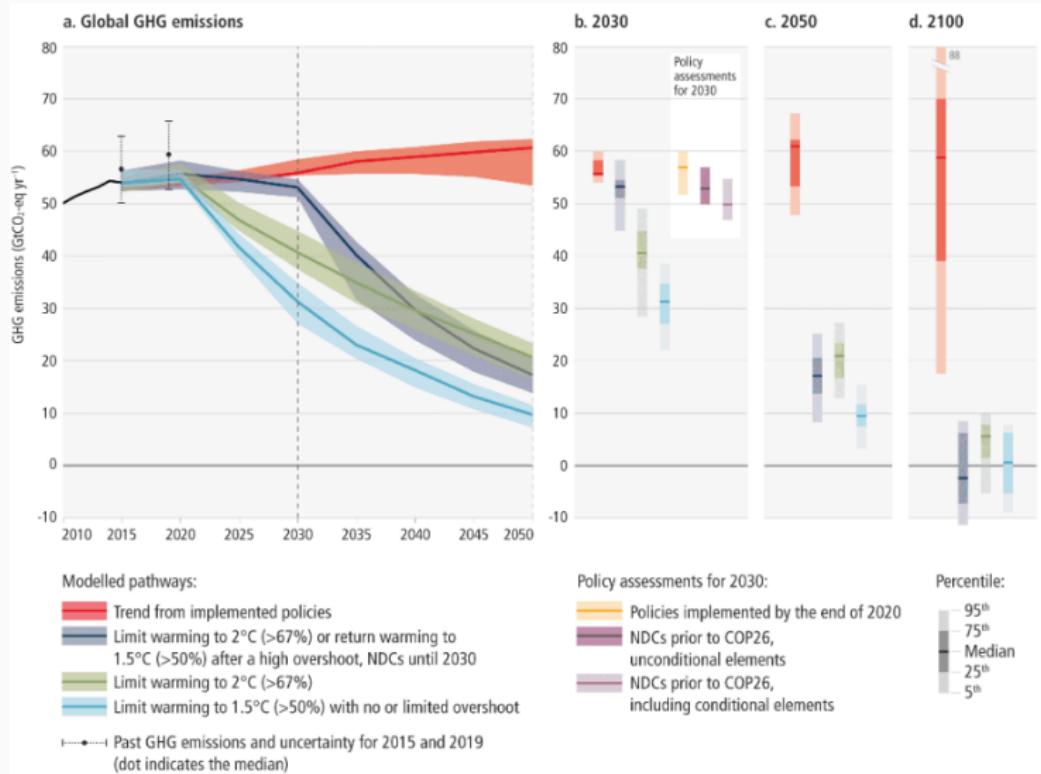
Additional Warming Since 2010–2019 ^a	Warming Since 1850–1900 ^a	Remaining Carbon Budget ^b starting from 1 January 2020 and subject to variations and uncertainties quantified in the columns on the right					Scenario Variation	Geophysical Uncertainties				
		Percentiles of TCRE ^{c,d} PgC (GtCO ₂)						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
°C	°C	12th	33rd	50th	67th	83rd	PgC (GtCO ₂)	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)						
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)						

Values can vary by at least ±60 PgC (±220 GtCO₂) due to choices related to non-CO₂ emissions mitigation
Values can vary by at least ±60 PgC (±220 GtCO₂) due to uncertainty in the warming response to future non-CO₂ emissions

^a ±15 PgC (±550 GtCO₂)
^b ±15 PgC (±420 GtCO₂)
^c ±6 PgC (±210 GtCO₂)

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

Emission reduction pathways



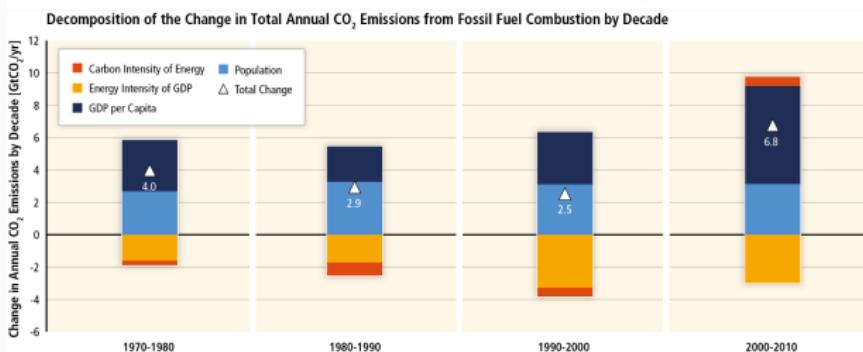
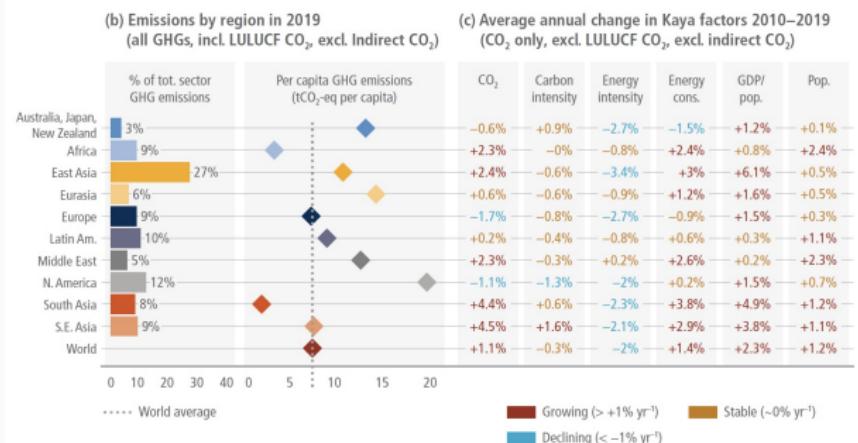
Global GHG pathways. Source: [IPCC 2021 WGIII, SPM](#)

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:
 - CO₂: emissions
 - P: population
 - Y/P: income per capita
 - E/Y: energy intensity of GDP
 - CO₂/E: carbon intensity of energy
 - $\rightarrow \hat{CO}_2 \approx \hat{P} + (\hat{\frac{Y}{P}}) + (\hat{\frac{E}{Y}}) + (\hat{\frac{CO_2}{E}})$

Kaya CO₂ emission decomposition



Decomposition of fossil fuel CO₂ emission drivers. Source: IPCC AR6 WGIII, Ch.2 (2022) (https://www.ipcc.ch/report/ar6/wg3/), Fig. 2.11

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 CO₂ 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, N₂O, etc.
- Most common in economics
 - Emission reduction, supply-side, CO₂

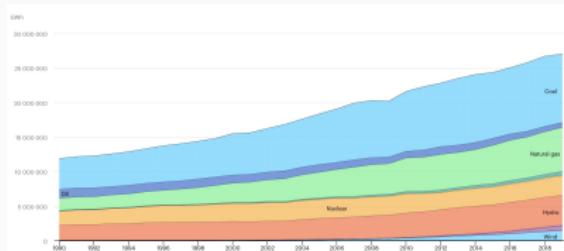
Electricity: main power-generating technologies

- Fossils
 - Burn coal, gas, oil → turbines spin generating electricity
 - Large emissions of CO₂ 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.

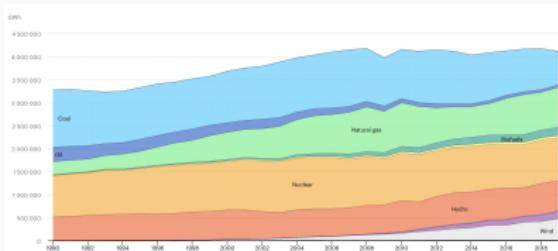
Electricity from renewable sources

- 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 → Energy storage issue
 - High demand of critical minerals → geopolitical implications
 - Land/sea use, visual impacts
 - Competitiveness!

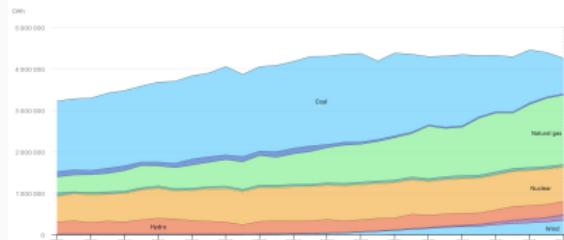
Electricity production by source



(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)

- 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? → 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 N₂O from fertilizer use
- Mitigation strategies?
 - Reduced deforestation, afforestation
 - New agricultural/farming techniques (e.g. nitrogen-fixing rotations)

Carbon capture and storage

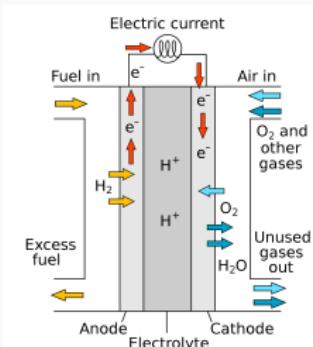
- Main idea:
 - Capture CO₂ emissions at their source (e.g. coal plants)
 - Store it somewhere safe, or use it
- Can we capture carbon?
 - Technologically doable, but very expensive
 - Pilot project stage → more R&D investment needed
- What to do with it?
 - Store in geological formations or oceans: safe?
 - Recycle in industry (e.g. carbonated drinks)
- BECCS concept
 - Bioenergy + CCS = BECCS (Negative emissions)

Carbon dioxide removal

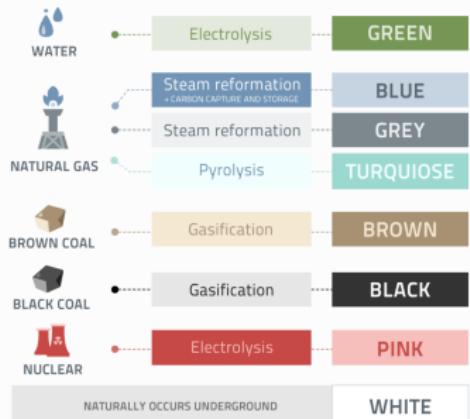
- Main idea
 - Remove GHGs already in the atmosphere
- Direct air capture
 - Several techs, but based on air contact with chemicals
 - Economic feasibility? **DAC 1** coming
- Ocean fertilization
 - Introduce nutrients in the ocean (e.g. iron) → increase in phytoplankton activity → increase in CO₂ absorption capacity of oceans
 - Concerns about efficacy and side-effects
- Sequestration by trees
 - Preserve/enhance CO₂ 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



THE HYDROGEN COLOUR SPECTRUM



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

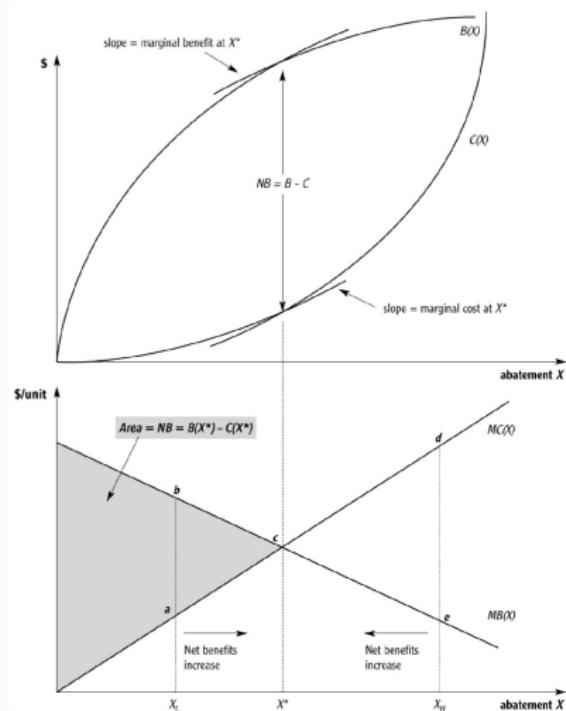
Abatement costs

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

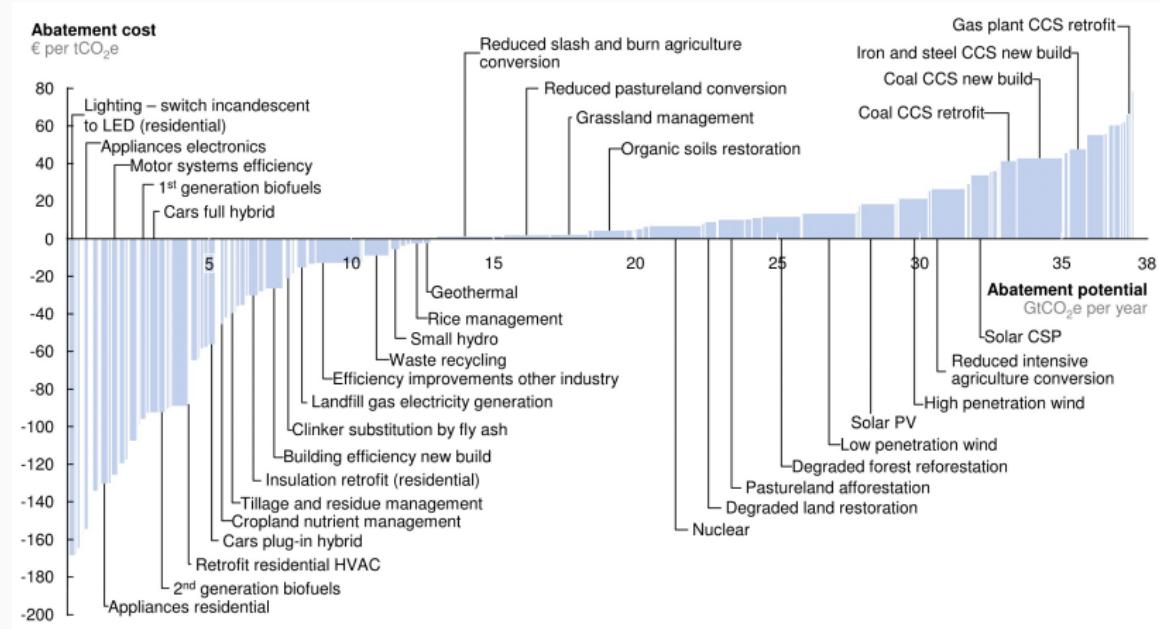
- Marginalist thinking
 - Should I emit the next ('marginal') unit of GHGs?
 - $MBA > MAC \rightarrow$ it makes sense to abate
 - $MAC > MBA \rightarrow$ it makes sense to emit
- Optimal state:
 $MAC = MBA$



Source: Keohane and Olmstead (2016)

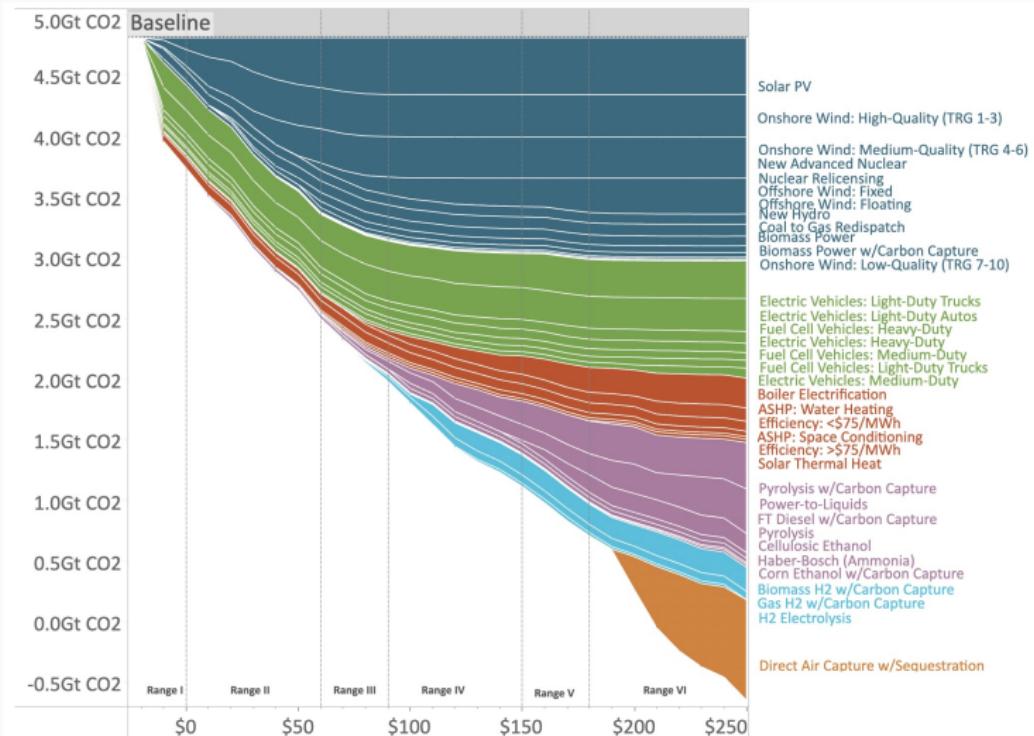
Empirical MAC curves

- The original McKinsey abatement cost curve



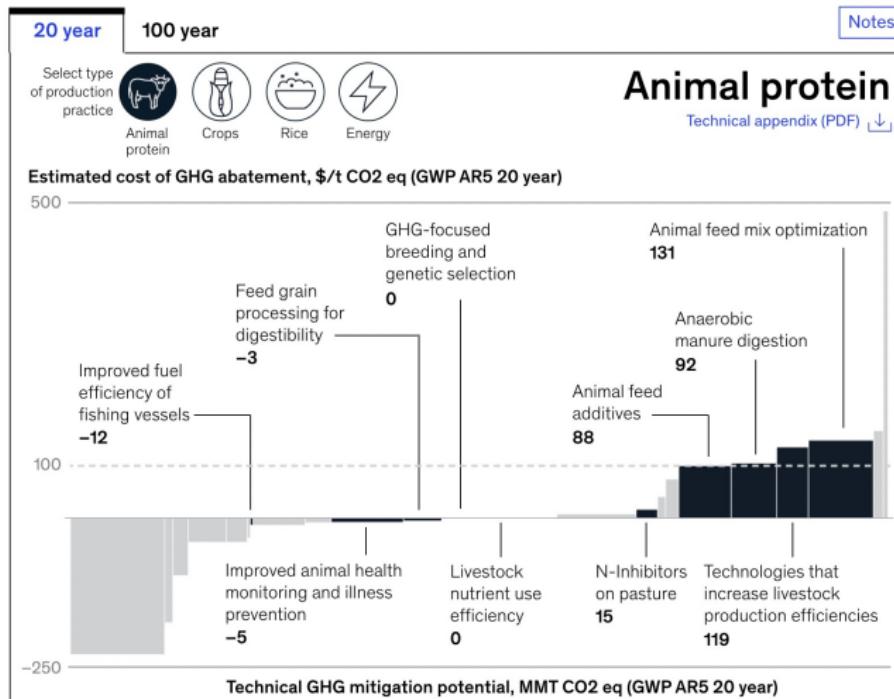
GHG abatement cost curve v2.1 (vs 2030 BAU). Source: [McKinsey \(2010\)](#)

A more recent MAC curve for the US



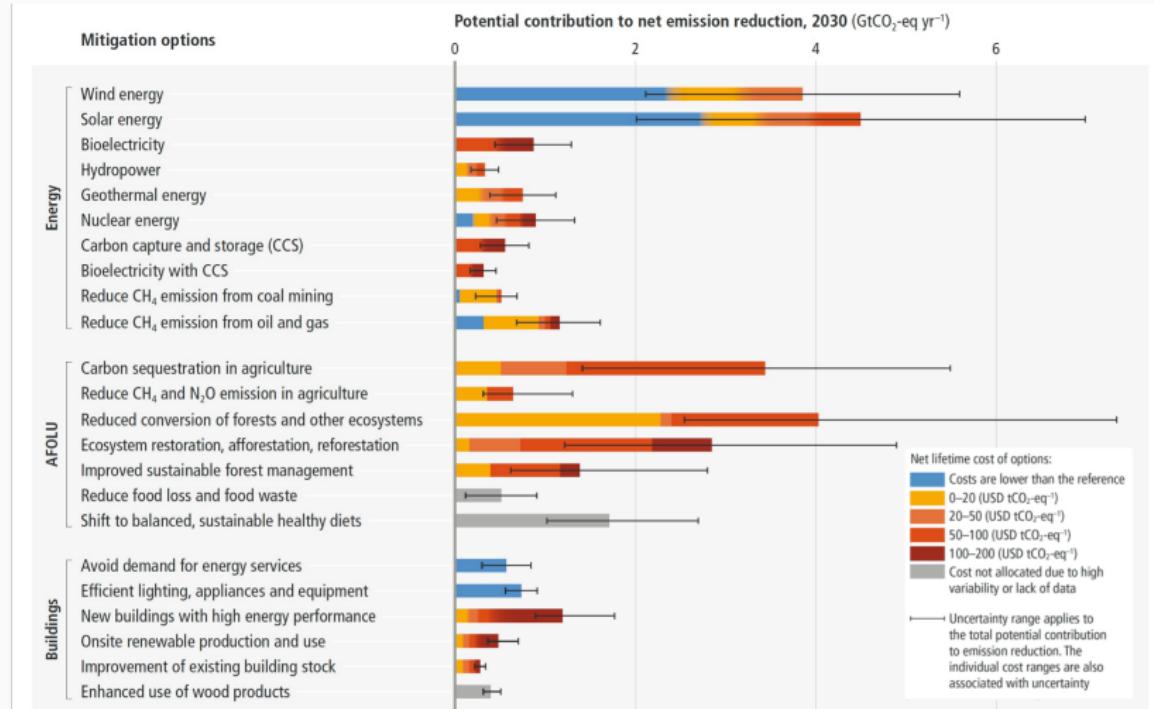
2050 MAC curve for US energy and industry CO₂. Source: EDF (2021)

A MAC curve for agriculture



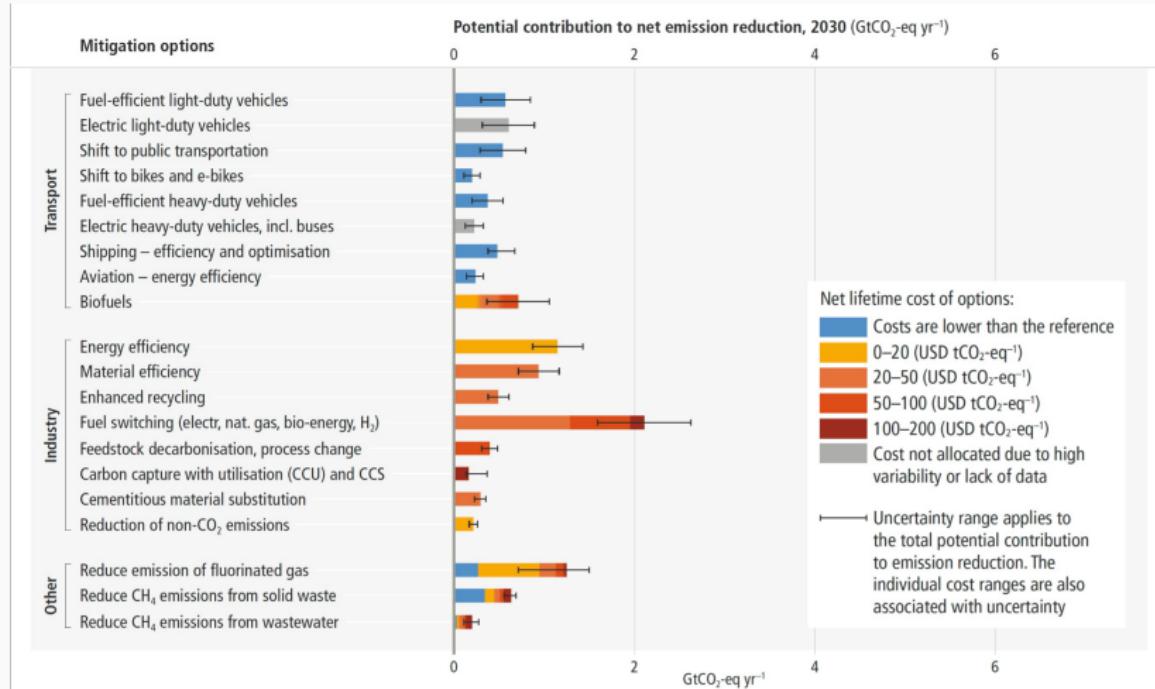
Agriculture abatement cost curve. Source: [McKinsey \(2020\)](#)

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)



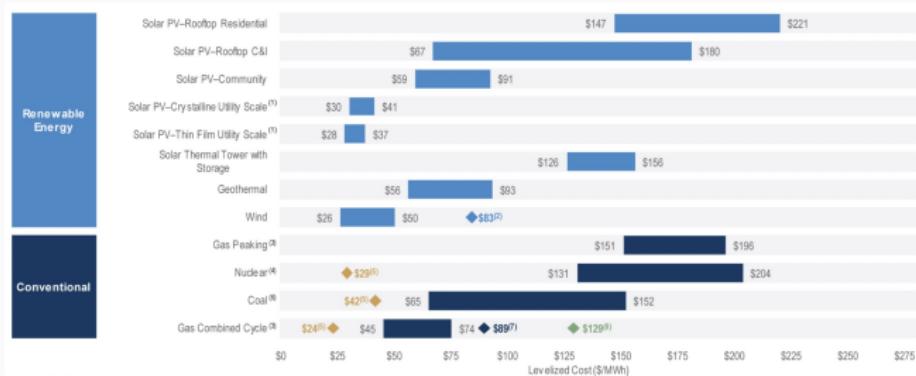
Overview of mitigation options and their estimated ranges of costs and potentials in 2030. Source: [IPCC AR6 WGIII, SPM \(2022\)](#)

- 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 → electric mobility
 - thin-layer nanotechnology → photo-voltaic energy on plastics

Note for electricity: the LCOE

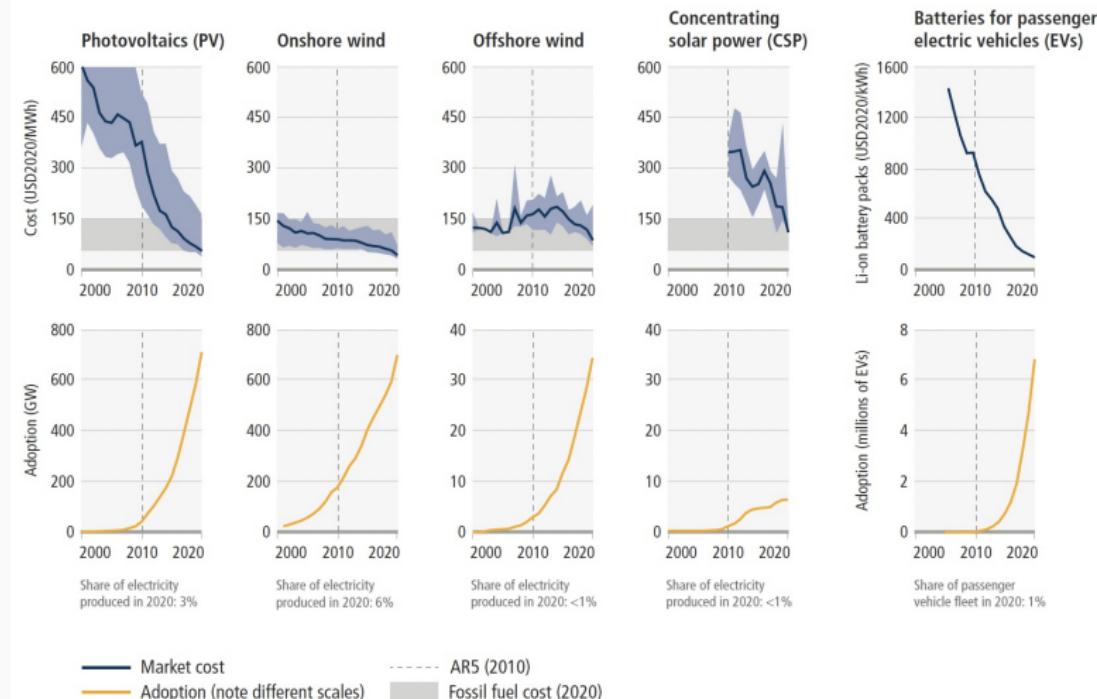
- Levelised cost of energy/electricity
 - Discounted life-time cost of producing electricity (\$/MWh)
 - Renewables: high CAPEX but no fuel costs
 - Fossil-fueled: lower CAPEX but volatile fuel costs

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



Levelised cost of energy estimates. Source: [Lazard \(2021\)](#)

Evolution of electricity costs

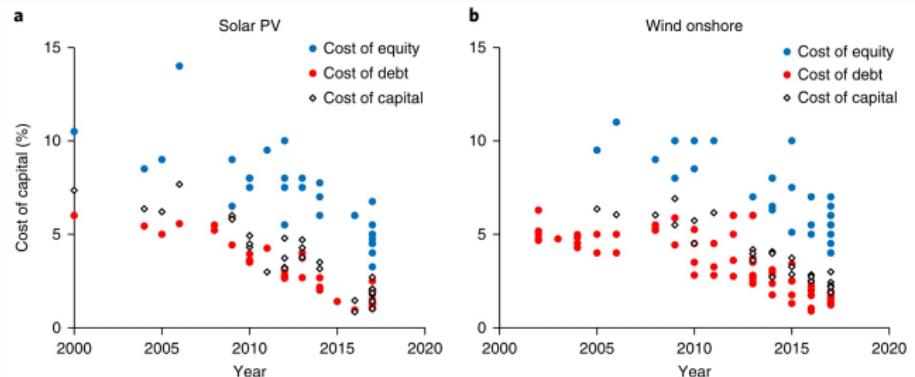


Evolution of costs and adoption dynamics. Source: [IPCC 2021 WGIII, SPM](#)

Cost of capital

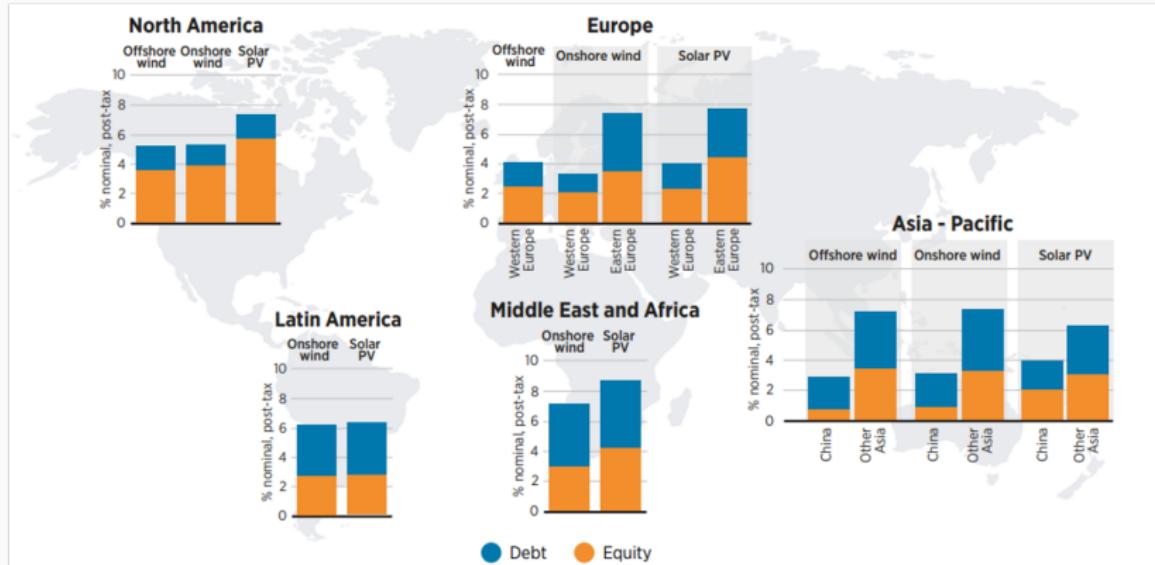
- Two main sources of finance
 - Equity (ownership) → Cost of equity (CoE)
 - Debt (lender) → Cost of debt (CoD)
 - Variable shares (common: 60% debt, 40% equity → $d = 0.6$)
- Weighted average cost of capital (WACC)

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



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