

Net Zero Plus Carbon Removal

Returning CO₂ to Holocene levels: timeline, costs, the Keeling curve and economic effects · October 2026

Overview

This briefing extends *The Road to Net Zero* by adding one measure, and a new temperature view,: a global CO₂ removal (CDR) program of all types, from forests and soils to enhanced rock weathering, bioenergy with carbon capture and direct air capture. It ramps up from 2035 to 2080 at twice the pace at which emissions are being cut, with the goal of removing the excess CO₂ humans have added to the atmosphere and oceans and returning to Holocene concentrations of 280–300 ppm.

The five views tell a consistent story. CDR at this scale changes the climate picture completely: net zero arrives around 2049 instead of 2074, CO₂ peaks lower and earlier at about 463 ppm (versus about 482 ppm without removal), falls back below 350 ppm around 2075, and reaches about 290 ppm by the mid-2080s. Global temperature follows a decade or so behind: it peaks at about 1.9 °C around 2052, drops back below 1.5 °C around 2074 and falls to about 0.8 °C by 2100. The price is enormous. Removal grows to about 85 billion tonnes a year, roughly twice today's total emissions, costing about \$8 trillion a year by 2080 and about \$215 trillion in total. Unlike clean energy it saves no fuel, so it only pays off once avoided climate damage is counted. On that basis the economy ends up clearly ahead from the late 2050s.

Full-size versions of each figure follow these pages.

1. Timeline to net zero, and back to 350 ppm

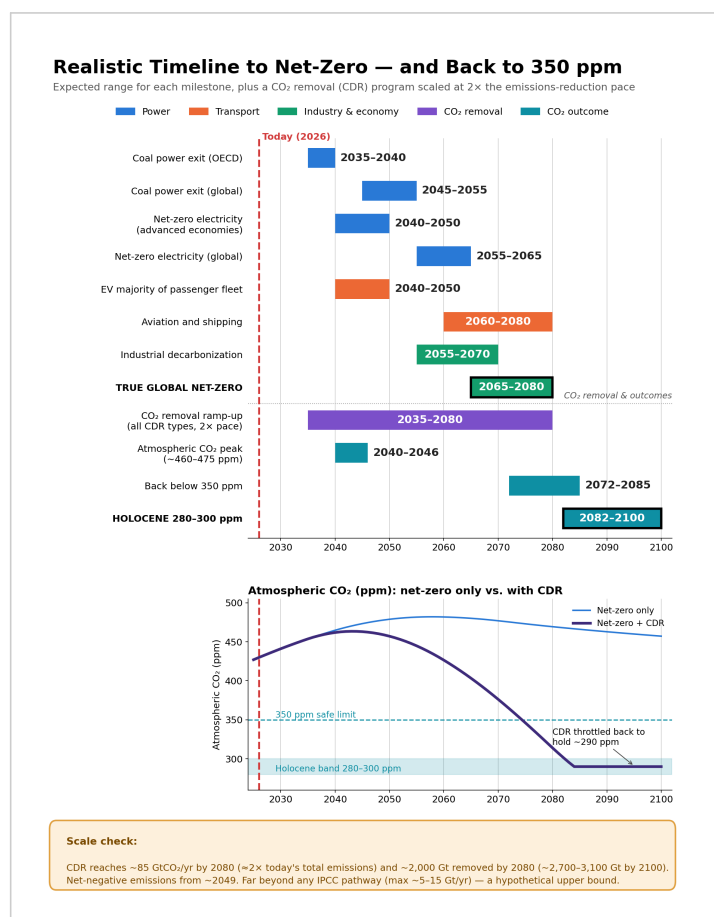


Figure 1 · Timeline with CO₂ removal and outcomes (full size on page 10)

Milestone	Realistic range
Energy transition milestones (Figure 1, previous briefing)	Unchanged
CO2 removal ramp-up (all types, 2× pace)	2035–2080
Net zero (net emissions)	~2049 (vs. 2065–2080 without CDR)
Atmospheric CO2 peak, ~460–475 ppm	2040–2046
Back below 350 ppm	2072–2085
Holocene levels, 280–300 ppm	2082–2100

The energy milestones are unchanged; CDR is added on top of them, not instead of them. Removal starts small in 2035 and grows by about 1.9 billion tonnes a year, every year. Because it scales so fast, it overtakes the remaining emissions around 2049, decades before aviation, shipping and heavy industry are fully decarbonized.

2. Global cost versus benefit

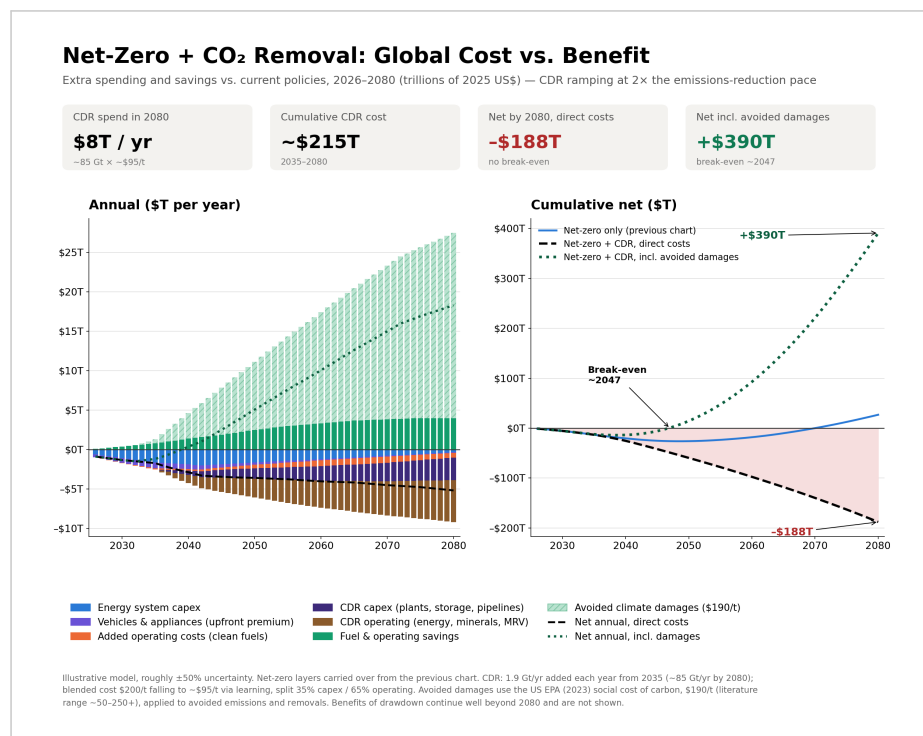


Figure 2 · Net-zero plus CDR cost vs. benefit (full size on page 11)

Figure 2 keeps the energy-transition layers from the previous briefing and adds two CDR layers. Because removal produces no fuel savings, the chart shows the result two ways: direct costs only, and with avoided climate damages included.

How the model is built

- **Volume.** 1.9 Gt a year of new removal capacity each year from 2035, reaching about 85 Gt a year by 2080 and about 2,000 Gt removed in total by then.
- **Cost.** A blended cost of about \$200 per tonne in 2035, falling to about \$95 by 2080 through learning. That is optimistic for direct air capture but realistic for a mix of methods. Nature-based options run out at roughly 5–10 Gt a year, so most removal must be engineered.
- **Split.** About 35% capital (plants, pipelines, storage) and 65% operating costs (energy, rock and minerals, monitoring).
- **Avoided damages.** The US EPA's 2023 central social cost of carbon, \$190 per tonne, applied to both avoided emissions and removals.

Key results

CDR spending reaches about \$8 trillion a year by 2080, roughly 2–2.5% of world GDP. On direct costs alone, the +\$29 trillion gain from the energy transition is swamped and the cumulative position ends near –\$188 trillion with no break-even. Including avoided damages, the cumulative position breaks even around 2047 and reaches about +\$390 trillion by 2080.

Caveats

- The damage estimate decides the verdict. Published social-cost-of-carbon values range from about \$50 to more than \$250 per tonne; at roughly \$70 the benefits only offset the costs. The current US administration has withdrawn the EPA figure.
- Removal is a public good: nobody's bills fall when CO₂ is removed, so it needs carbon pricing, mandates or public money.
- Holding CO₂ near 290 ppm after the 2080s would still cost an estimated \$1–3 trillion a year in ongoing removal.

3. CO₂ emissions and the Keeling curve

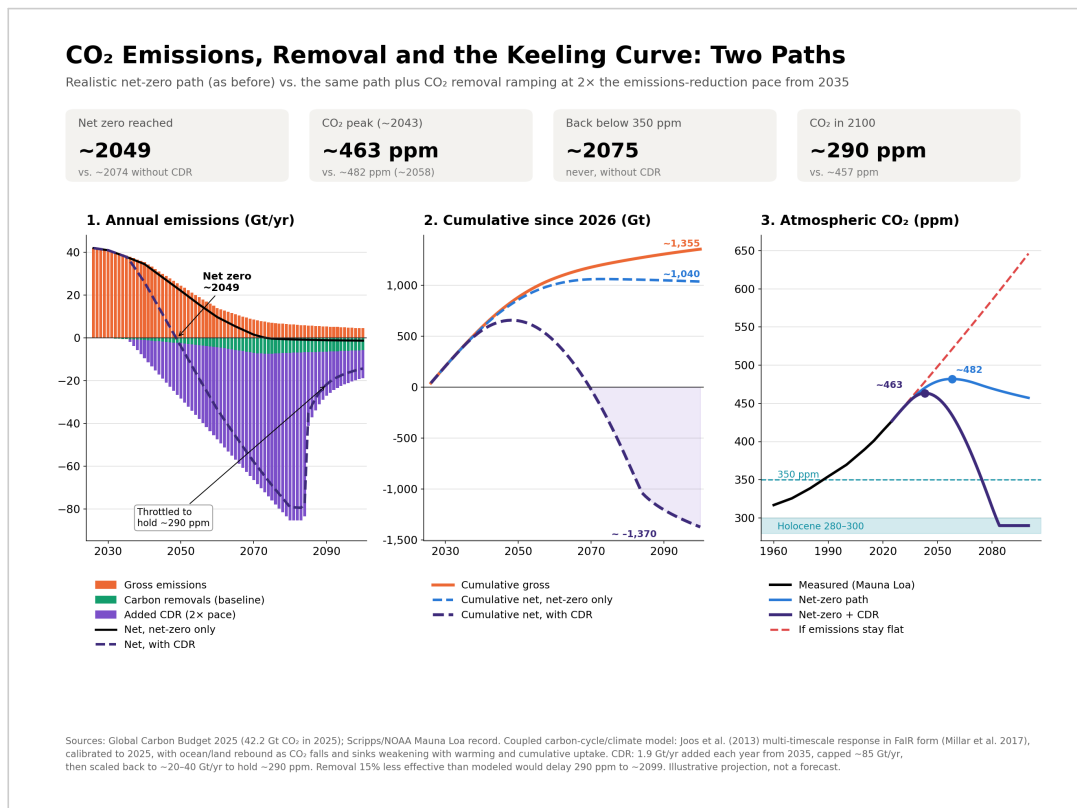


Figure 3 · Emissions, removal and the Keeling curve, two paths (full size on page 12)

Figure 3 starts from 42.2 billion tonnes of CO₂ in 2025 (Global Carbon Budget 2025) and uses a coupled carbon-cycle and climate model calibrated to observations. It includes the multi-timescale Joos et al. (2013) carbon cycle, in the FaIR form of Millar et al. (2017), so the ocean and land release CO₂ back to the air as concentrations fall, and sinks weaken as the world warms. Because of that sink weakening, the net-zero-only path here peaks higher than in the companion briefing: about 482 ppm around 2058 rather than 463 ppm, ending 2100 near 457 ppm rather than 435 ppm.

Key insight: the oceans push back

Removing a tonne of CO₂ from the air lowers concentrations by less than adding a tonne raised them, because the oceans and land release some of the CO₂ they absorbed as air concentrations fall. In this model the extra 2,400 Gt removed compared with net zero alone lowers CO₂ in 2100 by only about 1,300 Gt-equivalent: roughly 46% is offset by this rebound. That is why getting back to 290 ppm needs about 2,000 Gt of removal by 2080, far more than the roughly 1,100 Gt the atmosphere gained since 1850, and why removal of about 20–40 Gt a year must continue afterwards just to hold the level.

Results

- **Net zero** around 2049, 25 years earlier than without CDR.
- **Peak CO₂** about 463 ppm around 2043, versus about 482 ppm around 2058.
- **Below 350 ppm** around 2075; never this century without CDR.
- **CO₂ in 2100** about 290 ppm, versus about 457 ppm. Cumulative net emissions from 2026 to 2100 swing from about +1,040 Gt to about –1,370 Gt.

Re-check: removal needed to reach and hold 290 ppm

The table shows the coupled model year by year. Removal follows the 2× ramp until about 2084, when 290 ppm is reached, then is scaled back to hold that level. Costs use the blended cost per tonne from Figure 2.

Year	Removal (Gt/yr)	Cumulative (Gt)	\$/t	Cost (\$T/yr)	CO2 (ppm)	Warming (°C)
2030	0.2	0	–	~0	441	1.54
2040	9.5	31	169	1.6	462	1.80
2050	28.5	231	130	3.7	457	1.91
2060	47.5	620	111	5.3	426	1.86
2070	66.5	1,200	101	6.7	376	1.63
2080	85.5	1,969	95	8.2	314	1.19
2090	27.1	2,509	93	2.5	290	0.86
2100	18.8	2,726	91	1.7	290	0.83

Removal amounts and costs through 2080 match Figure 2 exactly, because the 2× ramp is the binding limit; holding costs afterwards, about \$1.7–2.5 trillion a year, fall within the \$1–3 trillion range quoted there.

Sensitivity tests

- **Removal 15% less effective than modeled**, reflecting the asymmetry noted in IPCC AR6: 290 ppm is not reached until about 2099, and cumulative removal rises to about 3,100 Gt, roughly \$35 trillion more.
- **Sink weakening twice as strong**: CO₂ peaks near 483 ppm and 290 ppm slips to about 2086.

- **Climate sensitivity of 4 °C:** peak warming rises to about 2.3 °C; 290 ppm is still reached around 2084.

4. Global mean surface temperature

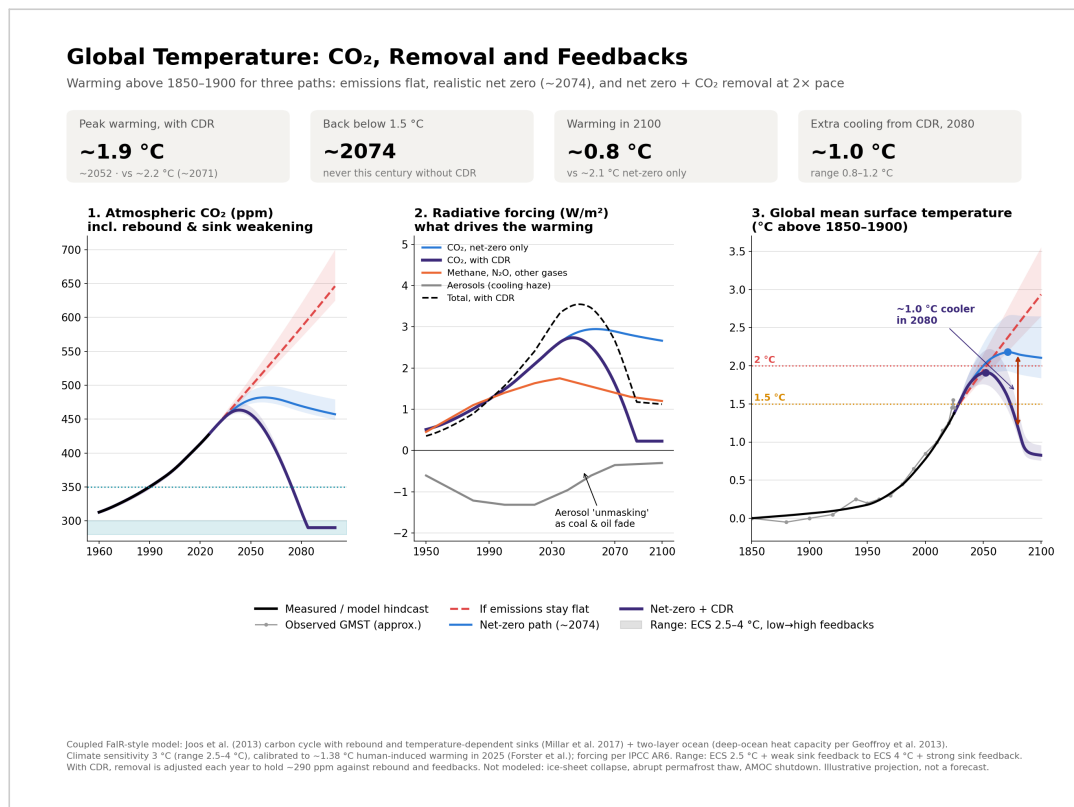


Figure 4 · Global mean surface temperature, three paths (full size on page 13)

Figure 4 converts the CO₂ paths from Figure 3 into global mean surface temperature, measured against 1850–1900. It adds a third path in which emissions stay flat, and shows the effect of methane, nitrous oxide, aerosols and Earth-system feedbacks alongside CO₂.

How the model is built

- **Climate model.** A two-layer energy-balance model, the kind used to emulate the IPCC's full Earth-system models, with deep-ocean heat capacity set to the CMIP5 model average (Geoffroy et al., 2013). A fast upper ocean and slow deep ocean make temperature lag CO₂ and limit how fast the surface can cool, to at most about 0.05 °C a year.
- **Sensitivity.** 3 °C of warming per doubling of CO₂, the IPCC's best estimate, with a 2.5–4 °C range. The model is calibrated to about 1.38 °C of human-caused warming in 2025.
- **Other drivers.** Warming effects follow IPCC AR6. Methane and other gases decline slowly on the net-zero paths; the cooling effect of aerosols fades as coal and oil burning falls.
- **Feedbacks.** Ocean and land sinks weaken as warming and cumulative uptake rise, and recover as they fall; the low case uses half-strength and the high case double-strength sink weakening. With CDR, removal is adjusted each year to hold about 290 ppm against rebound and feedbacks.

Result	Flat emissions	Net zero only	Net zero + CDR
Peak warming	still rising	~2.2 °C (~2071)	~1.9 °C (~2052)
Crosses 2 °C	~2053	~2051	no
Warming in 2100	~2.9 °C	~2.1 °C	~0.8 °C
Back below 1.5 °C	never	not this century	~2074

Key insights

- **Temperature lags CO₂.** With CDR, CO₂ peaks around 2043 but temperature peaks about 9 years later, because the oceans keep releasing stored heat.
- **Aerosol unmasking.** As fossil-fuel burning falls, its cooling haze disappears. That briefly makes the net-zero path slightly warmer than flat emissions, by up to about 0.1 °C, from the early 2030s until about 2058, and it is why even aggressive removal cannot avoid passing 1.5 °C.
- **Feedbacks matter most at the high end.** Weakening sinks combined with high climate sensitivity push net-zero-only warming to about 2.7 °C in the high case.
- **CDR's climate payoff.** Removal makes 2080 about 1.0 °C cooler than net zero alone (range 0.8–1.2 °C), and about 1.3 °C cooler by 2100.

Caveats

- Ice-sheet collapse, abrupt permafrost thaw and an Atlantic circulation (AMOC) shutdown are not modeled; their timing is too uncertain to put on a curve.
- Sea level keeps rising for centuries even after temperatures fall, because ice sheets and the deep ocean respond slowly.

5. Economic effects

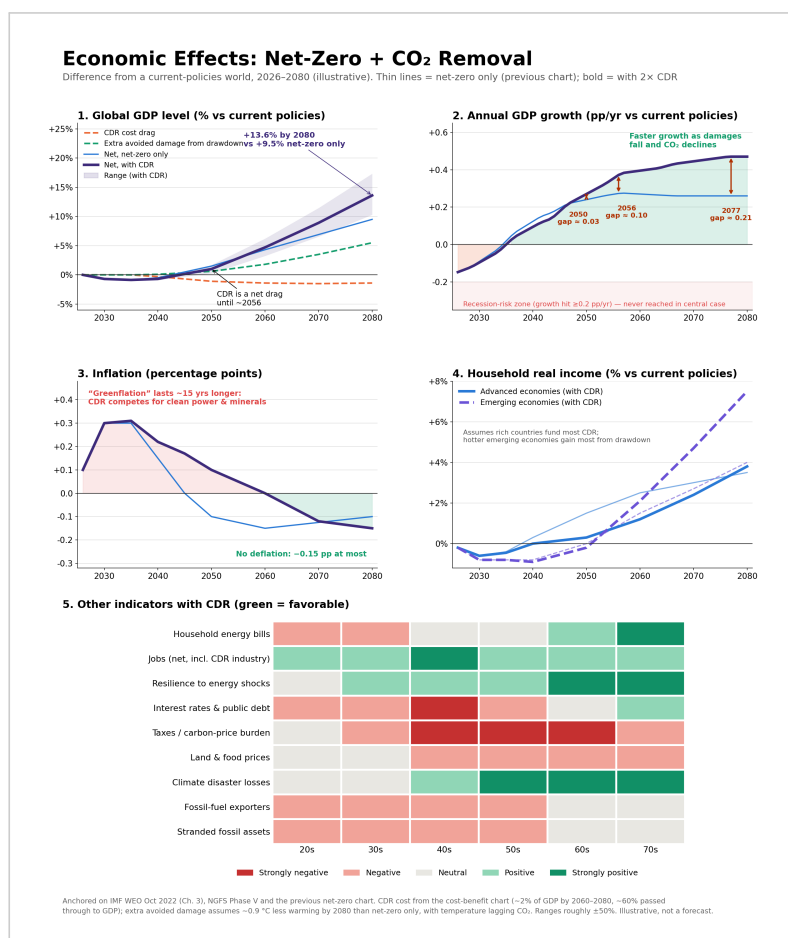


Figure 5 · Economic effects with CDR (full size on page 14)

As before, every line shows the difference from a current-policies world. Thin lines repeat the net-zero-only results; bold lines add CDR.

Reading the panels

- **GDP level (panel 1).** CDR is a net drag of about 0.5% around 2050, then pulls ahead around 2056 as reduced warming pays off. By 2080 GDP is about 13.6% above current policies, versus 9.5% for net zero alone.
- **GDP growth (panel 2).** The deepest dip is about –0.15 points a year in the late 2020s, from the transition rather than removal, and never reaches recession territory. The red arrows mark the extra growth from CDR: about 0.03 points in 2050, 0.10 in 2056 and 0.21 by 2077.
- **Inflation (panel 3).** CDR competes for clean power, minerals and land, extending mild greenflation from the mid-2040s to about 2060. It peaks near +0.3 points; there is no deflation.
- **Household income (panel 4).** Assuming rich countries fund most removal, advanced-economy households lose about 1 point of income in the 2040s–60s. Emerging economies gain most, about +7.5% by 2080, because they suffer most from heat and can host removal industries.

- **Other indicators (panel 5).** Taxes, public debt and land and food prices worsen in the 2040s–60s; jobs, disaster losses and resilience improve. Fossil-fuel exporters are hit less hard because their geology and skills can be reused for CO₂ storage.

Caveats

- Extra avoided damage in Figure 5 assumes about 0.9 °C less warming by 2080 than net zero alone. The coupled model in Figure 4 computes about 1.0 °C (range 0.8–1.2 °C), so the economic results are consistent and, if anything, slightly conservative. If damages per degree prove smaller, the crossover moves into the 2060s.
- Energy is the binding constraint. Removing 85 Gt a year could require a large share of all the energy the world uses today.

Bottom line

Returning to 350 ppm this century is physically possible, but only with a removal industry as large as the entire energy transition, built in parallel with it. Even then, warming would still overshoot 1.5 °C for about 45 years, from around 2029 until it falls back below around 2074. It is far beyond any IPCC pathway, which tops out at about 5–15 Gt a year, so this scenario is best read as a hypothetical upper bound: what it would take, not what is likely. It makes economic sense only when avoided climate damage is counted, and it cannot be financed the way clean energy can, because no one's fuel bill falls.

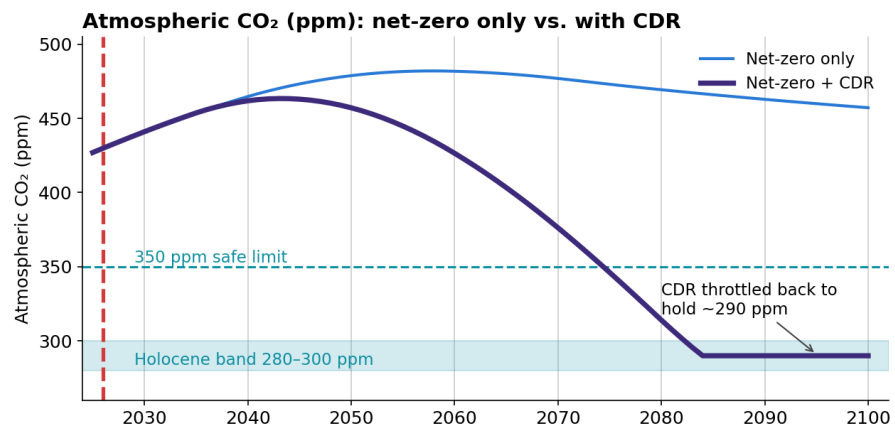
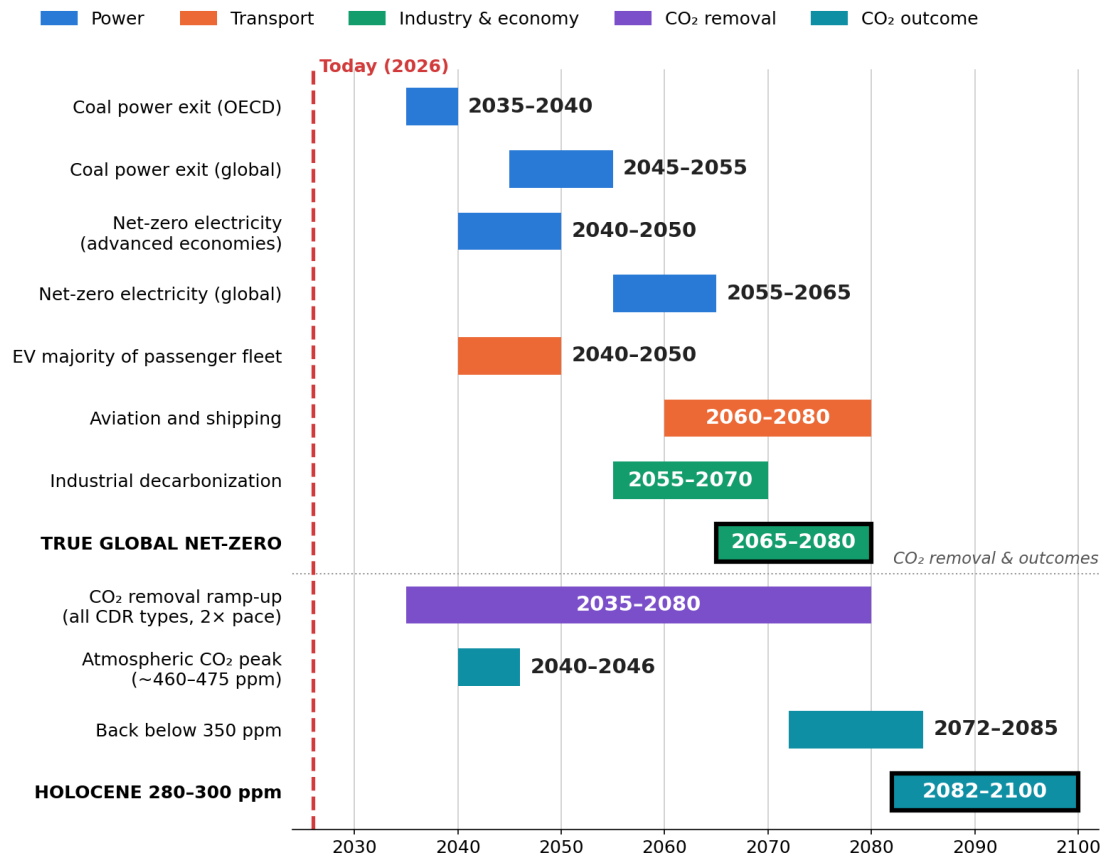
Sources

Global Carbon Project, Global Carbon Budget 2025. Scripps Institution of Oceanography and NOAA Global Monitoring Laboratory, Mauna Loa CO₂ record. Joos, F. et al., CO₂ impulse response functions, Atmos. Chem. Phys. (2013). Millar, R. et al., FaIR simple climate model, Atmos. Chem. Phys. (2017). IPCC AR6 Working Group I (2021), Chapter 5, carbon-cycle response to CO₂ removal. IPCC AR6 Working Group I (2021), effective radiative forcing and climate sensitivity. Forster, P. et al., Indicators of Global Climate Change, Earth Syst. Sci. Data. Held, I. et al. and Geoffroy, O. et al., two-layer energy-balance models, J. Climate (2010, 2013). IPCC AR6 Working Group III (2022), CDR pathways. US EPA, Report on the Social Cost of Greenhouse Gases (2023). International Monetary Fund, World Economic Outlook, October 2022, Chapter 3. NGFS Climate Scenarios Phase V (2024). IEA, World Energy Investment 2026. McKinsey Global Institute, The Net-Zero Transition (2022). Companion briefing: *The Road to Net Zero* (October 2026). All projections are illustrative models built from these sources, not forecasts.

Figure 1 · Timeline to net zero, and back to 350 ppm

Realistic Timeline to Net-Zero — and Back to 350 ppm

Expected range for each milestone, plus a CO₂ removal (CDR) program scaled at 2× the emissions-reduction pace



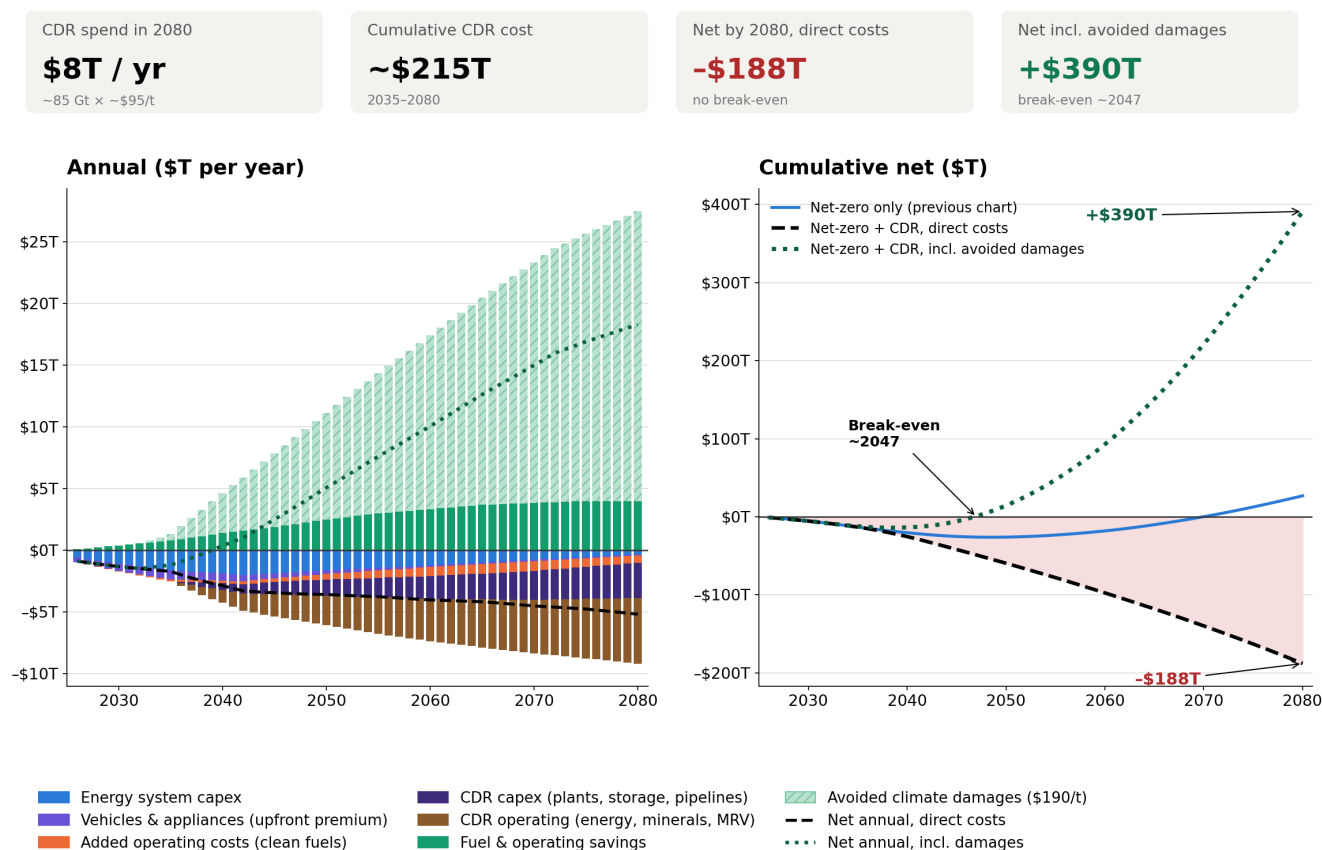
Scale check:

CDR reaches ~85 GtCO₂/yr by 2080 (≈2× today's total emissions) and ~2,000 Gt removed by 2080 (~2,700-3,100 Gt by 2100). Net-negative emissions from ~2049. Far beyond any IPCC pathway (max ~5-15 Gt/yr) — a hypothetical upper bound.

Figure 2 · Net-zero plus CO₂ removal: global cost vs. benefit

Net-Zero + CO₂ Removal: Global Cost vs. Benefit

Extra spending and savings vs. current policies, 2026–2080 (trillions of 2025 US\$) — CDR ramping at 2× the emissions-reduction pace

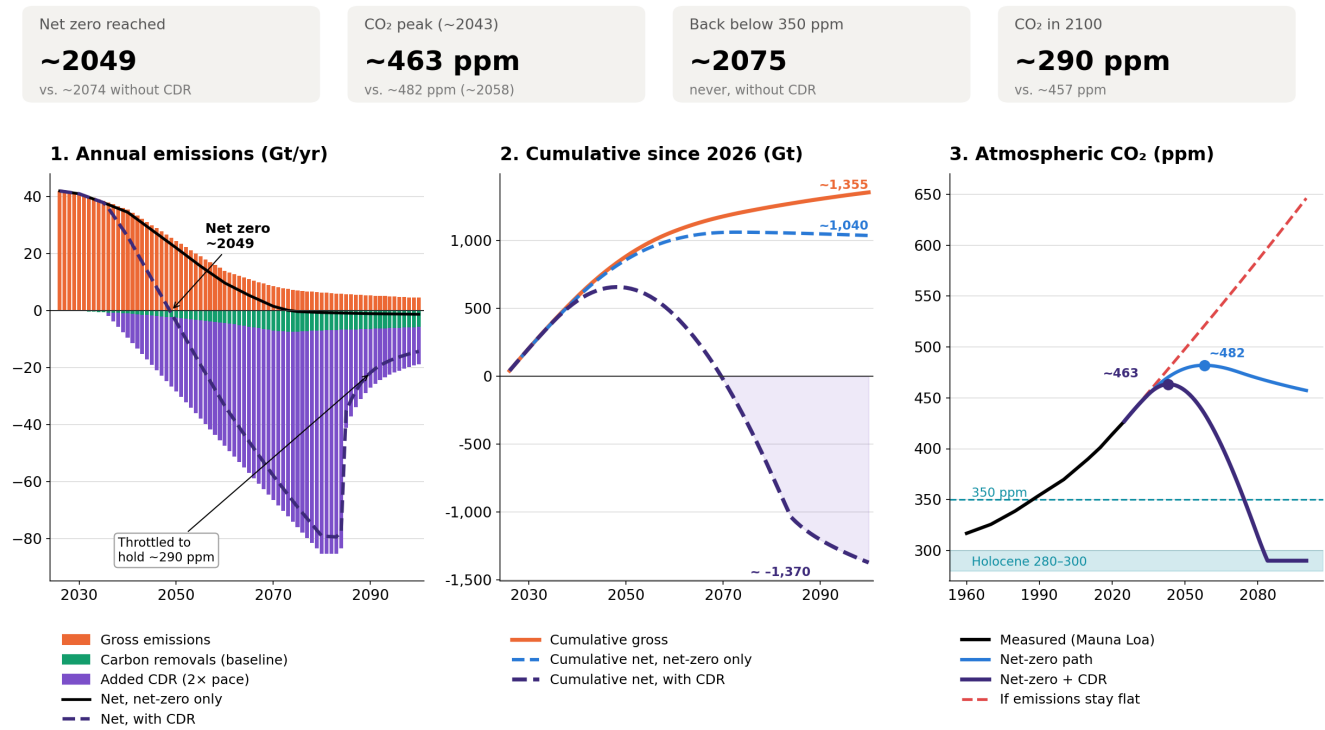


Illustrative model, roughly ±50% uncertainty. Net-zero layers carried over from the previous chart. CDR: 1.9 Gt/yr added each year from 2035 (~85 Gt/yr by 2080); blended cost \$200/t falling to ~\$95/t via learning, split 35% capex / 65% operating. Avoided damages use the US EPA (2023) social cost of carbon, \$190/t (literature range ~50–250+), applied to avoided emissions and removals. Benefits of drawdown continue well beyond 2080 and are not shown.

Figure 3 · CO₂ emissions, removal and the Keeling curve

CO₂ Emissions, Removal and the Keeling Curve: Two Paths

Realistic net-zero path (as before) vs. the same path plus CO₂ removal ramping at 2× the emissions-reduction pace from 2035

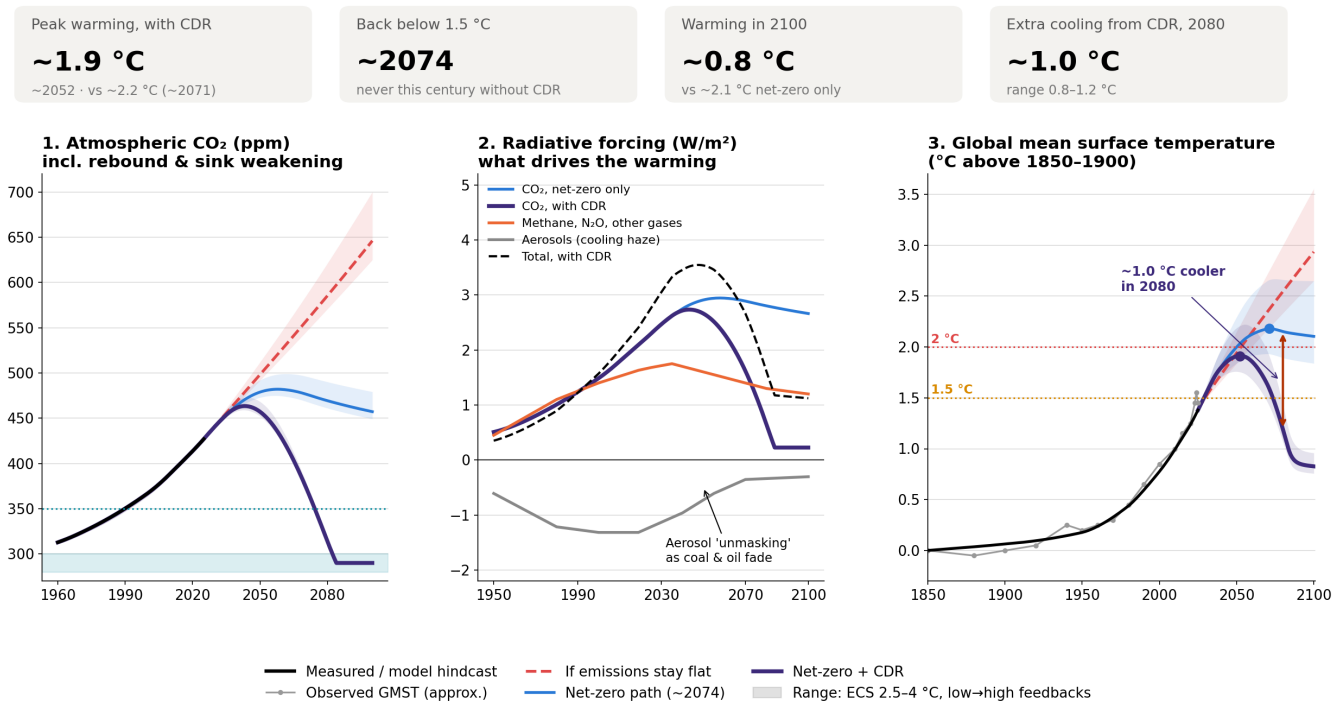


Sources: Global Carbon Budget 2025 (42.2 Gt CO₂ in 2025); Scripps/NOAA Mauna Loa record. Coupled carbon-cycle/climate model: Joos et al. (2013) multi-timescale response in FaIR form (Millar et al. 2017), calibrated to 2025, with ocean/land rebound as CO₂ falls and sinks weakening with warming and cumulative uptake. CDR: 1.9 Gt/yr added each year from 2035, capped ~85 Gt/yr, then scaled back to ~20–40 Gt/yr to hold ~290 ppm. Removal 15% less effective than modeled would delay 290 ppm to ~2099. Illustrative projection, not a forecast.

Figure 4 · Global mean surface temperature: CO₂ removal and feedbacks

Global Temperature: CO₂, Removal and Feedbacks

Warming above 1850–1900 for three paths: emissions flat, realistic net zero (~2074), and net zero + CO₂ removal at 2× pace

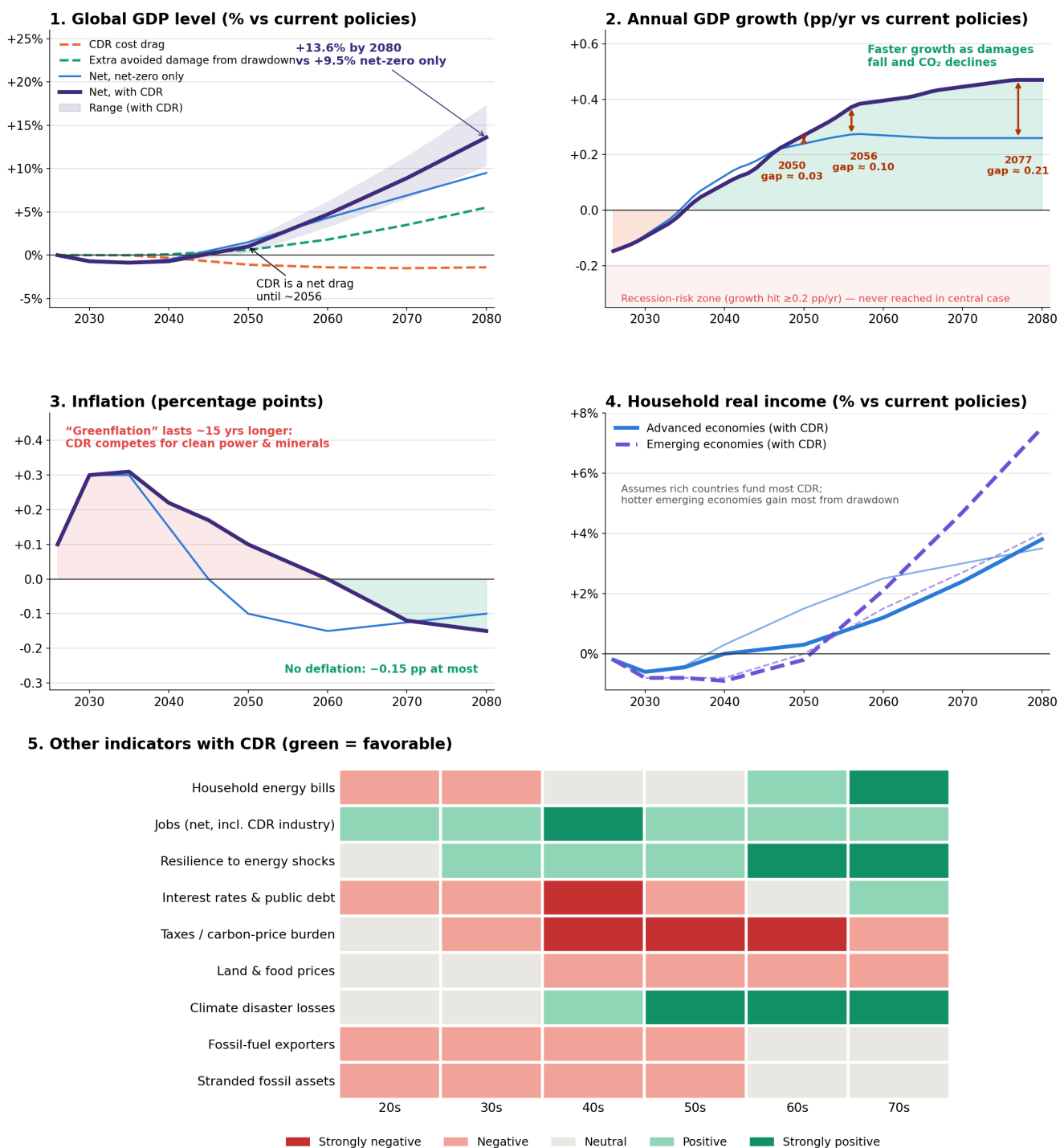


Coupled FaIR-style model: Joos et al. (2013) carbon cycle with rebound and temperature-dependent sinks (Millar et al. 2017) + two-layer ocean (deep-ocean heat capacity per Geoffroy et al. 2013). Climate sensitivity 3 °C (range 2.5–4 °C), calibrated to ~1.38 °C human-induced warming in 2025 (Forster et al.); forcing per IPCC AR6. Range: ECS 2.5 °C + weak sink feedback to ECS 4 °C + strong sink feedback. With CDR, removal is adjusted each year to hold ~290 ppm against rebound and feedbacks. Not modeled: ice-sheet collapse, abrupt permafrost thaw, AMOC shutdown. Illustrative projection, not a forecast.

Figure 5 · Economic effects of net zero plus CO₂ removal

Economic Effects: Net-Zero + CO₂ Removal

Difference from a current-policies world, 2026–2080 (illustrative). Thin lines = net-zero only (previous chart); bold = with 2× CDR



Anchored on IMF WEO Oct 2022 (Ch. 3), NGFS Phase V and the previous net-zero chart. CDR cost from the cost-benefit chart (~2% of GDP by 2060–2080, ~60% passed through to GDP); extra avoided damage assumes ~0.9 °C less warming by 2080 than net-zero only, with temperature lagging CO₂. Ranges roughly ±50%. Illustrative, not a forecast.