# Climate Solutions in Orders of Magnitude

A comprehensive overview of mitigation and removal technologies, their costs in euros per tonne of $CO_2$e, their scaling potential — and the professional leverage that accelerates them

*Research paper supporting the "Climate Positivity" lecture · compiled June 2026*

---

## 1. Executive summary

This paper surveys the landscape of climate solutions along two axes: **maturity** (research-stage ideas, startups and scale-ups, and solutions already working at scale) and **category** (engineered/technological, biological/agricultural, mineral, and geoengineering). For each solution it gives pros and cons, current and projected cost in euros per tonne of $CO_2$-equivalent (€/t$CO_2$e), and realistic scaling potential. It then examines the financial machinery that rewards emission cuts — from Rabobank's discounted agricultural loans to Frontier's advance purchase commitments — and the diverging policy directions of the EU, China and the United States. It closes with vetted order-of-magnitude numbers for the lecture's examples, which also live in the calculator's `examples.js` file.

Seven findings carry the paper:

1. **Cheap abatement is enormous and mostly boring.** The IPCC finds that options costing **under €92/t (US$100/t) could halve global emissions by 2030**, and that *more than half of that potential costs less than ~€18/t (US$20/t)* — dominated by solar, wind, efficiency, stopping ecosystem destruction, and plugging methane leaks [1]. The cheapest gigatonnes are not exotic.
2. **The technology we already have does most of the work.** In the IEA's Net Zero Scenario, technologies on the market today deliver **more than 80% of the emission cuts needed by 2030**; the share of 2050 reductions expected from not-yet-commercial technology has *fallen* from ~50% to ~35% between 2021 and 2023 as innovation matured [2][3].
3. **Carbon removal is real but five to six orders of magnitude too small.** Engineered removal today runs at roughly tens of kilotonnes per year; delayed action would require ~**5 Gt per year** later this century, at a projected cost around **US$1.3 trillion per year** [2][3]. A kilotonne industry must become a gigatonne industry.
4. **The cost curve is the argument for optimism.** Solar fell **85%**, wind **55%**, batteries **85%** in 2010–2019, while deployment grew >10× (solar) and >100× (EVs) [1]. First-of-a-kind removal at €460–1,750/t (DAC today) is where solar once was; the IEA projects ~€280/t by mid-century, with next-generation designs targeting ~€92/t [4].
5. **Carbon prices and removal costs still live in different worlds.** The EU ETS trades at **€60–80/t**, China's ETS near **€10/t**, the voluntary market averages **€4–6/t** — while engineered removal sells at **€385–470/t** in Frontier offtakes [5][6][7][8]. Finance that bridges this gap (offtakes, rebates, transition funds) is where professionals have leverage.
6. **Money is a mitigation technology.** Green bonds and loans are heading to ~**US$955 bn of issuance in 2026**; sustainability-linked loans to ~**US$160 bn**; Rabobank alone runs a **€3 bn** discounted-loan transition fund for farmers, €1 bn already deployed [9][10]. These structures move kilotonnes-to-megatonnes per institution — exactly the professional-leverage scale of the lecture.
7. **Policy is diverging, not converging.** The EU enters the CBAM compliance phase and launches ETS2 in 2027 [11]; China expanded its ETS to steel, cement and aluminium (+3 Gt $CO_2$e covered, ~8 Gt total) and added ~315 GW of solar in 2025 alone [12][13]; the United States, through the July 2025 "One Big Beautiful Bill", terminated or compressed most IRA clean-energy credits [14]. The direction of travel is set by economics; the speed is set by politics — and by professionals.

**Everything here is order-of-magnitude.** Currency conversions use ≈ €0.92 per US dollar (2024–25 average). Where a number is an informed estimate rather than a verified source figure, it is marked *(estimate)*.

---

## 2. How to read this landscape

### 2.1 Two different products: avoided tonnes and removed tonnes

- **Avoidance/abatement**: not emitting in the first place (a solar park displacing coal, a heat pump displacing gas). The cheapest tonnes are here, many at negative net cost.
- **Removal (CDR)**: taking $CO_2$ back out of the air (forests, weathered minerals, direct air capture). Always costs energy and money; the IPCC nonetheless calls CDR "unavoidable" for reaching net zero, to neutralise residual emissions [1].

A euro spent on avoidance at €10/t does ten times the work of the same euro spent on removal at €100/t. This asymmetry is the quantitative heart of the lecture: *the speed of adoption of cheap abatement is worth more than almost anything else*, and adoption speed is exactly what professional interventions – procurement, finance, law, knowledge-transfer – accelerate.

### 2.2 The grid of this paper

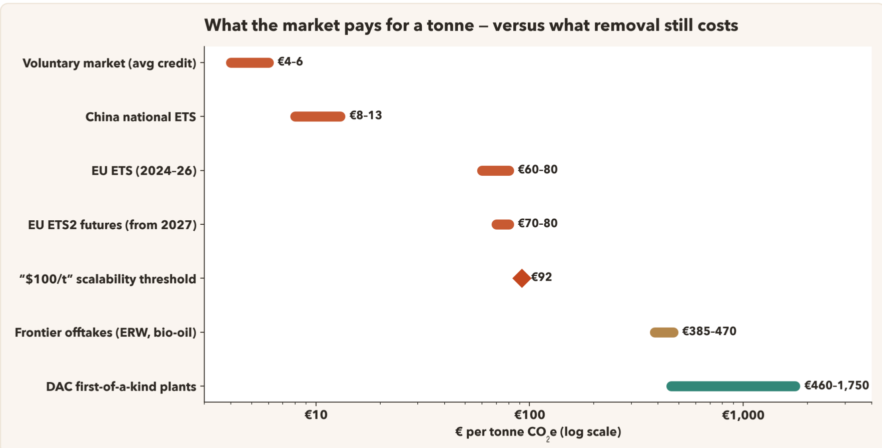
| | Engineered | Biological / agricultural | Mineral | Geoengineering |
|---|---|---|---|---|
| **At scale now** | solar+storage, wind, EVs, heat pumps, efficiency, methane repair, nuclear | forest conservation & restoration, soil carbon (early) | – | – |
| **Startups / scale-ups** | enhanced geothermal, low-carbon cement, DAC, bio-oil injection, green steel | feed additives entering market | olivine spreading, enhanced rock weathering | – |
| **Research stage** | passive/next-gen DAC | Asparagopsis seaweed feed, soil-carbon MRV | ocean alkalinity enhancement | SRM, marine cloud brightening (research only) |

### 2.3 The orders-of-magnitude ladder

All quantities in this paper and in the calculator live on one ladder: **1 kg → 1 tonne ($10^3$ kg) → 1 kilotonne ($10^6$ kg) → 1 megatonne ($10^9$ kg) → 1 gigatonne ($10^{12}$ kg)**. World emissions are ≈ 57 Gt $CO_2$e per year *(estimate, consistent with UNEP Gap Report figures)*. A professional's plausible reach is kilotonnes to megatonnes; an individual's is kilograms to tonnes. That gap – three to six orders of magnitude – is robust to any reasonable error in the underlying numbers.

---

## 3. What a tonne costs: the carbon-price context



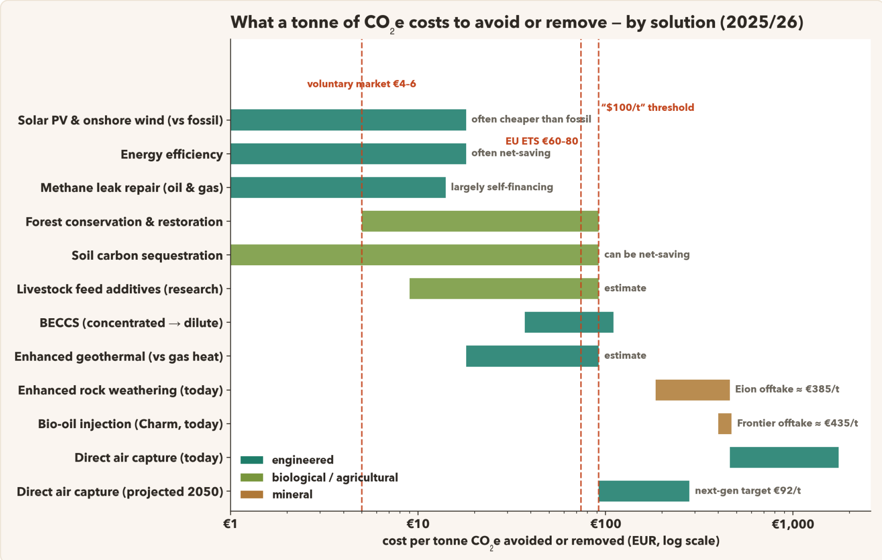

- **EU ETS**: allowances traded **€60-80/t** through 2024–2026, with Enerdata projecting ~€70–75/t in 2030; a directive revision is scheduled for 2026 [5].
- **EU ETS2** (buildings and road transport, from 2027): futures began trading on ICE in May 2025 at ~**€75/t**, projected to nearly double by 2040 [5].

- **China national ETS**: roughly **€8–13/t** *(estimate from reported CNY 70–100 allowance prices)* – low, but now covering ~8 Gt $CO_2e$ after the 2025 expansion [12].
- **Voluntary carbon market**: average asking price ~**€4–6/t** in 2024, with offers from €0.25 to €25 [6] – a market whose price collapse reflects a quality and trust crisis (additionality, permanence, phantom credits) more than a cost breakthrough.
- **The "$100/t" (≈ €92/t) threshold**: the de-facto bar for "scalable removal", used by Frontier and the IEA alike [4][7]. Below it, removal could plausibly absorb trillions of compliance euros; above it, removal stays a boutique product.
- **The IPCC's benchmark**: options ≤ US$100/t could halve global emissions by 2030; more than half of that potential sits below US$20/t [1].

**The lecture-ready fact:** a tonne is *bought* today for €5–80 depending on the market, while engineered removal *costs* €385–1,750. Every mechanism in §9 is an attempt to bridge that gap – and professionals operate those mechanisms.

---

## 4. Tier 1 – At scale now (the gigatonne machines)




### 4.1 Solar PV (+ storage) – engineered

- **Scale today / potential**: the single largest 2030 lever. Tripling global renewables to 11,000 GW by 2030 provides the largest emission reductions in the IEA NZE – solar PV's 2030 economic potential is ~2–7 Gt $CO_2e$/yr (IPCC SPM.7) [1][2]. China alone added ~315 GW in 2025 [13].
- **Cost**: module and system costs fell 85% in a decade [1]; new solar now routinely beats fossil generation, making abatement cost ≤ €0–20/t and often *negative*.
- **Pros**: cheapest electricity in history in good locations; modular; fast to build; pairs increasingly well with batteries (also −85% cost).
- **Cons**: intermittency (needs storage/grids); land use; supply-chain concentration in China; grid-connection queues are now the bottleneck in much of Europe.

### 4.2 Wind – engineered

- **Potential**: ~2–4 Gt $CO_2e$/yr by 2030 (IPCC SPM.7 range) [1]; costs fell 55% in 2010–2019 [1].
- **Pros**: complements solar seasonally; offshore opens huge resources near demand centres.
- **Cons**: permitting and public acceptance; recent offshore cost inflation; minerals and logistics.

### 4.3 EVs and heat pumps – engineered

- **Potential**: together nearly **one-fifth of the emission reductions to 2030** in the IEA NZE [2]. EV deployment grew >100× in 2010–2019 [1].
- **Pros**: better products (running cost, comfort); electrify the two biggest fossil end-uses (driving, heating); efficiency gains of 3–4× over combustion.

- **Cons**: upfront cost; grid and charging infrastructure; battery minerals; heat-pump retrofits in old building stock are craft-labour-limited.

### 4.4 Energy efficiency – engineered

- The permanently underrated gigatonne: large IPCC potential below US$20/t, much of it at *negative* net cost [1]. Cons: fragmented across millions of decisions – which is precisely why procurement officers and facility managers have leverage.

### 4.5 Methane leak repair – engineered, the low-hanging fruit

- **Potential**: cutting energy-sector methane 75% by 2030 ≈ 1–2 Gt $CO_2$e/yr *(derived)*; the IEA prices the oil-and-gas portion at ~**US$75 bn cumulative to 2030 – about 2% of the industry's 2022 net income** – much of it offset by selling the captured gas [3].
- **The Turkmenistan case** (used in the lecture): satellite analysis by Kayrros for *The Guardian* found two Turkmen fossil-fuel fields leaked methane equivalent to **366 Mt $CO_2$e in 2022 – more than the UK's entire annual emissions** [8].
- **Pros**: cheapest large-scale mitigation that exists; immediate climate effect (methane's 20-year potency ~80× $CO_2$); now *visible* thanks to satellites (Kayrros, MethaneSAT).
- **Cons**: requires action inside petrostates with weak incentives; "self-financing" fixes are still not happening without external pressure – visibility, procurement conditions, and journalism are the actual levers.

### 4.6 Forests and land use (AFOLU) – biological

- **Potential**: **8–14 Gt $CO_2$e/yr** below US$100/t between 2020 and 2050; 30–50% of it below US$20/t; the largest share (4.2–7.4 Gt/yr) from conserving, managing and restoring forests [1].
- **Pros**: available now; co-benefits (biodiversity, water); cheapest at the "stop destroying" end.
- **Cons**: permanence (fire, drought, politics); measurement and offset-quality scandals; land competition with food; saturation. The voluntary market's €4–6/t average price is partly a verdict on poor forest-credit quality [6].

### 4.7 Nuclear – engineered

- **Status**: ~9% of world electricity *(estimate)*; at-scale and low-carbon. Pros: firm power, small land footprint. Cons: in the West, high and uncertain capital cost and decade-plus lead times put its *marginal* abatement cost well above renewables (IPCC SPM.7 shows higher cost than wind/solar [1]); China and Korea build far cheaper. Lifetime extensions of existing plants are among the cheapest low-carbon electricity anywhere *(estimate)*.

---

## 5. Tier 2 – Startups and scale-ups (the megatonne candidates)

### 5.1 Enhanced geothermal – engineered (Fervo, Eavor)

- **What**: oil-and-gas drilling techniques (horizontal drilling, fibre-optic sensing) applied to heat. Fervo's Cape Station (Utah) is contracted toward ~500 MW *(reported; estimate)*; Eavor's closed-loop systems are under construction in Germany.
- **Cost/potential**: abatement cost roughly €20–90/t versus gas heat *(estimate)*; potential ~0.1–0.5 Gt/yr by mid-century if drilling costs keep falling.
- **Pros**: firm, dispatchable; tiny land footprint; *directly inherits the fossil workforce's skills* – the lecture's corrosion-specialist example is literally this transfer.
- **Cons**: drilling cost and geological risk; induced seismicity concerns; corrosion and materials know-how is exactly what young companies lack (hence the leverage of sharing it).

### 5.2 Low-carbon cement – engineered (Sublime Systems)

- **What**: cement ≈ 7–8% of global $CO_2$ *(estimate)*. Sublime's electrochemical process makes cement without fossil fuel or limestone calcination; first commercial plant (Holyoke, MA) opens 2026 at ~30,000 t/yr, backed by an $87 M DOE award and $75 M from CRH and Holcim [15].
- **The procurement story**: Microsoft signed a binding offtake for up to **622,500 t of Sublime cement over 6–9 years**, with the environmental attributes claimable separately from the physical cement [16] – a template for how *any* large buyer's procurement department can finance first plants.

- **Cost**: green premium today; falling with scale *(estimate: €50–150/t $CO_2e$ avoided as premium)*. Potential: 0.1–1 Gt/yr by 2050 if novel chemistries take a noticeable share of a ~4 Gt/yr cement market.
- **Cons**: cement is brutally cost-competitive and locally traded; certification and building codes are slow; needs cheap clean electricity.

#### 5.3 Direct air capture – engineered (Climeworks and peers)

- **Today**: first-of-a-kind plants cost **US$500–1,900/t (≈ €460–1,750/t)** [4]; all plants worldwide capture on the order of 0.01–0.04 Mt/yr (Climeworks' Mammoth nameplate ~36 kt/yr *(estimate)*) – versus **80 Mt/yr needed by 2030 and ~1 Gt/yr by 2050** in the IEA NZE [3].
- **Trajectory**: IEA projects ~US$300/t by mid-century; next-generation/passive designs target ~US$100/t [4].
- **Pros**: permanent, measurable, land-light; the gold standard for offset quality.
- **Cons**: energy-hungry; today 5–20× over the scalability threshold; risks becoming an excuse for delayed abatement ("moral hazard").

#### 5.4 Bio-oil injection – mineral/engineered (Charm Industrial)

- **Deal that defines the price**: Frontier's first offtake paid Charm **US$53 M for 112,000 t (2024–2030), ≈ US$473/t average, with the contracted price declining ≥37% (possibly 75%) by 2030** [7].
- **Pros**: uses agricultural residues; injects carbon as bio-oil into regulated wells – fast permanence.
- **Cons**: biomass supply limits; logistics; measurement of upstream emissions.

#### 5.5 Olivine and enhanced rock weathering – mineral (Eion, Vesta, Lithos)

- **The idea the lecture cites ("olivine")**: spread crushed silicate rock on farmland or coasts; natural weathering binds $CO_2$ in decades instead of millennia.
- **Reality check (Project Drawdown)**: classified **"Keep Watching"** – promising, not yet deployment-ready; current cost **>US$200–500/t**; total removals reported to date ~**10,000 t** (early 2025); potential **>0.1 Gt/yr** globally, with a US-agriculture estimate of 0.16–0.30 Gt/yr by 2050 [17].
- **The market signal**: Frontier buyers pay **Eion US$33 M for 78,707 t (≈ US$419/t)** of olivine-based removal delivered 2027–2030 [18].
- **Pros**: co-benefits for soil pH and crop yield; piggybacks on existing agricultural logistics; truly vast theoretical mineral supply.
- **Cons**: slow, diffuse, hard-to-measure removal (MRV is the core risk); mining and grinding energy; heavy-metal content of some rocks.

#### 5.6 Green steel – engineered (Stegra, others) *(brief)*

Hydrogen direct-reduction steel (Stegra's Boden plant, Sweden) targets conventional-steel parity with ~95% lower emissions *(estimate)*; steel ≈ 7–9% of global $CO_2$. Premium "green steel" offtakes from carmakers mirror the Microsoft-Sublime structure.

---

## 6. Tier 3 – Research stage (the options being earned)

#### 6.1 Livestock feed additives – biological (Asparagopsis, Bovaer)

- **What**: enteric (cow-burp) methane is on the order of 2 Gt $CO_2e$/yr globally *(estimate)*. The synthetic additive 3-NOP ("Bovaer") cuts enteric methane ~30% and is now approved in major markets *(estimate)*; red seaweed *Asparagopsis* has shown 80%+ reductions in controlled trials, with high variability in real-world feeding *(estimate)*.
- **Cost/potential**: ~€10–90/t $CO_2e$ *(estimate)*; realistic potential ~0.1–0.5 Gt/yr – meaningful, not decisive.
- **Pros**: works inside the existing dairy/beef system; pairs naturally with the banker's discounted-loan lever (§9).
- **Cons**: must be fed daily (pasture systems are hard); consumer acceptance; seaweed supply chains barely exist; effect sizes still being established at scale.

### 6.2 Ocean alkalinity enhancement – mineral/geo

The ocean variant of weathering: add alkaline minerals to seawater, increasing $CO_2$ uptake. IPCC ranks ocean alkalinisation among the *lowest-maturity* CDR options [1]. Theoretical potential is gigatonnes; verification in a moving ocean and ecological side-effects are unsolved. Cost today effectively unbounded; targets of €92–275/t are aspirational *(estimate)*.

### 6.3 Next-generation / passive DAC – engineered

The IEA singles out emerging "passive" DAC concepts that could fall **below US$100/t**, against ~US$1,000/t for today's developed technologies [3][4]. This is where the $100 threshold could actually be crossed – at research stage today.

### 6.4 Soil carbon at scale – biological

IPCC costs **US$–45 to 100/t** (often profitable for the farmer) [1], potential of 1–3 Gt/yr *(estimate within IPCC AFOLU envelope)* – but measurement, additionality and permanence make it research-grade *as a market product* even though the agronomy is old.

---

## 7. Geoengineering – a different kind of proposal

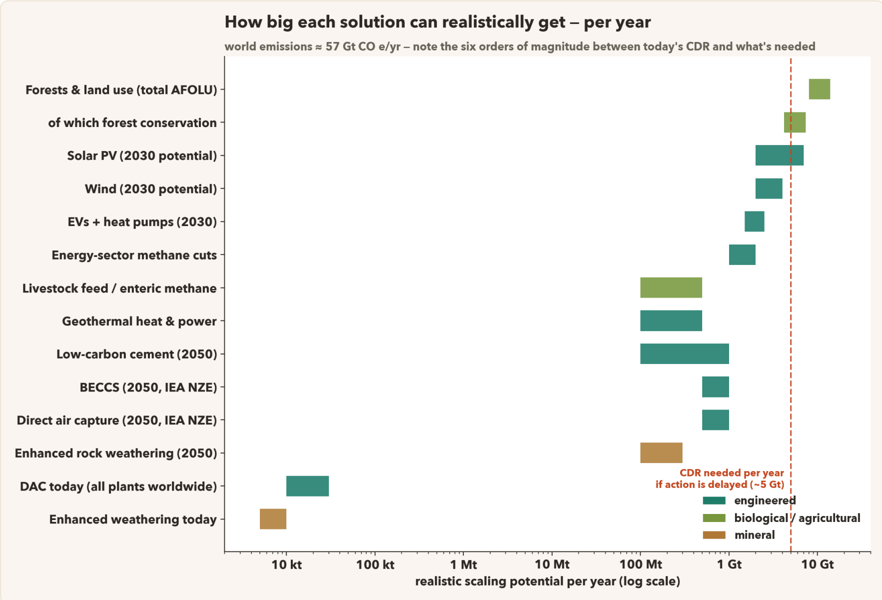
Solar radiation management (stratospheric aerosols, marine cloud brightening) is **not** a mitigation or removal technology: it offsets warming without touching $CO_2$, ocean acidification, or the accumulation problem.

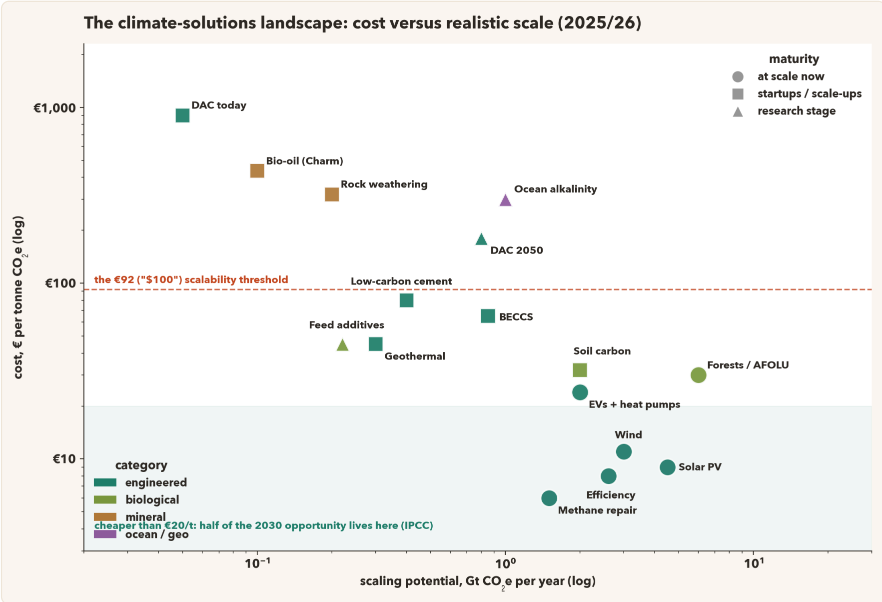
- **Pros**: the only known lever that acts in years, not decades; direct costs estimated at only US$1–10 bn per year for measurable cooling *(estimate – deployment cost, not €/t; no tonne is removed)*.
- **Cons**: termination shock (stop, and decades of masked warming arrive in years); regionally uneven side-effects (monsoons); no governance regime; moral hazard at planetary scale.
- **Status**: research and small experiments only; the legitimate near-term work is monitoring, modelling, and governance design.

For the lecture, geoengineering is best presented as the emergency brake whose existence must never become a reason to keep accelerating.

---

## 8. The comparative picture






Three readings of these charts:

1. **The lower-right quadrant wins the decade.** Solar, wind, efficiency, methane repair, forests: gigatonne-scale and under €20–30/t. Nothing in the upper-left (expensive, small) competes with accelerating the lower-right – it can only complement it.
2. **The mineral and engineered-removal cluster must travel left-to-right and down.** ERW and DAC sit at €200–1,750/t and kilotonne scale. Their entire credibility rests on the solar precedent: −85% in a decade under deployment pressure [1]. The Frontier price-decline contracts (−37…75% by 2030 [7]) are that precedent being engineered deliberately.
3. **Six orders of magnitude.** Today's engineered removal (~tens of kt/yr) versus the ~5 Gt/yr needed under delayed action [2][3]: a $10^5$–$10^6$ gap. This is the same kind of gap the calculator shows between an individual and a professional – and it is bridged the same way: not by scaling one actor's virtue, but by changing the systems that thousands of actors operate in.

---

## 9. Money as a mitigation technology: the financial mechanisms

The lecture's banker example generalises. Finance rewards emission cuts through margins, covenants and purchase commitments – and each instrument has a maturity tier of its own.

### 9.1 At scale now

| Instrument | 2025/26 size | Mechanism | Pitfalls |
|---|---|---|---|
| Green bonds | → **US$700 bn** issuance 2026 [9] | proceeds ring-fenced for green projects | "use of proceeds" ≠ corporate change |
| Green loans | → **US$255 bn** 2026 [9] | same, bilateral | ditto |
| Sustainability-linked loans (SLLs) | **US$139 bn** 2025 → ~**$160 bn** 2026 [9] | interest margin steps down if emission KPIs are met | weak/gameable KPIs |
| Sustainability-linked bonds (SLBs) | subdued ~**US$25 bn** 2026 [9] | coupon penalty if targets missed | credibility crisis – the market's verdict on soft targets |
| EU ETS / carbon markets | €60–80/t × ~1.4 Gt cap *(estimate)* [5] | price on every covered tonne | leakage (hence CBAM) |

Notable trend: the *green share* of corporate sustainable issuance rose from 34% (2022) to 68% (2025) [9] – money is migrating from promise-linked to project-linked instruments. The honest reading: **markets are punishing vague KPIs and rewarding verifiable physical change.** For a professional designing such an instrument, the lesson is to tie the rebate to measured tonnes.

### 9.2 Scale-ups – where the lecture's examples live

- **Rabobank's transition financing (the banker example, verified)**: a dedicated **€3 bn fund** (announced end-2023) offering **interest-rate discounts and more favourable terms** to Dutch farmers with credible transition plans; **€1 bn financed within two years**. Its *Planet Impact Loan* pilot ties dairy farmers' interest discounts to Biodiversity Monitor scores [10]. Order-of-magnitude: a €1 bn portfolio across a few thousand livestock farms, achieving 10–20% emission cuts (feed, fertiliser, energy), moves ~**0.1 Mt $CO_2$e/yr** *(derivation in §10)*.
- **Advance market commitments (Frontier)**: ~US$1 bn+ of pooled buyer commitments *(estimate)*; the Charm (US$53 M / 112 kt) and Eion (US$33 M / 78.7 kt) offtakes [7][18] show the structure: pay today's high price, contract tomorrow's lower one, give the startup bankable revenue.
- **Corporate offtakes as finance (Microsoft–Sublime)**: up to 622,500 t of cement over 6–9 years, with environmental attribute certificates separable from physical delivery [16] – procurement acting as project finance.
- **Green mortgages**: rate discounts for efficient homes; growing but supervisory treatment (capital-requirement relief) still pending *(estimate)*.

### 9.3 Research-level financial ideas

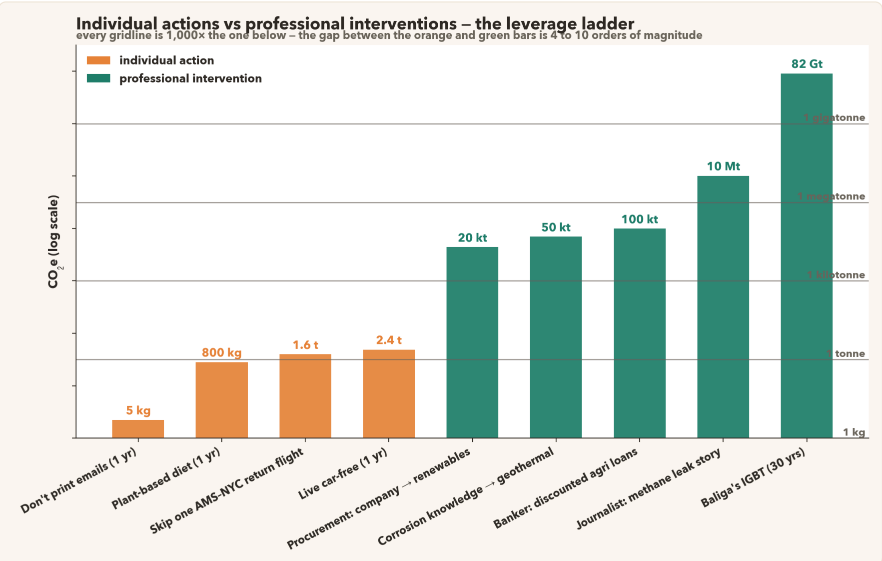
- Loan margins tied to *measured* farm methane (satellite + sensor MRV) rather than practice checklists.
- Methane-conditioned gas procurement: import contracts priced against verified upstream leakage (the Turkmenistan lever, contractualised).
- Transition-linked insurance pricing; internal carbon prices with teeth (budget transfers, not shadow numbers).

### 9.4 Successes and pitfalls, honestly

Successes: real scale (hundreds of billions), real rate incentives, real first plants financed by offtakes. Pitfalls: KPI gaming and greenwashing (SLB stagnation is the market self-correcting [9]); voluntary-market quality collapse (€4–6/t average ask [6]); additionality doubts – would the farmer have invested anyway? The design rule that survives all three: **pay for verified tonnes, not for promises.**

---

## 10. The lecture examples, vetted




These are the numbers now in the calculator (`examples.js`), with their derivations. Every entry is an order-of-magnitude estimate; the conclusion survives ±10×.

### Individual actions (kilograms to tonnes)

| Action | $CO_2e$ | Basis |
|---|---|---|
| Don't print your emails for a year | **~5 kg** | ~5 g $CO_2e$ per A4 sheet (paper production + printing, LCA-based *(estimate)*) × ~1,000 sheets |
| One fewer return flight AMS–NYC | **~1.6 t** | Wynes & Nicholas 2017: 1.6 $tCO_2e$ per round-trip transatlantic flight [19] |
| Live car-free for a year | **~2.4 t** | Wynes & Nicholas 2017 [19] |
| Household to green electricity | **~1 t** | W&N range 0.1–2.5 t depending on grid; NL: ~2,800 kWh × ~0.3 kg/kWh [19] |
| Plant-based diet for a year | **~0.8 t** | Wynes & Nicholas 2017 [19] |

### Professional interventions (kilotonnes to gigatonnes)

| Intervention | $CO_2e$ | Derivation |
|---|---|---|
| **Corrosion specialist** shares pipe know-how with geothermal startups | **~50 kt** | One geothermal district-heating doublet supplies ~4,000–6,000 households, displacing ~5–15 kt $CO_2e$/yr of gas heat *(estimate from NL geothermal sector data)*. Knowledge that keeps a handful of projects from corrosion failure – or from the bankruptcy that discredits the sector – preserves tens of kt/yr. |
| **Banker** offers discounted agri loans | **~100 kt** | Scaled from Rabobank: €1 bn deployed across ~2,000–4,000 farms *(estimate)*; Dutch dairy farm ≈ 1–2 kt $CO_2e$/yr; financed measures cutting 10–20% ⇒ ~0.05–0.15 Mt/yr [10]. |
| **Procurement officer** shifts company to renewable electricity | **~20 kt/yr** | Mid-size industrial firm ~50 GWh/yr × ~0.4 kg $CO_2e$/kWh grid displacement *(estimate)*. |
| **Lawyer** steers a settlement toward a lower-emission process | **~50 kt** | One settlement compelling process change at a single large industrial plant (which typically emits 0.1–1 Mt/yr) ⇒ tens of kt/yr *(reasoned estimate)*. |
| **Journalist** breaks the methane-leak story | **~10 Mt** | Turkmenistan's two fields: 366 Mt $CO_2e$ in 2022, more than the UK [8]. Reporting that contributes to even ~3% of fixes ⇒ ~10 Mt/yr. |
| **Baliga's IGBT** (the ceiling) | **~82 Gt / 30 yrs** | Millennium Technology Prize 2025 announcement: the insulated-gate bipolar transistor improved power-switching efficiency >40%, credited with >82 Gt $CO_2e$ avoided over 30 years – ≈ 3 years of all human emissions [20]. A claim with many ifs – which is the point: even off by 10×, it dwarfs everything else on the ladder. |

**The punchline in numbers**: email-printing (5 kg) → procurement (20 kt) is a factor of ~4,000,000 – six to seven orders of magnitude. Even flight-skipping (1.6 t) → banker (100 kt) is ~60,000×. The lecture's claim of "1,000–10,000×" is, if anything, conservative.

---

## 11. Policy: three blocs, three directions

### 11.1 European Union – pricing everything, slowly

- **EU ETS**: €60–80/t through 2024–26; 2026 directive revision pending [5].
- **ETS2** (buildings + road transport) starts 2027; futures already at ~€75/t – a *household-level* carbon price arriving into a politically sensitive moment [5].
- **CBAM**: entered its compliance phase (2026), extending the carbon price to imported steel, cement, aluminium, fertiliser [11] – the answer to leakage and the reason EU industry decarbonisation stays investable.
- Green Deal politics have turned rougher (2040-target negotiations, simplification packages), but the architecture – price + border + standards – is locked in *(assessment)*.

### 11.2 China – scale first, price later

- **ETS expansion (March 2025)**: cement, steel and aluminium added – ~1,500 more companies, **+3 Gt $CO_2e$ covered, ~8 Gt total (~60% of national emissions; the largest carbon market on**

**Earth by volume)**; first compliance deadline end-2025 [12]. Prices remain low (~€10) and allocation intensity-based – discipline is meant to tighten from 2027.
- **Renewables buildout**: ~**315 GW of solar added in 2025 alone** [13] – roughly an entire EU solar fleet, in one year *(comparison estimate)*. China is simultaneously the largest emitter and the largest deployer of every at-scale solution in §4.

### 11.3 United States – federal reverse gear

The July 2025 **"One Big Beautiful Bill"** [14]: - Solar/wind tax credits: only projects beginning construction before **July 5, 2026** (or in service by end-2027) qualify – years earlier than the IRA timeline. - EV credits (30D, 45W, 30C) and residential clean-energy credit (25D): terminated between **September 2025 and June 2026**. - Clean-hydrogen PTC ends for construction after 2027; SAF credit cut. - Preserved: storage, geothermal, hydro and nuclear largely keep credits, phasing down after 2033 – a notable carve-out that quietly keeps the Fervo-style build-out alive.

**Reading for the lecture**: US *technologies* (Sublime, Charm, Fervo, Frontier's buyers) keep appearing in this paper while US *federal policy* retreats – evidence that corporate procurement, state policy and private finance can carry momentum, and that none of these channels runs through a ballot box. They run through jobs.

---

## 12. What this means for Climate Positivity

1. **The professional tier is where the gap closes.** The cheap gigatonnes (§4) are adoption-limited, not invention-limited; adoption is decided in procurement departments, credit committees, settlement negotiations and standards bodies.
2. **Every financial instrument in §9 is someone's job.** "The banker" is not a metaphor: €3 bn of discounted transition loans exist because product managers at one Dutch bank designed them [10].
3. **Knowledge transfer is a megatonne instrument with zero capital cost.** The corrosion example generalises: incumbents hold exactly the engineering experience (wells, pipes, grids, chemistry) the scale-ups in §5 are short of.
4. **Visibility creates markets.** Satellites + journalism turned Turkmenistan's invisible 366 Mt into a negotiable object [8]. Procurement clauses can now reference measured leakage.
5. **The ceiling is real.** One engineer's switch design is credited with 82 Gt [20]. Nobody in the audience needs to match it; they need only notice that the *axis it lives on* is open to professionals and closed to consumers.

---

## 13. Method and caveats

- **Sources**: claims marked [n] were verified against primary documents (IPCC AR6 WG3 SPM, IEA Net Zero Roadmap 2023, IEA CDR commentary, Frontier offtake announcements, Project Drawdown, ICAP, Enerdata, ING Research, Rabobank, EurekAlert/NC State, Kayrros-Guardian reporting via Grist, Latham & Watkins analyses) in June 2026, with multi-vote adversarial checking for the core quantitative claims. Items marked *(estimate)* are the author's/compiler's order-of-magnitude estimates from general sector knowledge and should be treated as ±0.5–1 order of magnitude.
- **Currency**: €0.92 per US$ throughout; source figures kept in their original currency where quoted.
- **What costs mean**: €/t figures mix *marginal abatement costs* (IPCC), *technology costs* (IEA), and *contract prices* (Frontier) – comparable only at order-of-magnitude level, which is the resolution of this whole exercise.
- **The honest core caveat** (also printed on the calculator): being wrong by 10× on any single number does not change a conclusion that rests on gaps of $10^3$–$10^{10}$.

---

## 14. References


1. IPCC AR6 WG3 Summary for Policymakers (2022), incl. Figure SPM.7 – https://www.ipcc.ch/report/ar6/wg3/downloads/report/IPCC_AR6_WGIII_SPM.pdf ·

https://www.ipcc.ch/report/ar6/wg3/figures/summary-for-policymakers/figure-spm-7/

2. IEA, *Net Zero Roadmap: A Global Pathway to Keep the 1.5 °C Goal in Reach* (2023 Update), Executive Summary — https://www.iea.org/reports/net-zero-roadmap-a-global-pathway-to-keep-the-15-c-goal-in-reach/executive-summary
3. IEA, *Net Zero Roadmap* (2023 Update), full report — https://iea.blob.core.windows.net/assets/9a698da4-4002-4e53-8ef3-631d8971bf84/NetZeroRoadmap_AGlobalPathwaytoKeepthe1.5CGoalinReach-2023Update.pdf
4. IEA, *Driving down the cost of carbon removal* (commentary) — https://www.iea.org/commentaries/driving-down-the-cost-of-carbon-removal-why-innovation-matters
5. Enerdata, *Carbon price projections for the EU ETS* — https://www.enerdata.net/publications/executive-briefing/carbon-price-projections-eu-ets.html
6. CarbonCredits.com, *Live carbon prices* — https://carboncredits.com/carbon-prices-today/
7. Frontier, *Frontier facilitates first offtake: Charm Industrial* — https://frontierclimate.com/writing/first-offtake
8. Grist, *Turkmenistan's "mind-boggling" methane emissions revealed by satellite data* (Kayrros analysis for The Guardian) — https://grist.org/energy/turkmenistans-mind-boggling-methane-emissions-revealed-by-satellite-data/
9. ING Research, *Sustainable debt outlook 2026* — https://think.ing.com/articles/sustainable-debt-outlook-2026-higher-issuance-with-changing-compositions/
10. Rabobank — food-system transition financing & Planet Impact Loan: https://www.rabobank.com/knowledge/d011297552-how-to-unlock-the-green-potential-of-the-agricultural-sector · https://www.rabobank.nl/en/about-us/impact/article/011513506/rabobank-helps-farmers-invest-in-a-more-sustainable-future · case study: https://www.accountingforsustainability.org/content/dam/a4s/corporate/12567_FFTF%20Rabobank%20case%20study%2 · WBCSD: https://www.wbcsd.org/resources/regenerative-agriculture-as-a-response-to-financial-risk-and-driver-of-supply-chain-value/
11. ICAP, *EU CBAM enters compliance phase* — https://icapcarbonaction.com/en/news/eu-cbam-enters-compliance-phase-and-outlines-path-ahead
12. ICAP, *China officially expands national ETS to cement, steel and aluminum* — https://icapcarbonaction.com/en/news/china-officially-expands-national-ets-cement-steel-and-aluminum-sectors
13. pv magazine, *China adds 315 GW of solar in 2025* — https://www.pv-magazine.com/2026/01/28/china-adds-315-gw-of-solar-in-2025/
14. Latham & Watkins, *One Big Beautiful Bill: new law disrupts clean energy investment* — https://www.lw.com/en/insights/one-big-beautiful-bill-new-law-disrupts-clean-energy-investment · EU policy state of play: https://www.lw.com/en/insights/eu-sustainability-state-of-play-eu-climate-law-and-energy-transition
15. Sublime Systems — DOE award: https://sublime-systems.com/sublime-systems-selected-by-u-s-department-of-energy-to-receive-87m-investment-to-accelerate-commercial-scale-true-zero-cement-manufacturing-technology/ · Holyoke plant: https://sublime-systems.com/sublime-systems-selects-site-in-holyoke-massachusetts-for-first-commercial-kiloton-scale-manufacturing-of-its-low-carbon-cement/ · CRH & Holcim investment: https://sublime-systems.com/sublime-systems-secures-combined-75m-in-investments-from-global-building-materials-majors-crh-and-holcim-to-accelerate-scale-up-of-true-zero-cement-manufacturing-technology/
16. Microsoft–Sublime offtake — https://www.businesswire.com/news/home/20250522620990/en/Sublime-Systems-and-Microsoft-Sign-Binding-Long-Term-Purchase-Transforming-the-Market-for-Clean-Cement · context: https://trellis.net/article/microsoft-deal-low-carbon-cement-startup/ · https://www.cemnet.com/News/story/179253/microsoft-to-buy-600-000t-of-green-cement-from-sublime-systems.html
17. Project Drawdown, *Deploy enhanced rock weathering* — https://drawdown.org/explorer/deploy-enhanced-rock-weathering
18. Frontier, *Eion offtake* — https://frontierclimate.com/writing/eion
19. Wynes, S. & Nicholas, K. A. (2017), *The climate mitigation gap*, Environ. Res. Lett. 12 074024 — https://iopscience.iop.org/article/10.1088/1748-9326/aa7541
20. NC State / Millennium Technology Prize announcement on B. J. Baliga and the IGBT — https://www.eurekalert.org/news-releases/1056751

*Compiled June 2026 for the Climate Positivity lecture. All numbers are order-of-magnitude estimates; see §13.*