How Frontloaded ETS Revenues Can Close Europe’s Durable CDR Gap

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Abstract

The European Union's Emissions Trading System extension to buildings and transport (ETS2) will generate between €296 billion and €534 billion in revenues by 2032, depending on carbon price trajectories. A nascent frontloading proposal from the Institut Jacques Delors and others suggests converting future revenues into present investment through European Investment Bank bonds backed by a combined ETS1 and ETS2 guarantee base, mobilising up to €200 billion over 2028-2034. However, no frontloading proposal to date allocates funding to durable carbon dioxide removal (CDR) technologies, despite the European Commission forecasting a requirement for 75 Mt per year of durable removals by 2040 and 100-250 Mt per year by 2050. This paper proposes dedicating 5-15% of the frontloading envelope (€10-30 billion) to durable CDR and models the capacity, cost, employment and timing implications across the full deployment horizon to 2050.

Under the central 10% scenario, early investment in 2028-2034 builds 18.1 Mt per year of additional funded capacity by the end of the period and


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compounds to 137 Mt per year by 2050, a 2.5× multiplier relative to the no-frontloading baseline. The same €20 billion invested ten years later (2038-2044) yields only 100 Mt per year by 2050, falls short of the EU's projected needs (a 1.37× relative disadvantage), removes 512 Mt less cumulative CO_2, and costs 37% more per Mt per year of 2050 capacity. Employment effects mirror this pattern: the central scenario supports up to 82,000 jobs by 2050, with nearly 49,000 of those jobs attributable to frontloading over and above the baseline trajectory. These findings hold across all tested growth rate assumptions (5-15% cumulative annual growth rate), cost scenarios (€150-350 per tonne), and under differential-growth-rate tests that vary public and private deployment separately. The compounding logic is structural: a euro spent in 2028 buys substantially more removal capacity by 2050 than the same euro spent in 2038, independent of precise cost or learning assumptions.

The paper quantifies a policy blind spot and demonstrates that the timing of frontloaded investment is central to meeting EU CDR needs. Dedicating 5-15% of a €200 billion frontloading envelope to durable CDR is technically straightforward, deliverable through existing EU and national public funding channels, and would constitute the largest public CDR demand signal in European history. The analysis is deliberately agnostic on policy format: subsidies, procurement, contracts for difference, advance market commitments, tax credits, and grants are all plausible delivery vehicles, and the choice between them is outside the scope of this paper. In the scenarios modelled here, frontloading materially improves the prospects for Europe's 2040-2050 removal objectives, which the no-frontloading baseline falls well short of meeting. The paper concludes with a policy recommendation that any legislative proposal on ETS revenue allocation include a dedicated durable CDR funding window.

Table of Contents

1 | INTRODUCTION

The Frontloading Opportunity and the CDR Blind Spot

Climate policy succeeds or fails on build-out. Targets matter, scenarios matter, long-term strategies matter, but the real test is whether governments can turn climate ambition into financing, infrastructure, and deployment at the speed required. That question is becoming sharper in Europe, where the investment needs of decarbonisation are rising quickly and the role of carbon dioxide removal (CDR) in the Union's long-term climate pathway is becoming harder to ignore. Yet one gap remains striking: Europe is beginning to identify future revenue streams and future removal needs, without having built a credible bridge between the two. This paper examines that gap. Even with deep emission cuts, the EU's own climate-neutrality target implies removing hundreds of megatonnes of CO_2 per year by 2050: residual emissions that cannot be abated must instead be permanently removed from the atmosphere. Durable CDR is the infrastructure for that obligation, and like any infrastructure it must be financed and built before it is needed. The paper asks whether frontloading the future EU Emissions Trading System (ETS) could help finance durable CDR at the scale and pace that Europe's own climate architecture increasingly implies.

1.1 ETS2 Revenue Architecture

The European Union's extension of its Emissions Trading System to buildings and road transport (ETS2) represents one of the largest revenue streams in European climate policy. Following an agreement on a one-year delay in November 2025 (European Commission, 2025a), the ETS2 will start in 2028 and cover approximately 800 million tonnes of annual emissions across the building, heating, and transport sectors (EEA, 2026). Revenue projections vary substantially with carbon price assumptions: at a carbon price of €55 per tonne CO_2, the system will generate approximately €296 billion over the period 2026-2032; at €100 per tonne, revenues could reach €534 billion (T&E, 2025). The wide range reflects genuine policy uncertainty about price trajectories, but both bounds are very substantial, larger than the entire European Innovation Fund (EU grant scheme funding large-scale clean-tech projects) or the budgets of most national climate programmes.

The case for earmarking carbon-market revenues, that is legally ring-fencing a defined share of receipts for green industrial investment, begins with the scale of the investment challenge itself. The EU's decarbonisation and competitiveness objectives require a step-change in capital formation: the Draghi report (European Commission, 2025a) estimates that meeting Europe's strategic objectives will require an additional €750-800 billion of investment per year, equivalent to 4.4-4.7% of EU GDP, while the European Commission's recent Clean Energy Investment Strategy states that the clean energy transition alone will require around €660 billion annually until 2030, rising to €695 billion per year in 2031-2040. These figures suggest that the political question is not whether new green investment needs public backing, but how such backing can be made fiscally and politically durable (European Commission, 2026).

Against that backdrop, the Social Climate Fund (European Commission, 2023a) provides a model. It already allocates €86.7 billion (2026-2032) to support vulnerable households: €65 billion from ETS2 revenues and €21.7 billion in mandatory national co-financing. This earmarking is deliberate policy design: linking revenues to specific expenditures enhances political durability by creating constituencies for climate action and reducing the salience of regressive distributional concerns (Klenert et al., 2018; Muth, D. 2023). The current political fragility adds urgency. Poland, Czechia, and Bulgaria have called for delays or outright scrapping of ETS2, making the revenue base uncertain and strengthening the case for strategic pre-commitment through frontloading (gov.pl, 2025; Vlada.gov, 2025; Euronews, 2025). A frontloading mechanism that converts uncertain future revenues into immediate, visible infrastructure investments builds a broader coalition of support than abstract revenue earmarking.

The precedent established by the Social Climate Fund therefore matters beyond social policy narrowly understood: it demonstrates that revenue earmarking is already accepted within EU climate governance as a tool for political durability. In that light, extending earmarking logic to green industrial investment would likely face fewer political obstacles than directing additional carbon-market revenues towards generic fiscal consolidation. Nevertheless, the remaining frontloadable pool remains substantial. Once the Social Climate Fund commitment is met, €210-450 billion in ETS2 revenue is available for other climate and energy purposes over 2028-2034. This is the envelope within which the frontloading debate unfolds (Nguyen, 2025).

1.2 The €200 Billion Frontloading Envelope

Frontloading converts future ETS revenues into present-day investment through European Investment Bank bonds backed by guaranteed carbon revenues. ETS2 is the new system around which the frontloading debate is politically organised, but the Institut Jacques Delors proposal (Nguyen, 2025) makes a deliberate design choice: it uses ETS1 as part of the guarantee base alongside ETS2 in order to reach a meaningfully larger envelope. On this basis, Nguyen estimates up to €200 billion available for frontloading over 2028-2034, anchored in price corridors, regulated bands that hold the carbon price between a floor and a ceiling, at the 2034 horizon of €110-180 per tonne for ETS1 and €70-125 per tonne for ETS2, with the envelope allocated roughly 75% to ETS1 and 25% to ETS2.

The earlier ETS2 range (€296-534 billion) reflects gross auction receipts through 2040, the bulk of which are pre-allocated to the Social Climate Fund and Member State uses and therefore unavailable for EU-level frontloading at scale. The €200 billion figure, by contrast, reflects the European Investment Bank's borrowing capacity against a minimum guaranteed revenue stream created by proposed price floors on both ETS1 and ETS2. The borrowing period is explicitly aligned with the 2028-2034 Multiannual Financial Framework, the EU's seven-year

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budget cycle, reflecting the view that ETS2 politics will remain bound up with the next EU budget cycle.

The political fragility of ETS2 noted above raises a legitimate question about the risk profile of the frontloading envelope itself. Three features limit the exposure. First, the envelope is not predominantly an ETS2 instrument: following Nguyen (2025), roughly 75% of the €200 billion guarantee base derives from the mature ETS1, trading near €80-90 per tonne in early 2026 with an unearmarked auction stream, and only about 25% from ETS2, so the bulk of the envelope is not contingent on ETS2 materialising as modelled. Second, the CDR allocation proposed here is deliberately small, at 5-15% (€10-30 billion); even a quarter-size €50 billion envelope, consistent with a severely curtailed ETS2, still supports a viable programme (see the curtailed-ETS2 stress test in Section 3.3, where the €50 billion downside case is modelled in full). Third, frontloading is itself a hedge against this fragility, since committing revenues earlier reduces exposure to the later political reversal that the ETS2 opposition illustrates. The envelope's dependence on ETS2 is thus bounded, and the CDR carve-out is robust to plausible downside scenarios for ETS2 revenue.

The European Investment Bank (EIB, 2026) ETS2 Frontloading Facility was formally approved by the EIB Board on 4 February 2026, with the European Commission announcing the initiative the same day as part of a broader package to support the rollout of ETS2. The facility makes €3 billion of EIB financing available to Member States to pre-finance investments in buildings and road transport ahead of the start of ETS2 auction revenues in 2028. This comes on top of approximately €4 billion in early disbursements linked to the Social Climate Fund, corresponding to the frontloading of the first tranche of ETS2 auction revenues (Euronews, 2026). Taken together, these elements amount to around €7 billion of funding available before 2028, illustrating both the operationalisation of frontloading in practice and its current limited scale relative to the broader investment needs implied by ETS2. EPICO and Frontier Economics estimate that ETS2 alone could generate approximately €50 billion in frontloaded revenues under more conservative assumptions but over a shorter period (EPICO, 2025).

This builds on existing EIB lending infrastructure, sovereign guarantee mechanisms, and well-established carbon revenue projections. What makes the €200 billion figure plausible in Nguyen (2025) is that it proposes the creation of a corridor-based revenue floor that gives lenders greater certainty over repayment capacity. The financial mechanism exists; the question is what it buys and how it should be allocated to achieve maximum climate benefit. The frontloading concept draws on established fiscal practice. Sovereign and quasi-sovereign entities regularly issue bonds against predictable future revenue streams to finance present-day infrastructure. Carbon revenues are analytically identical: they are backed by a legal entitlement to charge emitters, provided that the Union creates a credible minimum-price architecture, a guaranteed revenue floor under the carbon price, capable of underpinning repayment. In this framing, the price floors are not delivered by the Market Stability Reserve, the ETS mechanism that adjusts allowance supply to manage surplus, itself, but by a proposed reform introducing explicit ETS1 and ETS2 price corridors. The floors secure minimum revenues, while the ceilings are politically important because they bound volatility and provide the "certainty" that Member States are demanding[1].

1.3 The CDR Blind Spot

Despite increasingly ambitious projected removal needs, a comprehensive certification framework, and growing political consensus that carbon dioxide removal is non-optional for net zero, durable CDR still lacks funding at anything close to the scale implied by its future role. Existing support remains largely confined to research grants, innovation programmes, and limited demonstration funding. Yet none of the frontloading proposals published to date allocates a dedicated funding period to durable CDR, despite the growing recognition that removals will be needed at a very large scale. This is the policy gap the paper addresses. Frontloading is one possible answer, but not the only one. The essential point is that durable CDR needs a financing instrument commensurate with its strategic importance.

This paper focuses exclusively on durable[2] CDR rather than temporary, nature-based removals, because it is the durable subset that faces the financing gap addressed here. Temporary removals are already supported through established land-use, agricultural and forestry instruments, whereas durable CDR has yet no comparable demand-side mechanism at EU

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[1] Member states are actively pushing for greater ETS2 price certainty (Carbon Market Watch, 2026), price corridors are a well-established carbon-market instrument (Borghesi et al., 2025), and ETS2 already runs price-management provisions a corridor can build on (FfE, 2026b).

[2] Durable, engineered, techno-based or permanent CDR all refer to CDR methods that store CO_2 for centuries to millennia with low reversal risk, typically including DACCS, BECCS, BCR, enhanced rock weathering and mineralisation as opposed to temporary removals (conventional, nature-based solutions such as afforestation, reforestation and soil carbon sequestration)

level despite its centrality to the 2040-2050 net-zero architecture[3].

European climate policy has already embedded large-scale durable removals into its scenarios, making the current absence of funding mechanisms internally inconsistent. The European Commission's 2040 Climate Target Impact Assessment (Scenario 3) projects around 75 $MtCO_2$/year of industrial (durable) removals by 2040, rising to 119 $MtCO_2$/year by 2050 (European Commission, 2024a). The Commission's lower figure for industrial CDR is contingent on substantial contributions from the land use, land-use change and forestry (LULUCF) sector. The 2040 Impact Assessment (2024) assumes that LULUCF net removals will recover from current levels to approximately -320 $MtCO_2$-eq by 2040 and remain at broadly similar levels through 2050 under its central S3 scenario, slightly above the 2030 LULUCF Regulation target of -310 $MtCO_2$-eq (European Commission, 2024a). This assumption is demonstrably out of line with observed trends. According to the European Environment Agency (2025a), the EU's LULUCF net sink has already declined sharply: between 2014 and 2023, the average annual carbon sink dropped by 30% compared with the previous decade, falling from approximately 335 $MtCO_2e$/year in 1991-2013 to an average of around 198 $MtCO_2e$ in recent years. Eight Member States (Austria, Estonia, Finland, Germany, Ireland, Latvia, Malta and the Netherlands) reported net LULUCF emissions rather than removals in 2023, shifting from sinks to sources (EEA, 2025b). Looking further ahead, Member State projections suggest EU LULUCF net removals will decline to between 160 and 201 $MtCO_2e$ per year over 2023-2050, depending on the scenario (EEA, 2025b). This is a range of less than two-thirds of the Commission's 320 Mt assumption. Any such shortfall in LULUCF delivery would have to be compensated by additional durable removals, pushing the effective durable CDR requirement closer to or beyond the ESABCC's upper range of 256 $MtCO_2$/year by 2050. (ESAB, 2025). Domestic CDR deployment is a necessity embedded in the legal architecture of European climate policy.

The EU has already constructed most of the supply-side architecture for CDR, but has stopped short of creating the demand that would make this architecture operational. The Industrial Carbon Management Strategy, adopted in February 2024, specifies an objective to capture 280 $MtCO_2$ by 2040 and 450 Mt by 2050, and plans for the development of CO_2 infrastructures (European Commission, 2024b). The Carbon Removal and Carbon Farming (CRCF) certification framework, adopted in December 2024, establishes measurement, reporting and verification standards alongside permanence requirements that distinguish durable removals from temporary carbon storage (European Union, 2024a). The Net Zero Industry Act (European Union, 2024b) targets 50 Mt per year of geological injection capacity by 2030. CDR has evolved from a

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[3] Direct integration of durable removals into the EU ETS (letting capped installations discharge part of their obligation with certified removal units) is widely regarded as the eventual route to compliance-scale demand, potentially worth tens of billions of euros a year (Manhart and Cario, 2025a). It is not, however, a near-term answer. The Commission's integration proposal is due only in July 2026, with implementation unlikely before 2031, and even once removals are admitted the cheapest durable pathways still sit above prevailing allowance prices, so inclusion without complementary support would pull little additional deployment forward this decade (Manhart and Cario, 2025a). ETS integration is therefore best understood as the demand mechanism that frontloaded public funding must bridge to, not a substitute for it.

scientific concept into a recognisable industrial sector: since 2018, the sector has grown at over 200% annually, with more than 600 firms operating across a dozen technological pathways (CDR.fyi, 2025). BCG and DVNE (2024) estimate that CDR could become a global €470-940 billion per year industry by 2050, with a €110-220 billion opportunity for Europe alone.

Yet neither the CRCF nor other existing EU legislations create demand. These are supply-side instruments building regulatory capacity for a market that does not yet exist beyond voluntary corporate action. There is an asymmetry across jurisdictions: CDR objectives are expected to lead to public funding by governments, but in the European Union, at EU level, industrial funding mechanisms remain absent (Manhart and Cario, 2025a). The ICAP (2025) thematic brief on CDR integration into emissions trading systems confirms that while several jurisdictions are exploring compliance-market integration, no ETS globally has yet established a dedicated funding budget for durable removals. The European Commission is preparing a proposal for CDR integration into the EU ETS, which is due in July 2026, but the earliest plausible timeline for implementation is 2031, leaving a gap during which no compliance demand for removals exists.

In the Nguyen (2025) frontloading proposal, the EPICO analysis, and the EIB facility terms published to date, carbon dioxide removal does not appear as a spending category. The absence of a demand signal is a structural bottleneck. As we argued in the context of Global South CDR deployment (Manhart and Cario, 2025b), conducive government policy is the precondition for long-term planning by investors, buyers, and suppliers. The same logic applies within Europe: without a credible public funding mechanism, private capital cannot commit to the multi-year investment cycles that durable CDR infrastructure requires.

Current installed durable CDR capacity across the European Union stands at around 0.2 Mt, three orders of magnitude below the 2050 requirement[4]. Durable CDR must scale approximately 1,300 times by 2050 relative to current levels (State of CDR, 2026), and 50 times before 2030 to reach the 5 Mt EU indicative objective (European Commission, 2024a). This is a gap that cannot be closed by incremental R&D, pilot-scale demonstration, or voluntary corporate purchasing alone. It requires industrial-scale public funding of the kind that contracts for difference, long-term contracts that top up or claw back the gap between a guaranteed strike price and the market price, have delivered for offshore wind and solar in the United Kingdom, Denmark, and Germany.

The paper's contribution is to propose dedicating 5-15% of a frontloading envelope (€10-30 billion over 2028-2034) to durable CDR funding. We quantify the capacity, cost, and employment implications of this allocation under three distinct scenarios and, critically, demonstrate the compounding value of deploying this revenue early rather than waiting for dedicated ETS revenues as the system expands in the 2030s and 2040s.

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[4] BCR alone accounts for approximately 0.19 Mt in 2025 (European Biochar Market Report; 2025) and BECCS and DACCS still contributing only marginal volumes from early demonstration projects.

2 | Quantifying the CDR Allocation

This section quantifies what a dedicated CDR financing period would actually buy. It takes three allocation shares of the €200 billion frontloading envelope, 5%, 10% and 15%, and converts them into annual funding budgets, and new capacity by 2034 under a blended-cost, learning-curve framework. The result is that even the smallest scenario, €10 billion, exceeds the combined scale of existing EU and national CDR programmes, while the largest, €30 billion, would create a demand signal large enough to deliver 28.3 $MtCO_2$ per year of new capacity by 2034. Relatively small shares of the frontloading envelope therefore move CDR out of the pilot phase and into industrial scale.

2.1 Three Allocation Scenarios

Allocating 5-15% of frontloaded funding to carbon dioxide removal is proportionate to its role in the EU's net-zero architecture. EU emissions were approximately 5 $GtCO_2e$ in 1990 and are around 3.0-3.3 $GtCO_2e$ in 2025 (EEA, 2025c). By 2050, total CDR (including both land-based and durable removals) is expected to reach 400-800 $MtCO_2$/year (ESAB, 2025), equivalent to 7-14% of 1990 emissions and 12-24% of 2025 emissions. Within this, durable CDR alone is expected to contribute a major part of these projections. A 5-15%[5] funding allocation for durable CDR therefore represents a proportionate share of overall climate effort, consistent with the scale at which removals are expected to contribute to the net-zero balance.

The model tests three allocation shares of the €200 billion frontloading envelope: 5% (€10 billion), 10% (€20 billion), and 15% (€30 billion). These translate to annual CDR budgets of €1.43

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[5] Considering CDR will represent 12-24% of the remaining climate effort between 2025 and 2050, this is the share of the overall effort that removals must deliver, and therefore the share of climate funding that should be dedicated to CDR as a whole. Within this envelope, durable CDR warrants a distinct sub-share, which can be sized in three ways. A volume-based approach takes durable CDR's projected 2050 contribution (~150-250 $MtCO_2$/yr) as a share of total CDR, giving durable removals roughly 25-40% of the envelope. A scale-up gap approach compares the tonnes each pathway must add between now and 2050: temporary CDR must roughly double from ~210 $MtCO_2$/yr today (EEA, 2025b), while durable CDR must grow from under 1 $MtCO_2$/yr to 150-250 $MtCO_2$/yr, a ~1,000× expansion, lifting durable CDR's share of the new-capacity gap closer to 50%. A capital-intensity approach weights these tonnes by their cost of deployment (€20-100/t for temporary CDR vs. €100-600/t for durable pathways), pushing durable CDR's share above 70%. Taken together, these three logics bracket durable CDR's fair share at roughly 30-60% of total CDR needs. Applying a central value of 50% to the 12-24% of 2025 emissions dedicated to CDR yields a durable CDR funding share of approximately 5-15% of the relevant climate financing envelope, which is the range adopted here. Additionally, the State of CDR report (2026) points out that in their Highest Ambition pathways, limiting warming well below 2ºC is achieved primarily through reducing sources of emissions (around 84% of total mitigation effort) while also deploying CDR (around 16% of total effort, 9%-20%). Limiting warming to 1.5ºC will take additional effort to achieve and sustain net-negative CO_2 emissions with CDR taking an even stronger role.

billion, €2.86 billion, and €4.29 billion respectively, spread evenly over the seven-year funding period from 2028 to 2034.

To contextualise the scale: Denmark has committed €1.3 billion to durable CDR through its biochar subsidy scheme running from 2027 onwards (KEFM, 2022); Sweden's Bio-CCS programme is budgeted at approximately €3.3 billion over 2026-2046 (Swedish Energy Agency, 2025); Germany's Bundestag approved a €476 million CDR budget in November 2025, covering 2026-2033, with €156 million earmarked for 2026 alone (DVNE, 2025); the European Union's Innovation Fund has allocated approximately €0.6 billion to carbon removal-relevant projects (Carbon Gap, 2025). Even the 5% scenario (€10 billion) exceeds the combined budgets of all these programmes. The 15% scenario (€30 billion) would represent a step-change in the scale of public CDR funding, comparable in ambition to the early German solar feed-in tariff programme or the UK offshore wind contracts for difference (CfD) programme, both of which catalysed global industries from high-cost first-of-a-kind projects.

2.2 Cost Benchmarks for Durable CDR

A reasonable central benchmark for a European blended portfolio of durable CDR technologies in the late 2020s is around €250/tCO_2. This estimate should be understood as a portfolio-based benchmark, rather than the cost of any individual pathway. The composition follows the BCG/AFEN balanced portfolio as a structuring device: excluding the 50% temporary CDR share, the remaining durable mix is reweighted to 40% bioenergy with carbon capture and storage (BECCS), 20% direct air carbon capture and storage (DACCS), 20% biochar carbon removal (BCR), 10% enhanced rock weathering (ERW) and 10% residual durable pathways. Applying this structure to European cost ranges from the literature yields a late-2020s to 2030 blended cost in the €200-250/tCO_2 range, making ~€250/tCO_2 a credible central benchmark.

At the level of individual pathways, European cost benchmarks for 2024-2026 place biochar carbon removal (BCR) at roughly €110-200/tCO_2 (Puro.earth, 2026; CDR.fyi, 2026; EU Scientific Advisory Board, 2025; State of CDR, 2026), BECCS at approximately €120-250/tCO_2 on an all-in basis (Abegg et al., 2024; IEA, 2025; EU Scientific Advisory Board, 2025; State of CDR, 2026), DACCS at roughly €350-1,000/tCO_2 depending on maturity and energy inputs (Abegg et al., 2024; Sievert et al., 2024; EU Scientific Advisory Board, 2025; Belfer Center), and ERW at approximately €150-350/tCO_2 (Buma et al., 2026; Breuning, 2024; Beerling et al., 2020; CDR.fyi, 2026; EU Scientific Advisory Board, 2025; State of CDR, 2026). The residual category can be interpreted as a mix of emerging durable pathways, including ocean-based CDR, with indicative costs in the €200-600/tCO_2 range and a central assumption of ~€400/tCO_2, consistent with early-stage market and literature estimates (Frontier Climate, 2026; Grantham Institute, 2024; RSC, 2023).

Applying these values directly yields a transparent portfolio calculation. Using mid-point estimates, BECCS €170/tCO_2, DACCS €475/tCO_2, BCR €140/tCO_2, ERW €215/tCO_2, and residual pathways €400/tCO_2 and the weights above,places the central estimate in the low-to-mid €200s per tonne, confirming that ~€250/tCO_2 is a consistent and internally derived benchmark.

The €250/tCO_2 starting cost is concordant with the European Commission's 2025 study *Carbon* *removals in the EU*: *Review of current carbon removal projects and early-stage financing* (EC/Ramboll, 2025), which reports permanent-CDR cost ranges for the current, 2030 and 2035 horizons. Applying the blended portfolio breakdown, the central weighted cost falls from €361/t today to €233/t by 2030, with the linearly interpolated 2028 value at €284/t. Because the frontloading window opens in 2028, we set the starting cost at €250/t, within this 2028–2030 descending path: just below the interpolated 2028 figure and above the 2030 level, reflecting continued global learning by the time contracts are signed

For future costs in 2040 and 2050, we use a 10% learning rate per doubling of cumulative capacity. Empirical work on clean energy and CDR technologies supports this learning rate[6]. Meta-analyses of technological learning in the renewable energy sector find that most energy technologies cluster around ≈15-16% learning, with a typical band of 10-20% once extreme outliers are excluded, while detailed clean-tech studies report roughly 9% for onshore wind and up to 30-40% for solar PV, with 10-15% common for modular technologies implying that low-teens values are representative for advanced but partly site-specific low-carbon infrastructure (Schmidt, 2017; Rubin, 2015; Fukui; 2017; Al Juaied and Whitmore, 2023; REFLEX project, 2018).

Major DACCS rates studies report learning rates of 5-20% (Sievert, 2024; Kanayko and Craig, 2025; Wei et al., 2025), Other studies looking at broader CDR technologies find a 5-16% range (Gogerty, 2026). Climeworks (2023a) internally assesses DACCS learning at 10-12% and a Boston Consulting Group study proposes 11-13%, again with 15% as an upper-bound scenario (BCG, 2023). CCS deployment modeling in Sweden similarly uses 3% as a conservative and 12% as a high learning-rate case for post-combustion capture, treating 12% as feasible when cross-project learning is strong (Beiron et al., 2024). Within CDR-adjacent systems, BECCS and CCS learning studies adopt similar single- to low-teens rates for capture costs under scaling, reinforcing that capture-based CDR is unlikely to fall outside this empirical range. The experience curve mechanism means that higher-allocation scenarios, which deploy more capacity per annum, achieve faster cost reductions than lower-allocation scenarios, creating a self-reinforcing feedback loop between funding scale and cost efficiency.

Two qualifications are warranted. First, cost reductions are not assured: experience curves describe a central tendency rather than a deterministic relationship, and blended unit costs may plateau or increase where energy, materials, financing or monitoring and verification costs rise faster than scale economies are realised, or where demand outpaces supply. Observed market prices for durable CDR have to date remained elevated and have not yet declined along a smooth experience curve (Abegg et al., 2024; CDR.fyi, 2026). Second, in light of this

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[6] A more sophisticated specification could have used a time-varying learning rate, starting above 15% to reflect the rapid cost declines typically observed during early commercial scale-up of frontier clean energy technologies (Rubin et al., 2015; IRENA, 2022) and decaying below 10% by the late 2030s as the technology matures. A further refinement could have differentiated between CAPEX and OPEX learning rates, which empirical work shows tend to diverge (Malhotra and Schmidt, 2020). Given the diversity of durable CDR pathways considered here and the comparatively low sensitivity of our results to this parameter relative to the cost, funding duration, and revenue allocation share, we retain a constant 10% learning rate as a transparent central case.

uncertainty we adopt a single blended learning rate of 10% per doubling of cumulative capacity, applied uniformly across the portfolio rather than disaggregated by pathway. This lies at the lower end of the empirical range reported above and below the central estimates for most individual technologies, and is therefore a deliberately conservative benchmark: it understates rather than overstates the cost reductions achievable as deployment scales, ensuring that the compounding results reported below are not driven by optimistic cost assumptions.

To verify that this rate produces a plausible cost path, the prices generated by our central (10%) frontloading scenario can be compared with the European Commission's independent projections over the horizon for which the latter are available. Applying the 10% rate per doubling of cumulative capacity to the deployment trajectory, the central scenario yields a blended cost of approximately €250/tCO_2 in 2030 and €220/tCO_2 in 2035. These values fall within the European Commission/Ramboll (2025) projected cost ranges, namely €151-316/tCO_2 in 2030 (central €233) and €128-257/tCO_2 in 2035 (central €193), sitting between the central and upper estimates in both years. The modelled path therefore follows the Commission's short- and medium-term projections while remaining marginally above the central estimate, consistent with the deliberately conservative choice of rate. For the short to medium term, where independent benchmarks exist, a 10% learning rate per doubling thus represents a defensible basis for modelling durable CDR cost decline.

2.3 From Euros to megatonnes (Mt)

The budget-to-capacity mapping follows a straightforward relationship: annual public expenditure divided by the product of unit cost (€/tCO_2) and funding duration yields the volume of publicly funded capacity (MtCO_2 per year).

This conversion embeds a modelling assumption worth making explicit: each euro of public funding is treated as translating directly into contracted capacity at the prevailing unit cost. The mapping is most literal under a procurement-style instrument, where the public buyer commits to pay a known price per tonne for a known volume. Under other instrument designs (contracts for difference, production tax credits, capital grants, feed-in tariffs, advance market commitments) the euro-to-tonne translation is less direct, because part of the public euro may compensate for market-price risk, cover capex rather than output, or leverage private revenues that vary with external conditions.

To account for induced private co-investment, a crowd-in factor of $\alpha = 1.0$ (range of 0.5-1.5) is applied, implying that each €1 of public funding mobilises €1.00 of additional private capital. This assumption is defensible in light of available empirical evidence. Data from the EU Innovation Fund indicate that public grants typically mobilise €0.5-1.0 of private capital per €1 of public support, corresponding to total leverage ratios of approximately 1.5-2× across CCUS and CDR-relevant projects (European Commission, 2023b; Carbon Gap, 2024). Cross-country analysis of renewable projects finds 2.5-3× total leverage from direct public investment, while OECD climate finance data report 2-4× for concessional support and 3-5× for EBRD sustainable energy projects (Semieniuk, 2019; OECD, 2015). CCS modelling implies 2-3× private follow-on from demonstration funding (Beiron et al., 2024), and green bonds yield 1.5-2× economic multipliers without crowding-out (Křístková et al., 2025).

Project-level evidence is consistent with this range: The Stockholm Exergi BECCS project combines €180 million in Innovation Fund support with ~€440 million in public-backed loans (EIB and NIB), for a total of ~€620 million in upfront public financing within a ~€1.1 billion project (Innovation Fund, 2025; EIB, 2025; NIB, 2025). This implies roughly €0.8 of additional capital per €1 public, while more recent projects such as Climeworks Cypress DACCS (2023b) and Heidelberg Materials BECCS (2023) show similar ratios in the €0.5-1 private per €1 public range. Aggregate data further reinforce this pattern: across 400+ climate projects, €4.9bn of public funding mobilised €7.6bn in total investment, corresponding to approximately €0.55 private capital per €1 public (Rienks, 2023). Carbon Gap focusing on CDR-relevant investments reach comparable conclusions, with median leverage ratios around 1.5-1.7× and private contributions typically in the €0.5-0.7 per €1 public range (Carbon Gap, 2025).

Comparable policy instruments in adjacent sectors have achieved significantly higher leverage. UK Contracts for Difference (CfDs) for offshore wind have historically delivered 3-5× total leverage, reflecting strong revenue de-risking effects (Janssen, 2026; DECC, 2013), while the US 45Q tax credit has mobilised approximately 2× total investment relative to public support (CRS, 2023; OCED, 2024).

Against this broader benchmark, a 1.0 (0.5-1.5) crowd-in factor represents a defensible central estimate, particularly for early-stage durable CDR markets where technology, regulatory, and demand uncertainties remain more pronounced. The mechanism is conceptually analogous to advanced market commitments, which accelerate deployment by providing credible long-term demand signals and reducing investment risk for nascent technologies (Kremer, Levin and Snyder, 2020).

Table 1 below summarises the budget-to-capacity conversion across the three allocation scenarios. It should be interpreted relative to the very low starting point of the European durable CDR market. With installed capacity still below 0.1 $MtCO_2$ in the EU, even the 5% scenario would represent a move from pilot activity to early industrial deployment. The 10% and 15% scenarios would go further, generating funding volumes large enough to affect financing conditions, project development, and supply-chain investment across several pathways.

TABLE 1.

Budget-to-Capacity Conversion

Scenario	FL Budget (€bn)	Total investment (€bn)	New Capacity by 2034 (Mt/yr)	Average Cost (€/t)	Contracted Removals (Mt)
5% (small)	10	20	8.6	232	43.2
10% (central)	20	40	18.1	220	90.7
15% (ambitious)	30	60	28.2	213	141.2

3 | COMPOUNDING GROWTH

Trajectories to 2050

This section extends the analysis from the funding period to the full 2050 horizon. It uses a reduced-form growth model to test how early frontloaded CDR funding changes long-run capacity once cost decline, private crowd-in and post-2034 compounding are taken into account. Without frontloading, EU durable CDR capacity reaches only 55.4 $MtCO_2$ per year by 2050, below the Commission's low-end objective. Under the central 10% scenario, capacity rises to 51.4 Mt by 2040 and 136.8 Mt by 2050, while the 15% scenario brings the EU close to the 2040 benchmark and above the 2050 range. Even the 5% scenario produces a large effect, raising 2050 capacity by 73% relative to the baseline. Early funding therefore changes the scale of the sector, not merely the timing of its capacity build-out.

3.1 Model Architecture

The model is a reduced-form growth projection designed to isolate the timing advantage of early CDR funding. It operates in three distinct stages.

Stage 1 is the funding conversion phase covering 2028 to 2034. Each year, the annual CDR budget is divided by the prevailing unit cost and a ten-year funding length to determine publicly funded capacity. A 10-year funding length is used as a stylised assumption for early CDR funding[7]. A crowd-in factor of **α = 1.0** is applied, adding private co-investment equal to 1:1 of the public commitment. This value is consistent with observed leverage ratios in European Innovation Fund carbon removal projects and analogous technology funding programmes.

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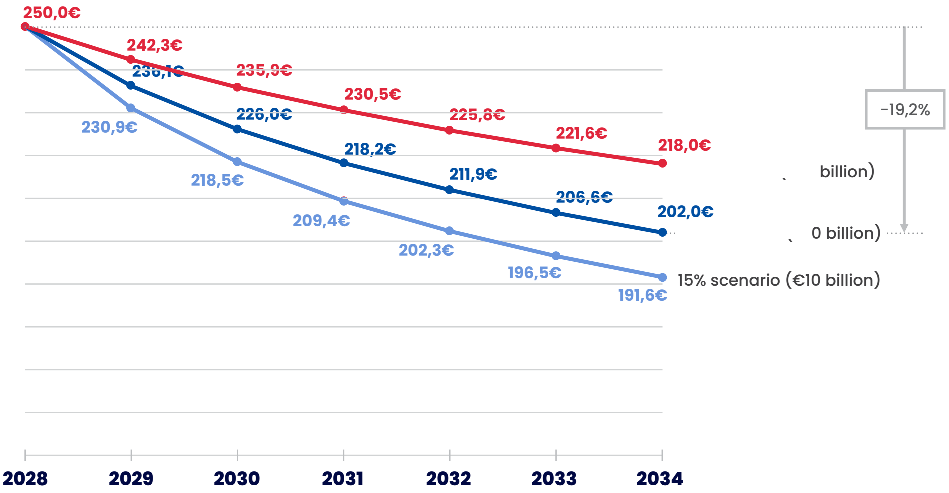
[7] Two distinct parameters govern Stage 1. The seven-year funding window (2028-2034) is set exogenously by the EU Multiannual Financial Framework cycle and determines when new public funding tranches are committed. The ten-year contract length is a separate modelling assumption that determines how long each annual tranche's cohort of publicly funded capacity is kept operational, on the stylised assumption that each tranche funds the full lifetime cost of a 10-year support agreement. Seven annual tranches therefore generate seven overlapping cohorts, each active for ten years from its commitment year; the final cohort (committed in 2034) remains operational through 2043, nine years after the funding window closes. Mechanically, the contract length determines how much capacity each euro of annual budget supports: a longer term spreads the same annual budget over more tonnes of cumulative funded removals, while a shorter term concentrates it. A 10-year horizon sits within the range used or considered in comparable long-duration public support instruments, which have converged on contract lengths in the 8-20 year band regardless of form. Examples: UK renewable CfDs (15 years); the UK engineered GGR business model consultation referencing carbon-management precedents at 10-15 years (Dispatchable Power Agreement) and 10 years with a possible 5-year extension (Industrial Carbon Capture) (DESNZ, 2023); the Danish NECCS scheme (8 years) and larger Danish CCS contracts (20 years) (ENS.dk, 2024). A 10-year term therefore provides a credible middle-ground assumption, consistent with the instruments most likely to deliver durable CDR support at EU or Member State level, whether structured as contracts for difference, fixed-price public funding, or hybrid mechanisms.

Stage 2 implements an endogenous experience curve. Unit costs decline as cumulative installed capacity grows, following the 10% rate.[8] All scenarios assume the 5 Mt EU ambition for durable CDR capacities in 2030 (based on European Commission, 2024a). This is already an optimistic assumption considering that current capacities are well below this, despite a growing market, and that the EU is poised to miss this first objective without fast policy developments.

FIGURE 1.

CDR Cost Under Three Allocation Scenarios



Stage 3 parameterises post-2034 capacity compounding following funding closure. Global installed durable CDR capacity grows at a decaying annual growth rate that begins at 15% and falls by 9% with each doubling of cumulative installed capacity, so the rate declines from 15% toward approximately 11% by 2050, an effective compound growth rate of about 13%. The 15% starting rate is a moderate diffusion rate benchmarked against empirical clean-tech trajectories and CDR-specific forecasts, while the per-doubling decay reflects the slowdown in growth observed empirically as a technology scales, calibrated across six benchmark technologies (Table 2). Recent market analyst forecasts converge on roughly 12-18% CAGR for CDR through 2034: Zion Market Research (2026) projects 14.2% CAGR; Precedence Research (2025) projects 14.53% CAGR; Custom Market Insights (2026) projects 14.8% CAGR; InsightAce Analytic (2025) projects 19.4% CAGR; Precision Business Insights (2025) projects 12.3% CAGR.

ClimeFi (2026) reports durable contracts surging 299% year-on-year in 2025. This 15% rate remains conservative relative to analogues: solar PV (42% CAGR, 5 GW to 230 GW, 2005-2015; Nemet, 2019); onshore wind (28% CAGR, 17 GW to 198 GW, 2000-2010; GWEC, 2010); lithium-ion storage (55% CAGR, 1 GW to 80 GWh, 2013-2023; IEA, 2023). Given CDR's nascent scale (<1 $MtCO_2$/yr, <0.1% of 2050 $GtCO_2$ target), the assumption reflects sustained policy/market momentum without implausible acceleration.

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[8] Following the standard formulation: $P(t) = P_0 \times ((C_0 + H\_t\text{-}1) / C_0)\hat{}\beta$, where P_0 = €250/tonne is the initial blended portfolio cost, C_0 = 5 Mt per year is baseline global CDR capacity in 2030, H_t-1 is cumulative capacity added through funding up to year t-1, and $\beta = \ln(1 - LR) / \ln(2) = -0.152$ is the learning exponent corresponding to a 10% learning rate per doubling of cumulative capacity.

A conceptual distinction underpins the growth specification. Demand for durable CDR is not market-pull demand of the kind that saturates as a product captures its addressable market. It is created by a climate mandate, namely the need for net-negative emissions to meet the European Union's 2040 and 2050 ambitions and to balance residual hard-to-abate emissions. This has two implications. First, the relevant ceiling on deployment is set by climate need, on the order of 75 $MtCO_2$/yr by 2040, rising toward 100-250 Mt/yr by 2050. These projections are not premised on a consumer market that fills up, which supports the non-saturating growth form used here over the deployment horizon. Second, because the demand is policy-created, the growth rate is contingent on the durability of political commitment rather than on autonomous market dynamics. Empirical analogues from policy-driven environmental technologies, such as flue-gas desulphurisation scaling under sustained regulatory mandate (van Ewijk and McDowall, 2020), are therefore apt, but remain conditional on the mandate being maintained. The model's growth path should be read as the trajectory available if commitment is sustained, which is itself the central argument for frontloading.

The choice of a declining growth rate, and of 9% in particular, rests on two layers of evidence: the functional form established in the diffusion literature, and an empirical calibration against analogous technologies. A constant compound growth rate is an implausible long-run assumption for a maturing technology, since it implies that proportional expansion never slows even as the installed base grows by orders of magnitude. We instead let the annual growth rate fall by a fixed fraction r for each doubling of cumulative deployment, the capacity-indexed form of the power-law growth model that best describes solar and wind.[9]

The rate is estimated from the three emerging modular technologies whose diffusion most closely resembles durable CDR. Solar PV, wind and electric vehicles show per-doubling decays of 6.6%, 8.7% and 10.9% respectively, an average of 8.7% (Table 2).[10] As a cross-check, three mature energy carriers with far longer records, coal, oil and natural gas, give 9.8%, 15.5% and 10.0%, an average of 11.7%, confirming that the decay clusters around 9 to 10% across very different diffusion histories.[11] We adopt r = 9% as the central value, between the two medians,

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[9] The diffusion literature has traditionally represented technological growth with saturating logistic and Gompertz curves (Marchetti and Nakićenović, 1979; Grübler et al., 1999), but a strict logistic imposes a fixed ceiling that is difficult to justify for a sector whose ultimate scale is set by climate need rather than by a physical resource limit. Rypdal (2018) resolves this tension by showing that the deployment of solar and wind power is better described by a power-law model, in which the relative growth rate declines continuously as cumulative deployment rises without converging to a fixed ceiling, than by either a constant-exponential model, which implies implausibly persistent growth, or a logistic model, which saturates at unrealistically low levels. The per-doubling decay used here is the discrete, capacity-indexed expression of that power law: a constant fractional reduction r per doubling corresponds to a power-law exponent n through r = 1 - 2^(-1/n), so that the central value of 9% is equivalent to n ≈ 7.

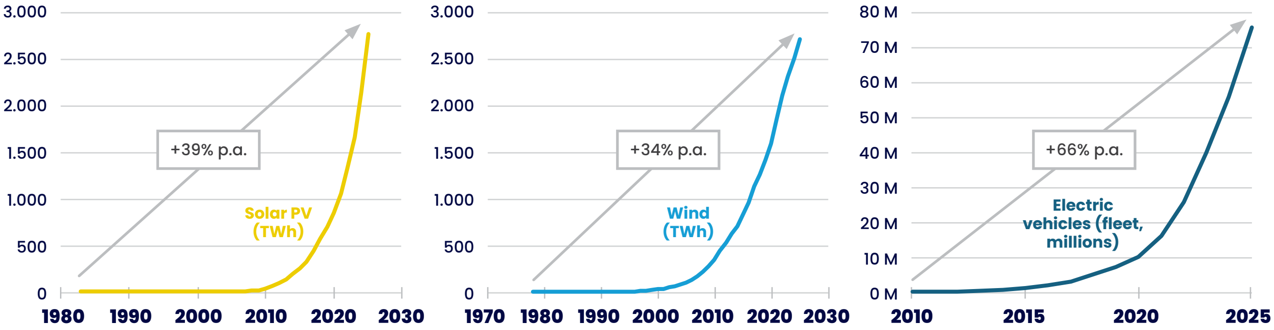
[10] For each technology, annual growth rates of cumulative deployment are grouped by successive doublings, a geometric-mean growth rate is taken per doubling, and its logarithm is regressed on the doubling index; the slope gives r. Solar PV (generation, 1983-2025, ~20 doublings) and wind are from Our World in Data, compiling Ember and the Energy Institute Statistical Review of World Energy; electric vehicles are from the IEA Global EV Outlook. Solar's low fit ($R^2 = 0.11$) reflects that its growth rate has barely decayed and remains near-exponential, consistent with Rypdal (2018).

[11] Coal, oil and natural gas are long-run consumption series compiled by Smil (2017), *Energy Transitions: Global and National Perspectives* (2nd edn, Praeger), and the Energy Institute Statistical Review, accessed via Our World in Data.

and carry a sensitivity band of 7 to 11% spanning the green technologies benchmark; Section 3.3 confirms that the frontloading result is robust across this band.[12]

FIGURE 2.

Green technology historical growth



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[12] A declining rather than constant growth path is supported across the feasibility literature: growth that peaks then decays, with later adopters not growing faster (Cherp et al., 2021); declining, phase-dependent benchmarks applied to CCS (Kazlou et al., 2024); the implausibly early saturation of a logistic fit, which argues for a non-saturating form (Hansen et al., 2017); and regulation-driven abatement that need not slow after materiality, making a positive decay conservative (van Ewijk and McDowall, 2020; see also Wilson et al., 2013).

TABLE 2.

Technology growth benchmark

Technology	r (per doubling)
Benchmark: emerging modular	
Solar PV	6.6%
Wind	8.7%
Electric vehicles	10.9%
Average	***8.7%***
Cross-check: mature energy carriers	
Coal	9.8%
Oil	15.5%
Natural gas	10.0%
Average (green + cross-check)	***10.25%***
Adopted central r	**9% (band 7-11%)**

Key modelling choices include: the retirement rate (ρ) is set to zero over the modelling horizon because carbon dioxide removal plants commissioned from approximately 2030 onward have expected operational lifetimes of 20-30 years, meaning no significant asset depreciation occurs before 2050. DACCS techno-economic studies commonly assume plant lifetimes of around 20-30 years: IEAGHG (2021) uses 30 years for liquid DACCS and 25 years for NOAK solid DACCS, while Fasihi et al. (2019) assume 20 years for low-temperature solid DAC in 2020, rising to 25-30 years in later periods, and 25 years for high-temperature DAC, rising to 30 years. BECCS facilities are likewise generally modelled with 25-40 year or 30-year project lifetimes (Wollnik et al., 2024), consistent with the broader CCS literature on industrial and power-sector assets. BCR pyrolysis plants show similar lifespans (10-30 years; Trollip and Merckel, 2025; Bergman et al., 2022; Agraso-Otero et al., 2025). This zero-retirement assumption is most defensible for the long-lived capital assets in the portfolio, BECCS and DACCS, and is a stronger simplification for biochar and enhanced rock weathering.[13] The blended portfolio cost of €250 per tonne represents the expected weighted-average cost of CDR.

All installed-capacity and removal figures are reported on a net-delivered basis. The per-tonne cost benchmarks used to convert the funding envelope into capacity are defined per tonne of CO_2 actually removed rather than per tonne of nameplate throughput, so the removal volumes already incorporate real-world utilisation: dividing the procurement budget by a cost expressed per net tonne yields the quantity delivered at the operating capacity factor. In practice, carbon dioxide removal plants operate below full utilisation: direct air capture plants report capacity factors of 70-90% depending on energy source, climate, and operational maturity (IEAGHG, 2024; Climeworks, 2026; Keith et al., 2018). Because this utilisation is already embedded in the per-net-tonne cost, applying a further capacity-factor adjustment to the removal results would double-count the same derating. We therefore reconcile in the opposite direction, reporting the nameplate capacity that would have to be installed to deliver the headline removals at a realistic capacity factor (nameplate capacity = removals / capacity factor). At an illustrative 80% factor the required nameplate is approximately 25% above the net figures reported above, rising to roughly 43% at the 70% lower bound and 11% at the 90% upper bound; the removal and cost results are themselves unchanged.[14]

This paper does not take a position on the policy format through which public funding should be delivered. Subsidies, procurement, contracts for difference, advance market commitments, tax credits, grants, or hybrid instruments are all plausible vehicles, each with distinct operational and distributional implications. The analysis here is deliberately instrument-agnostic: it speaks to the scale and timing of public funding, not to its legal form.

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[13] Biochar units built early in the 2030s, at the lower end of the lifetime range noted above, could in principle reach end of life before 2050; in practice, under a sustained procurement signal of the kind modelled here, such units are replaced or repowered rather than abandoned, since the site, feedstock logistics and offtake arrangements are reused. This is the conventional capital-stock turnover assumption in deployment modelling, and is consistent with the prevailing end-of-life treatment of modular energy assets, where ageing equipment is replaced on existing sites rather than retired (IRENA, 2019). $\rho = 0$ therefore represents a replace-at-end-of-life assumption rather than indefinite single-asset operation, and in any case the carbon already sequestered as biochar is durable and is not reversed by plant retirement. Enhanced rock weathering is not a discrete capital asset: removal is delivered by a continuing process of feedstock application and subsequent weathering rather than by a fixed installation, so conventional asset depreciation does not apply, although sustained removal depends on continued application rather than on plant longevity. Because retirement, where relevant, would affect the early and delayed deployment scenarios symmetrically, it does not bias the central comparison between frontloaded and late investment; its only material effect would be a modest overstatement of gross installed capacity in the biochar segment toward 2050, an effect bounded by that segment's 20% portfolio weight.

[14] For the central frontloading scenario, net delivered capacity of 18.2 $MtCO_2$/yr at the close of the funding window implies installed nameplate capacity of 20.2, 22.7 and 25.9 $MtCO_2$/yr at capacity factors of 90%, 80% and 70% respectively; the 5% and 15% scenarios scale identically, from 8.6 and 28.2 $MtCO_2$/yr net to 10.8 and 35.3 $MtCO_2$/yr at 80%. The reconciliation is an ex-post statement of the physical plant implied by the delivered volumes and feeds back into neither the cost nor the capacity trajectory.

3.2 Trajectory Results

TABLE 3.

Capacity Trajectories to 2050
(EU objectives: 75 Mt/yr by 2040; 100-250 Mt/yr by 2050)

Scenario	2035 (Mt/yr)	2040 (Mt/yr)	2050 (Mt/yr)	vs 2040 (75 Mt)	vs 2050 low (100 Mt)	vs 2050 high (250 Mt)
Baseline (no FL)	9.8	18.3	55.4	24%	55%	22%
5% (€10bn)	19.4	34.4	96.1	46%	96%	38%
10% (€20bn)	30.0	51.4	136.8	69%	137%	55%
15% (€30bn)	41.1	69.0	177.4	92%	177%	71%
10%, flat price (€250/t)	27.6	47.6	127.9	63%	128%	51%

The baseline scenario, representing no frontloading allocation, undershoots the European Union's linear capacity objective path from 2031 onwards and fails to recover. The capacity reaches only 55.4 Mt per year by 2050, falling substantially short of the Commission's 100 megatonne low-end objective.

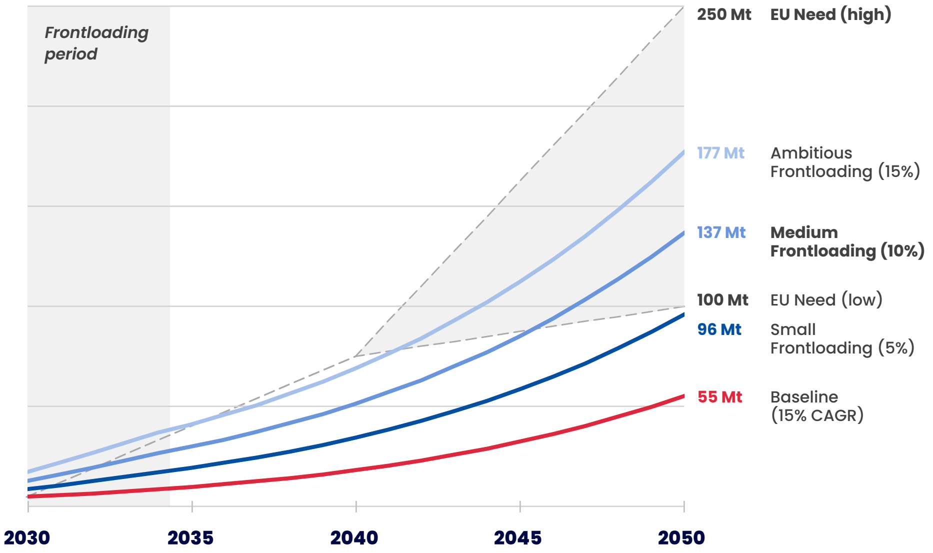
The 10% frontloading scenario closes roughly 69% of the 2040 gap, delivering 51.4 Mt per year versus the 75 Mt ambition. By 2050, it reaches 136.8 Mt per year, exceeding the low objective by 37 Mt and approaching the high end of the Commission's range. The 15% scenario comes within 8% of the 2040 objective at 69.0 Mt per year and comfortably exceeds the low 2050 objective, delivering 177.4 Mt per year. Even the 5% scenario (the minimum tested allocation) increases baseline 2050 capacity by 73% (from 55.4 to 96.1 Mt per year), demonstrating that modest frontloading has outsized effects on long-run trajectories.

To confirm the headline trajectory does not depend on the cost-decline assumption, the central frontloading scenario is re-run under two alternative price paths: a flat real price held at €250 per tonne throughout, and a rising path in which unit costs increase by 5% per capacity doubling (negative learning). Under the flat-price path the frontloaded trajectory reaches 11.9, 27.6, 47.6 and 127.9 $MtCO_2$/yr in 2030, 2035, 2040 and 2050, against 12.8, 30.0, 51.4 and 136.8 Mt/yr under the central assumption of a 10% cost reduction per doubling. The rising-cost path still reaches 124.7 Mt/yr by 2050. The central conclusion is therefore robust to the cost assumption: even with no learning at all, frontloading delivers within the range of 2050 capacity needed, because the binding constraint on deployment is growth dynamics and envelope size. Cost decline affects how much capacity a given euro buys at the margin; it does not change the order of magnitude of the outcome.

The capacity multiplier (the ratio of frontloaded to baseline capacity) declines modestly across the milestone years as the baseline trajectory itself matures. At 2035, the 10% scenario delivers 3.1 times baseline capacity; at 2040, 2.8 times; and at 2050, 2.5 times. The asymmetry between 5% and 15% multipliers (1.7× versus 3.2×) is super-linear, because cost decline is endogenous to funding scale.

FIGURE 3.

CDR Capacity Trajectories 2030–2050 Under Three Allocation Scenarios



3.3 Sensitivity to Model Variables and Growth-Path Assumptions

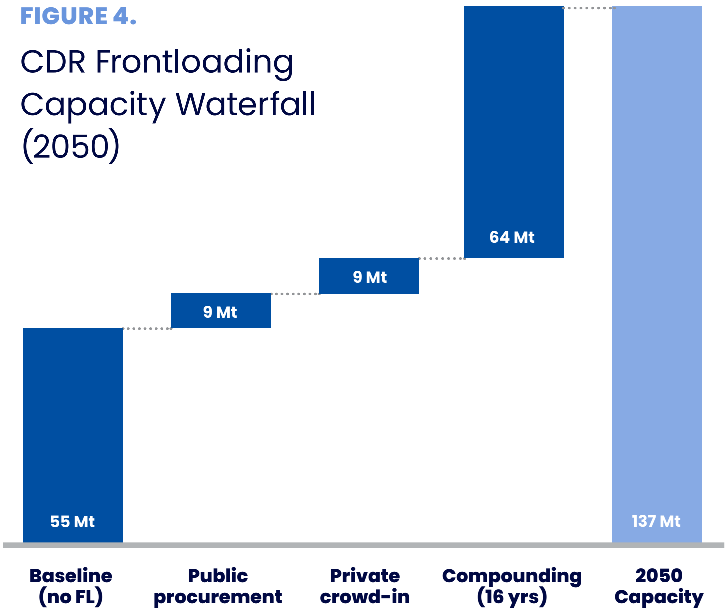
The central result rests on a set of input assumptions, and this section reports its sensitivity to each, giving particular attention to the assumed growth path. The emphasis is deliberate. Because the result is produced by compounding, the trajectory of the growth rate matters more than any other input, and the growth path is in any case the assumption most open to question. That path is governed by two parameters: the initial growth rate and the fraction by which it decays per doubling of cumulative capacity, and the analysis varies both before turning to the procurement, cost and behavioural parameters and to a set of adverse stress cases.

A one-at-a-time sensitivity across the full parameter set confirms that the 2050 outcome is most sensitive to the growth path (Figure 4). Varying the initial growth rate across 10 to 20% moves 2050 frontloaded capacity by roughly 143 $MtCO_2$/yr, the largest single effect, and steepening the decay rate has an effect of comparable magnitude. The procurement levers the policymaker controls directly, the size of the envelope and the share allocated to CDR within it, form a second tier of around 60 to 80 $MtCO_2$/yr each, while the cost and learning assumptions and the crowd-in factor are smaller still. The growth path is therefore examined first.

Along the initial-rate dimension, the frontloading multiplier, defined as the ratio of installed capacity under frontloading to the no-frontloading baseline, is robust across the plausible range. At a 10% initial rate it is approximately 2.9 times; at the central 15% it is 2.5 times; at 20% it is approximately 2.2 times. The multiplier is larger at lower growth rates because frontloading's relative contribution is greatest when the counterfactual baseline is weakest: a slow-growing market benefits more from an early capital injection than one already on a steep trajectory. Across the entire growth-rate range the multiplier never falls below 2, so frontloading at minimum doubles installed capacity relative to the no-frontloading baseline under any reasonable growth assumption. Along the decay dimension, steepening the per-doubling decay from 9% to 20% lowers every trajectory, reducing 2050 frontloaded capacity from 136 to 82 $MtCO_2$/yr and the baseline from 55 to 39, and narrows the early-versus-late advantage from 1.51 to 1.25 times, because the frontloaded path reaches the slower-growth regime sooner. The advantage nonetheless remains decisive across the full 5 to 20% decay band.

FIGURE 4.

CDR Frontloading Capacity Waterfall (2050)



The remaining parameters move the result far less. Holding the blended cost flat at €250/tCO_2 with no learning lowers 2050 frontloaded capacity only modestly, from 136 to 128 $MtCO_2$/yr, and because early and late deployment face the same prices it leaves the comparative case intact. The central CDR cost is a second-tier driver: varying it from €350 to €150 per tonne moves 2050 frontloaded capacity across 113 to 188 $MtCO_2$/yr, and a cheaper sector widens the early-versus-late advantage to 2.09 times because low costs convert the early budget into more capacity before compounding begins. The learning rate matters least for the 2050 stock: across the full range from a negative 5% rate, under which unit costs rise rather than fall with deployment, to a 20% rate, 2050 frontloaded capacity moves only between 125 and 148 $MtCO_2$/yr. Even in the adverse negative-learning case the headline result is preserved, because the compounding of installed capacity, not the cost path, dominates the long-run outcome.

This is because the 16-year compounding runway (2034 to 2050) dominates the growth-rate differential. The pattern is consistent with the technology scale-up literature: publicly supported deployment consistently catalyses broader market growth at comparable or faster rates (Way et al., 2022), and early solar photovoltaic procurement in Germany and Japan drove cost reductions that benefited global deployment (Nemet, 2019).

Given the political fragility of the ETS1 and ETS2 revenue base discussed in Section 1.2, we also tested a reduced €50 billion envelope, a quarter of the headline figure, consistent with a severely curtailed ETS2. Under this scenario the durable-CDR allocation falls to €5 billion, and 2050 frontloaded capacity reaches 75.8 $MtCO_2$/yr, against 136.8 $MtCO_2$/yr under the full €200 billion envelope. Cumulative removals over 2030 to 2050 fall to 666 $MtCO_2$, from 1,264 $MtCO_2$. The early-versus-late advantage holds at 1.19 times. The programme therefore remains viable, and the qualitative result unchanged, even if only a quarter of the headline envelope materialises.

A final check addresses the starting point itself. The baseline assumes durable CDR capacity reaches 5 $MtCO_2$/yr in 2030, an optimistic figure against current installed capacity below 0.2 Mt. Substituting a more conservative 2 Mt starting point lowers 2050 frontloaded capacity by roughly 35 $MtCO_2$/yr, from 136 to 101. A weaker starting point in fact strengthens the case for frontloading: the early-versus-late advantage rises from 1.51 to 1.75 times, because a market with less inherited momentum gains proportionally more from an early capital injection. The policy implication is therefore robust to baseline pessimism, even if the absolute capacity figures are not.

Across every check the qualitative result is unchanged. Frontloaded deployment delivers materially more 2050 capacity than delayed deployment of the same budget; the multiplier exceeds 2 across the full growth-rate range; and the early-versus-late ratio remains above 1.19 in every case tested. The headline finding is therefore a structural consequence of early compounding and not an artefact of any single parameter choice.

FIGURE 5.

Sensitivity Analysis Across Parameter Ranges (+/- Mt/yr)

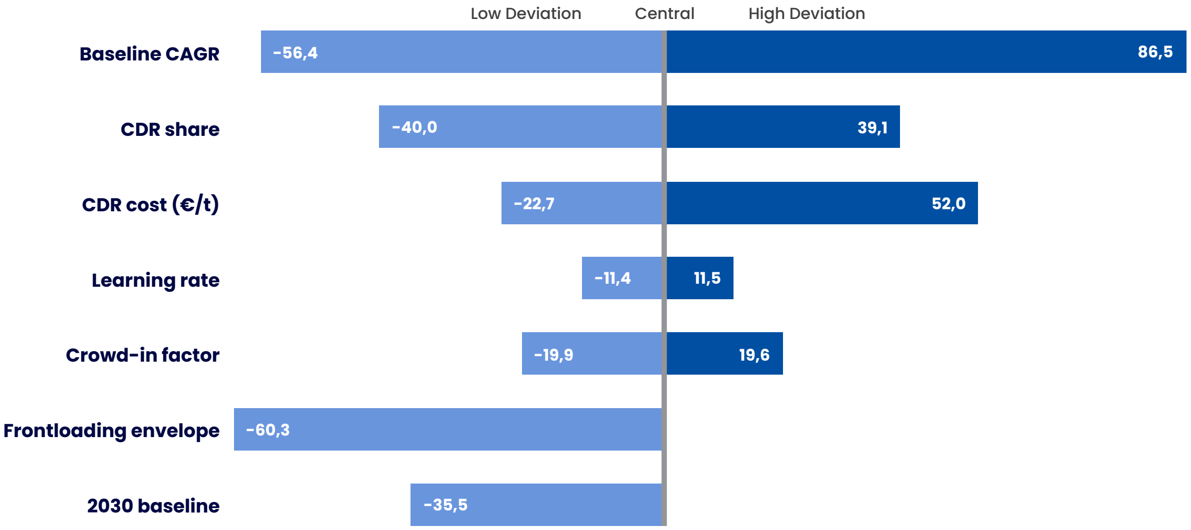
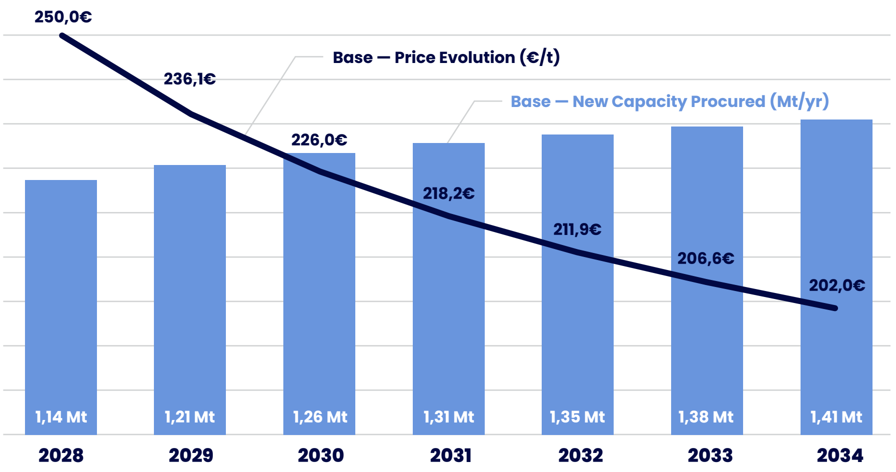


FIGURE 6.

Budget Flow and Cost Decline Across Allocation Scenarios (2028-2034)



3.4 Timing Matters: Deployment Begets Deployment

Early deployment facilitates later deployment through multiple channels: knowledge spillovers from first-of-a-kind projects to subsequent generations, supply-chain maturation as equipment manufacturers scale production, institutional learning as regulators develop operating experience, and human capital accumulation as a skilled workforce grows. This 'deployment begets deployment' effect is well documented in the technology scale-up literature. Knowledge spillovers from first-of-a-kind projects reduce risks and costs for next-generation units, a pattern well documented for modular, mass-manufactured technologies such as solar photovoltaics and batteries, where supply-chain maturation as manufacturers ramp production from first-of-a-kind orders has cut equipment costs by 25-30% through economies of scale (Nemet et al., 2023; Aghion, 2015; Schmidt et al., 2016; OECD, 2000).

In the modelled trajectories, delaying carbon dioxide removal to the post-2035 period implies steep ramp-up rates and higher system costs, which weakens the prospects for meeting European Union climate targets on the modelled pathways; delayed CDR would cost an extra 0.12-0.19 trillion EUR per year of inaction (Galán-Martín et al., 2021).

Delayed mitigation narrows the feasible corridor between large-scale carbon dioxide removal dependence and prohibitively high costs. Modelling of cost-optimal climate pathways consistently shows that early deployment of emerging abatement technologies keeps future options open, whereas delay forces a choice between accepting higher warming or deploying removal technologies at much larger scale and consequently much higher unit cost (Strefler et al., 2018).

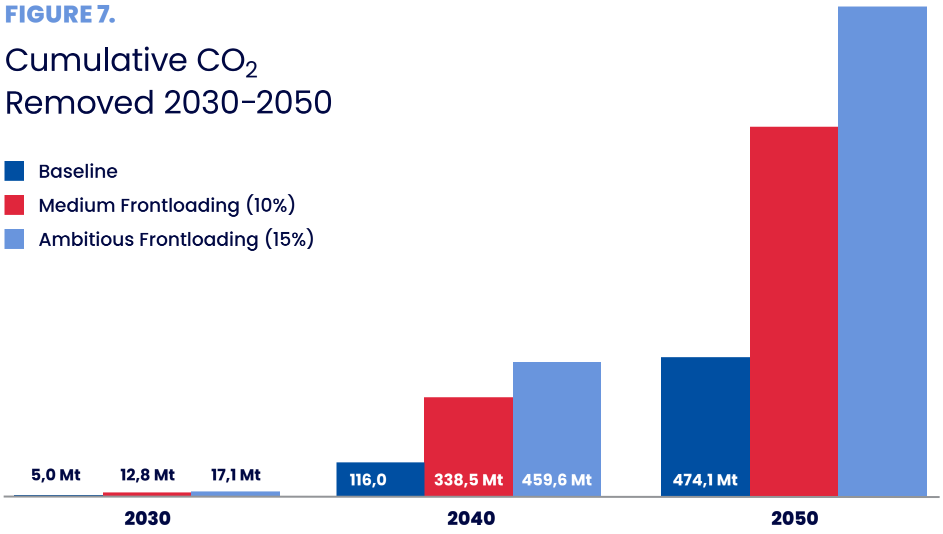
3.5 Cumulative Removals

Cumulative CO_2 removed in the EU over the period 2030-2050 determines the atmospheric CO_2 stock trajectory and therefore the global temperature pathway. Baseline cumulative removals equal 474 Mt; the 5% frontloading scenario increases this to 862 Mt (1.8 times); the 10% scenario to 1,264 Mt (2.7 times); and the 15% scenario to 1,674 Mt (3.5 times). The 789 Mt difference between the 10% frontloading scenario and the baseline is equivalent to approximately 1.2 years of Germany's total CO_2 emissions.

Cumulative removals are irreversible in their climate impact: every Mt not removed during 2030-2050 must be removed later at higher cost, or accepted as permanent warming. This follows directly from the near-linear relationship between cumulative CO_2 emissions and global temperature change (IPCC, 2019). The remaining global carbon budget consistent with 1.5°C is approximately 400 gigatonnes CO_2 from 2020, of which roughly half has already been consumed. The shared socioeconomic pathways used in the IPCC Sixth Assessment Report consistently project that pathways limiting warming to 1.5°C or well below 2°C require substantial net negative emissions in the second half of the century.

FIGURE 7.

Cumulative CO_2 Removed 2030-2050



4 THE TIME VALUE OF CDR INVESTMENT

Early vs Late

The results show that timing is a first-order determinant of outcomes: allocating €20 billion in 2028-2034 delivers 1.37 times more capacity by 2050, generates an additional 512 Mt of cumulative removals, and achieves substantially lower cost per unit of capacity than the same investment delayed by a decade. The value of CDR investment is therefore governed by its position along the deployment trajectory as much as by its scale, with early investment benefiting from a longer compounding horizon that dominates initial cost disadvantages.

A central asymmetry runs through these results: because compounding has until 2050 to work, even a five-year delay leaves the 2050 capacity stock almost intact, but it sharply undermines the nearer-term 2040 milestone, where there is far less time for early deployment to be recovered. The cost of waiting is therefore borne first and most heavily at 2040, a point developed in detail at the close of this section.

4.1 Framing: Same Money, Different Decades

The central thought experiment compares deploying the same €20 billion across three distinct time periods: 2028-2034 (early, frontloading), 2033-2039 (mid, delayed five years), and 2038-2044 (late, delayed a decade). All other model parameters remain identical across the three scenarios. This mirrors the canonical climate investment timing problem in economic theory: when abatement capital is long-lived and subject to learning-by-doing, sequential optimisation favours front-loading investment even at higher initial unit costs (Vogt-Schilb et al., 2018; Goulder and Mathai, 1998; Grubb et al. 2024).

The comparison is deliberately generous to the delayed scenarios. Carbon dioxide removal costs in 2033 are assumed to start at €235 per tonne (approximately 6% lower than 2028's €250 per tonne) and in 2038 at €213 per tonne (approximately 15% lower), reflecting global learning from deployment outside the European Union even in the absence of European Union funding. Despite this cost advantage, the analysis demonstrates that the late scenario produces far less capacity by 2050.

4.2 The Compounding Gap

The critical difference between scenarios is the length of the compounding runway. Early capacity compounds from 2034 to 2050 (a 16-year period) while mid capacity compounds from 2039 to 2050 (11 years) and late capacity compounds from 2044 to 2050 (6 years only). The post-window growth rate itself decays as installed capacity scales, falling from roughly 11% per year in the mid-2030s to under 9% by 2050. Compounding these declining scenario rates, early investment grows its added capacity from 18.1 to 81.4 $MtCO_2$/yr over the sixteen-year runway, a 4.5-fold increase. Mid investment grows 4.1-fold over eleven years, and late investment only 2.2-fold over six years.

This compounding is not purely financial and it represents structural market transformation. Supply chains mature, skilled workforces develop, CO_2 transport and storage infrastructure expands, regulatory frameworks stabilise, and private capital is attracted by demonstrated public demand. The crowd-in factor of $\alpha = 1.0$, under which each euro of public procurement is matched one-for-one by private co-investment, captures only direct co-investment during the funding period; the post-financing CAGR of 15% represents broader market growth driven by installed infrastructure, workforce capabilities, and regulatory certainty. These mechanisms are temporally distinct: crowd-in operates during funding as a direct leverage multiplier, while the CAGR operates afterwards as an organic growth rate applied uniformly to the entire installed base regardless of funding source.

4.3 Head-to-Head Results

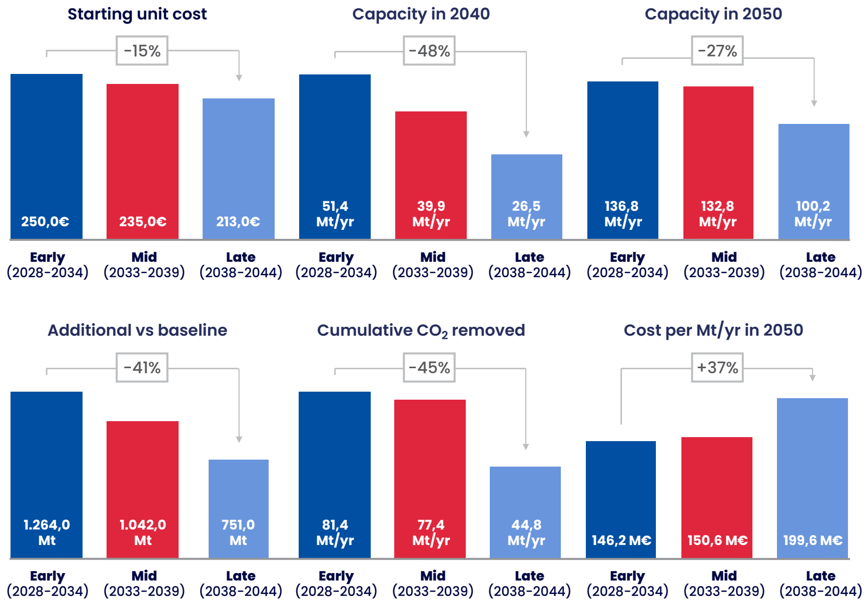
TABLE 4.

Head-to-Head Early vs Mid vs Late Comparison (€20bn in each scenario)

Metric	Early (2028-2034)	Mid (2033-2039)	Late (2038-2044)	Early vs Late
Total budget invested	€20bn	€20bn	€20bn	Same
Starting unit cost	€250/t	€235/t	€213/t	Late starts 15% cheaper
Capacity at period end	18.1 Mt/yr	18.8 Mt/yr	20.1 Mt/yr	0.90×
Capacity in 2040	51.4 Mt/yr	39.9 Mt/yr	26.5 Mt/yr	1.94× early
Capacity in 2050	136.8 Mt/yr	132.8 Mt/yr	100.2 Mt/yr	1.37× early
Additional vs baseline	81.4 Mt/yr	77.4 Mt/yr	44.8 Mt/yr	1.82× early
Cumulative CO_2 removed	1,264 Mt	1,042 Mt	751 Mt	+512 Mt more
Cost per Mt/yr in 2050	€146.2m	€150.6m	€199.6m	1.37× cheaper

FIGURE 8.

Head-to-Head Early vs Mid vs Late Comparison



At the European Union's 2040 milestone, the early scenario delivers 51.4 Mt per year versus only 26.5 Mt per year for the late scenario. The mid scenario reaches 39.9 Mt per year in 2040, showing that even a five-year delay cuts 2040 capacity by approximately 22%. The mid scenario (2033-2039) provides a particularly policy-relevant data point because a five-year delay is the most plausible alternative to immediate action. If political negotiations postpone CDR funding to 2033, the mid scenario shows 132.8 Mt per year by 2050, only about 3% below the early scenario but roughly 33% above the late scenario.

The 512 Mt cumulative removal gap between early and late deployment is irreversible: carbon dioxide not removed during 2030-2044 cannot be retroactively captured. The additional capacity above baseline that the early scenario delivers (81.4 Mt per year by 2050) is 1.8 times the additional capacity delivered by the late scenario (44.8 Mt per year). This 1.8× ratio on the margin is more policy-relevant than the 1.37× ratio on total capacity, because it isolates the incremental contribution of frontloading.

The 2040 milestone is where delayed action is least recoverable, because it arrives before compounding can offset an interrupted trajectory. The European Commission projects a 75 $MtCO_2$/yr industrial-removal objective for 2040; under the 85% domestic-share rule with 5% flexibility, the share that must be met by removals inside the Union falls to roughly 49 $MtCO_2$/yr (Impact Assessment, Scenario S2 against S3). Measured against that domestic mark, the early scenario meets the objective at 51.4 Mt, whereas delay falls progressively below it: the mid scenario reaches only 39.9 Mt (about 22% below early, and short of the domestic objective), and the late scenario 26.5 Mt, roughly half the early figure.

The contrast with 2050 is pronounced. By mid-century the mid scenario recovers to within 3% of early action (132.8 against 136.8 Mt), because the additional sixteen years of compounding from the 2034 funding close are sufficient to offset most of the initial gap. At 2040 that runway does not yet exist: a scenario beginning five years later remains in its low-capacity early phase when the milestone arrives, and subsequent compounding cannot retroactively supply the removals foregone during the 2030s. The policy implication is specific. If the binding constraint is the 2050 target, a modest delay is tolerable; the 2040 domestic objective, by contrast, is met only on the early-action path, because the 2040 outcome is determined largely by how early deployment begins rather than by how rapidly it compounds thereafter.

FIGURE 9A.

Early vs Late Deployment Comparison, 2050

🟦 Installed capacity at end of window ($Mt\ CO_2/yr$)

🟥 Installed capacity in 2050 ($Mt\ CO_2/yr$)

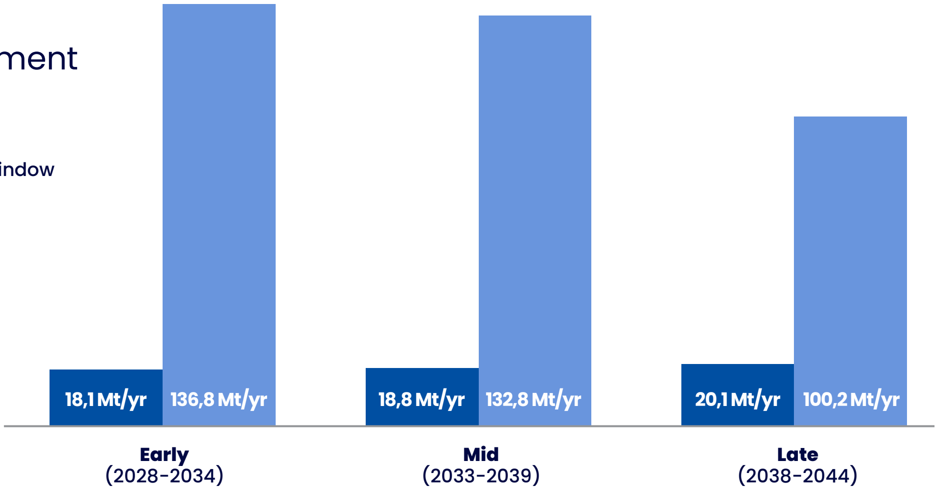
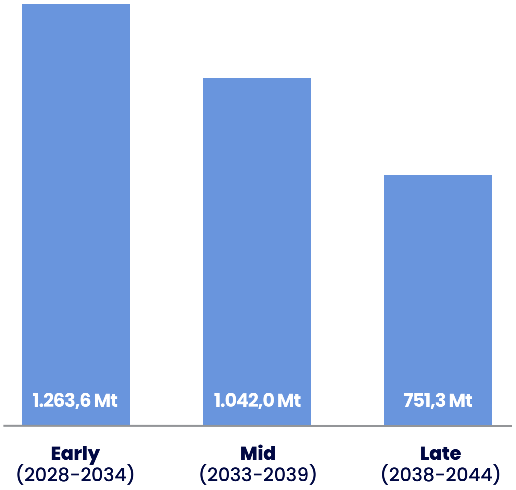


FIGURE 9B.

Early vs Late Deployment Comparison, 2050

Cumulative CO_2 removed 2030-2050 (Mt)



4.4 Cost-Effectiveness Across Metrics

A natural objection is that the early scenario invests €20 billion today while the late scenario invests the same amount a decade later, making the late investment ‘cheaper’ in present-value terms. When both budgets are discounted to 2028 at the European Commission’s social discount rate of 2%[15],the early budget has a net present value of €18.9 billion and the late budget of €15.5 billion. The mid scenario has a net present value of €17.1 billion. However, the capacity generated by the late scenario is worth even less: only 100.2 Mt per year by 2050 versus 136.8 for early. For the early-versus-late comparison the compounding advantage therefore outweighs the discounting advantage; the mid scenario, which retains most of the compounding runway while benefiting from modestly lower discounted outlays, is the one case examined below in which discounting narrows the gap.

On the two metrics that matter most for climate outcomes, early deployment is the cheapest of the three. Measured by public cost per tonne of carbon dioxide actually removed by 2050, early action costs €15.8 million per Mt against €19.2 million for mid and €26.7 million for late: early is 1.21 times cheaper than mid and 1.69 times cheaper than late, because its longer compounding runway removes far more carbon for the same budget (1,264 Mt cumulative, versus 1,042 Mt for mid and 751 Mt for late). The same ordering holds for the cost of reaching a given capacity ambition, set out in Section 4.5: hitting 100 $MtCO_2$/yr by 2050 costs €14.6 billion early, €15.1 billion mid and €20.0 billion late, so early is cheapest at every ambition level and around 27% cheaper than late. The choice of discount rate itself affects optimal carbon dioxide removal timing, with lower social discount rates further favouring early deployment (Emmerling et al., 2019). The structural property is that the exponential growth rate of capacity (15% CAGR) always exceeds any plausible social discount rate (0-5%), ensuring that the compounding return dominates.

4.5 What Does It Cost to Reach a Target?

For any given 2050 capacity target, early deployment requires 27% less public money than late deployment. This ratio is constant across objectives because the efficiency gap (capacity per euro spent) is driven by the compounding period, which is identical across all allocation scales. Reaching 100 Mt per year by 2050 costs €14.6 billion with early deployment versus €20.0 billion with late, a €5.3 billion saving, equivalent to a 27% reduction in total programme budget, a ratio that holds for every capacity target in Table 5.

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[15] EU regulatory appraisal often relies on higher benchmark discount rates, typically of 3% to 4% range (European Commission, 2022) while the OECD (2025) notes that countries use different methods, with the EU and UK leaning on normative welfare approaches and the US having updated its default regulatory discount rate to 2%. For a long-horizon, intergenerational question such as CDR deployment, this paper therefore adopts a 2% social discount rate. That choice is well within the mainstream of the climate-economics literature: Drupp et al. (2018) report a median expert recommendation of 2%, Carleton and Greenstone (2021) argue that climate investments are difficult to justify discounting above 2%, and the wider literature has long accepted even lower values in climate contexts, including the 1.4% rate associated with the Stern Review (2006).

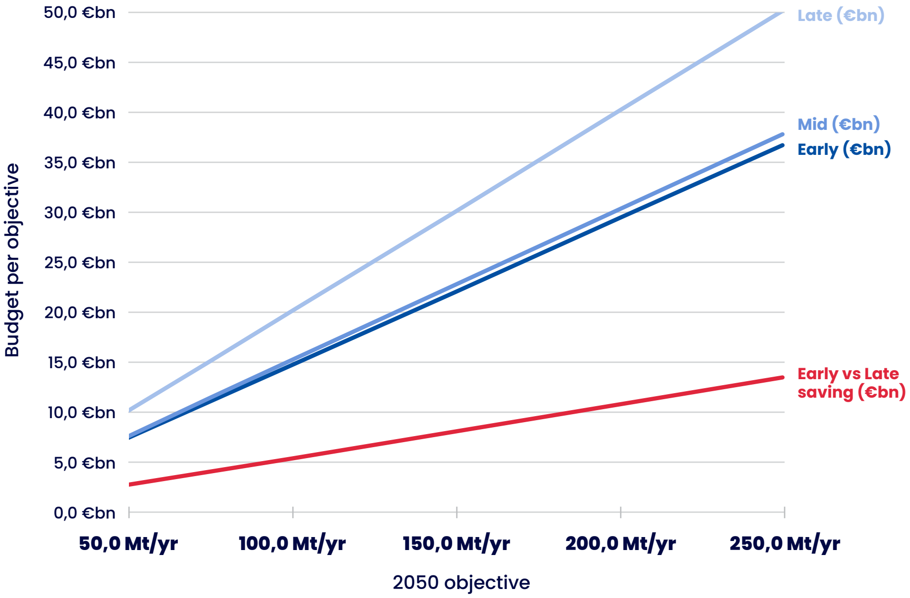
TABLE 5.

Budget Required to Reach Various 2050 Capacity Objectives[16]

2050 Objective (Mt/yr)	Early (€bn)	Mid (€bn)	Late (€bn)	Early vs Late Saving
50	7.3	7.5	10.0	2.7
75	11.0	11.3	15.0	4.0
100	14.6	15.1	20.0	5.3
150	21.9	22.6	29.9	8.0
200	29.2	30.1	39.9	10.7
250	36.5	37.6	49.9	13.4

FIGURE 10.

Budget Required to Reach Various 2050 Capacity Objectives



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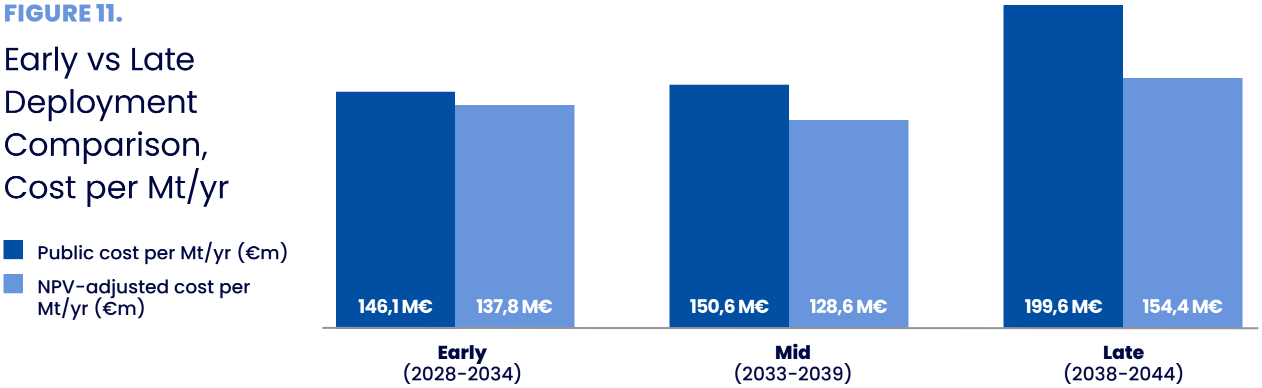
[16] The budget estimates derive from a single back-calculation: given a 2050 capacity ambition, the model identifies the public funding volume required during the deployment window such that the installed base, compounding at the assumed market CAGR over the remaining years, converges to the ambition by 2050. The total budget is then the product of that required capacity and the average cost prevailing over the window. The inverse relationship between deployment timing and cost follows directly from this logic. Capacity supported under the Early scenario (window closing 2034) benefits from sixteen years of market-driven compounding before 2050; capacity supported under the Late scenario (window closing 2044) compounds over only six. Earlier public investment therefore requires a smaller initial outlay to reach an identical 2050 endpoint, with the cost differential widening non-linearly as the deployment window shifts later.

FIGURE 11.

Early vs Late Deployment Comparison, Cost per Mt/yr



5 | Industrial and Employment Impacts

This section examines the wider industrial effects of a dedicated CDR funding period. It moves beyond tonnes and costs to consider what these scenarios would mean in terms of jobs, turnover, and regional industrial development. CDR deployment at the scale modelled here would build removal capacity and, in doing so, support the emergence of a new European industrial base, with employment concentrated in port clusters, industrial regions, biomass areas, and technical hubs already linked to the transition.

5.1 Employment Intensity

Employment intensity estimates for durable CDR vary considerably across the literature, reflecting methodological differences and the immaturity of the sector. This paper adopts a range of 200 to 600 jobs per Mt of annual removal capacity, with a central estimate of 350 jobs per Mt used for headline calculations. The range rests on two recent sectoral studies by the Boston Consulting Group commissioned by national CDR associations, BCG and DVNE (2024) and BCG and AFEN (2025), and on Manhart and Cario (2025b), which adapts the BCG methodology with a regional employment-multiplier and benchmarks it against Rhodium Group (2025) and on-the-ground case studies in Global South countries. The BCG studies estimate up to roughly 620,000-670,000 CDR-related jobs across the EU-27 by 2050 at 0.9-1.9 $GtCO_2$/yr of deployment, with 65,000-130,000 in France at 185-365 $MtCO_2$/yr, implying about 350 jobs per Mt. Both derive employment top-down, applying Eurostat ratios of jobs per million euros of value added to projected CDR economic potential across the value chain, adjusted downward for automation and digitalisation to 2050. These are gross sectoral figures, employment associated with the sector in a given year rather than jobs additional to the economy, a point the studies make explicit and that Section 5.2 takes up. Because they attach to the value-chain share, domestic firms could capture rather than to removals on national territory, the per-Mt ratio applied to installed capacity here is a gross proxy.

The lower bound of 200 jobs per Mt reflects direct operational employment only, the operators, technicians, engineers, control-room and MRV field staff, and on-site logistics personnel who run CDR facilities day to day. It isolates the jobs most directly tied to physical deployment and is the most conservative basis, consistent with the direct-only figures Manhart and Cario (2025b) derive from BCG's value-added totals and with bottom-up operational estimates for DACCS and BECCS facilities in Rhodium Group (2025).

The central estimate of 350 jobs per Mt adds the broader value-chain footprint, from equipment manufacture and component supply through feedstock sourcing and processing, construction and installation, MRV services, and market intermediaries. This is the value used for this paper's headline figures.

The upper bound of 600 jobs per MT reflects the elevated labour intensity of first-of-a-kind and early-deployment projects, where bespoke engineering, manual MRV, and non-standardised construction raise the workforce required per tonne. It is implied when BCG's alternative ratio of about 3.05 jobs per million euros of value creation is applied to the higher turnover of early-2030s deployment, when unit costs remain well above the 2050 mature-portfolio benchmark of €120-130 per tonne.

5.2 Scenario Employment Readouts

TABLE 6.

Employment and Turnover Across Allocation Scenarios (2034)

Scenario	Capacity (Mt/yr)	Jobs (low, 200/Mt)	Jobs (central, 350/Mt)	Jobs (high, 600/Mt)	Turnover (€bn/year)
5% (small)	8.6	1,728	3,023	5,183	~1.99
10% (central)	18.1	3,629	6,351	10,887	~3.73
15% (ambitious)	28.2	5,646	9,881	16,939	~5.43

The figures above are gross sectoral employment, so the relevant policy question is how much of it is net. Net additionality depends on the counterfactual use of the same labour, and two features of CDR indicate the net effect is positive though smaller than the gross total. First, durable CDR is largely a new activity rather than a substitute for an existing product, so it adds output rather than displacing an incumbent the way one generation technology displaces another. Second, as set out below, deployment concentrates in regions and occupations exposed to fossil-fuel and heavy-industry decline, so part of this labour demand absorbs workers displaced elsewhere in the transition rather than competing for scarce labour. The net gain is therefore real but smaller than the gross figure, particularly near full employment, where new sectoral demand redistributes labour more than it expands the total.

Jobs would be concentrated in port and industrial regions (Rotterdam, Antwerp, Le Havre, Gdańsk) where carbon dioxide removal infrastructure integrating with existing petroleum and chemicals sectors provides natural location advantages; in rural biomass regions where feedstock cultivation and processing generate seasonal and permanent employment; and in technology hubs (Copenhagen, Paris, Berlin) where measurement, reporting and verification expertise and digital infrastructure are established. These employment patterns substantially overlap with territories exposed to Emissions Trading System 2 implementation and designated as just-transition territories eligible for Social Climate Fund support. This would create a natural political alignment between CDR funding and the Social Climate Fund's distributional objectives.

TABLE 7.

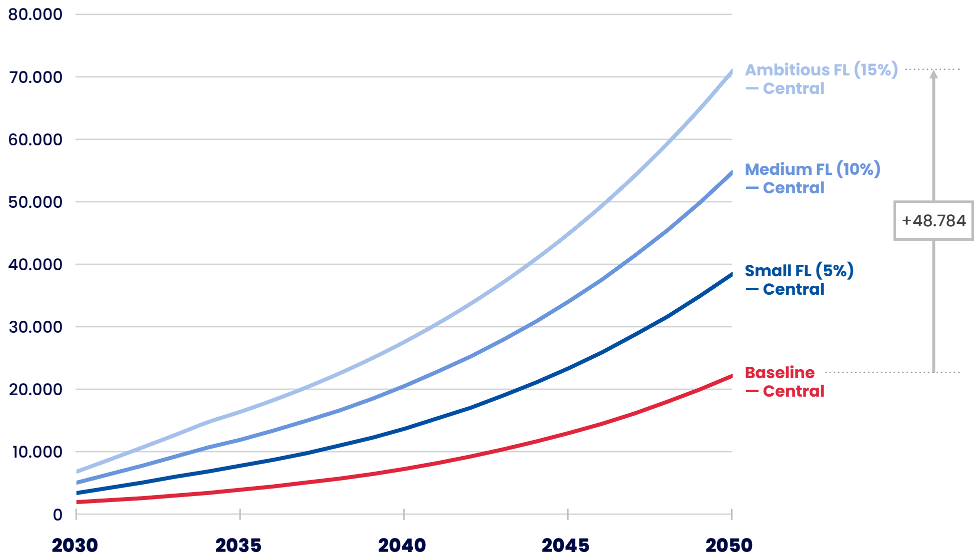
Employment and Turnover Across Allocation Scenarios (2050)

Scenario	Capacity 2050 (Mt/yr)	Jobs (central, 350/Mt)	Δ Jobs vs baseline (central)	Turnover 2050 (€M/yr)
Baseline (no frontloading)	55.4	19,405	—	9,541
5% (small)	96.1	33,652	+14,247	15,329
10% (central)	136.8	47,896	+28,491	20,650
15% (ambitious)	177.4	62,091	+42,686	25,748

The green-jobs literature finds that directed clean-energy investment is more labour-intensive than fossil-fuel spending and generates net employment gains: input-output and sectoral studies put renewables and efficiency at roughly two to three times the jobs per unit of spending as fossil fuels (Garrett-Peltier, 2017; Wei et al., 2010), and the ILO estimates a net creation of around 18 million jobs globally by 2030 under a 2°C pathway, with losses concentrated in petroleum and coal (ILO, 2018). These gains are not automatic at the regional level: displaced fossil-fuel workers are often appropriately skilled but not located where new jobs emerge, so net local benefit depends on reskilling, social protection, and the active labour market policies set out in the just-transition literature (ILO, 2015; OECD, 2024). A carbon dioxide removal sector operating at 18.1 Mt per year by 2034 (the central 10% scenario) would constitute a new European industrial sector comparable in employment to geothermal energy (approximately 5,000 jobs in the EU; JRC, 2024). The annual turnover of the sector, estimated at approximately €3.73 billion under the central scenario, would support a supply-chain ecosystem spanning sorbent manufacturing, compressor fabrication, heat exchanger production, geological survey services, pipeline construction, and digital monitoring and verification platforms.

FIGURE 12.

2030–2050 CDR job creation



By 2050, the employment levels implied by these scenarios sit at the scale of established European industrial sectors. The central scenario reaches 27,000-82,000 jobs (central ~47,900), essentially the size of the current EU offshore-wind workforce (around 47,000 full-time equivalents in 2024; European Commission, 2024c) and of the EU container-glass industry (around 50,000 direct employees; FEVE, 2025). The ambitious scenario supports 35,000-106,000 jobs (central ~62,100), modestly exceeding the European cement and clinker sector's direct workforce of approximately 57,000 across more than 200 plants (Cement Europe, 2025). The two lower scenarios sit proportionately below: the baseline reaches roughly 11,000-33,000 jobs (central ~19,400) and the small frontloading scenario 19,000-58,000 jobs (central ~33,700), about 40% and 70% of the offshore-wind workforce respectively. For scale, the larger heat-pump (around 168,000 direct; EHPA, 2024) and semiconductor (on the order of 200,000 direct; ECSA, 2024) workforces sit above even the ambitious scenario, marking the upper ceiling of comparable industrial employment.

Expressed as the incremental employment gain attributable to frontloading itself, that is, jobs supported over and above the baseline organic-growth trajectory, a 10% frontloading scenario would generate between approximately 16,000 and 49,000 additional jobs in 2050 (central estimate ~28,500), while the ambitious 15% scenario would generate between 24,000 and roughly 73,000 additional jobs (central estimate ~42,700).

6 | Conclusion

The absence of durable carbon dioxide removal from Europe’s current frontloading proposals reflects a policy gap, not a technical constraint. The core elements are already in place. The Union has articulated the scale of removals it expects by 2040 and 2050 (2034 marks the end of the funding window, while 2040 and 2050 are the Commission's removal-ambition milestones). It has adopted a certification framework through the CRCF. It has identified a major future revenue stream through ETS2. It has also begun to operationalise frontloading through the European Investment Bank. What remains missing is the decision to connect these elements through a dedicated demand instrument for durable CDR.

It should be emphasized that financing is only one of the constraints on durable CDR deployment. Even with capital secured, build-out depends on permitting and consenting timelines, the availability of shared CO_2 transport and storage infrastructure, workforce formation, administrative and institutional capacity, and the social licence that siting decisions require. The REDD+ experience of the 2010s is instructive: sustained readiness finance did not produce proportionate deployment where governance, coordination and monitoring capacity lagged (Pham et al., 2021). These enabling conditions carry particular weight in the European context, where civil society engages closely with such infrastructure and can lengthen consenting processes (van der Zwaan et al., 2022). Frontloading relaxes the financing constraint this paper isolates; the deployment trajectories modelled above are therefore conditional, and realising them requires parallel progress on these enabling conditions.

This paper has examined one specific way of doing so: allocating 5 to 15% of a €200 billion frontloading envelope, or €10 to 30 billion over 2028 to 2034, to durable removals funding. On this basis, the analysis shows that relatively limited shares of the broader envelope would already be sufficient to move durable CDR from pilot activity to early industrial scale, while preserving the large majority of resources for other decarbonisation and social objectives. At the upper end of the range, such an allocation would create a public demand signal of unprecedented scale for the sector in Europe.

The quantitative results are clear. Under the central 10% scenario, early investment produces 18.1 $MtCO_2$ per year of capacity by 2034 and 136.8 $MtCO_2$per year by 2050. The same €20 billion deployed a decade later yields only 100.2 $MtCO_2$ per year by 2050. Early deployment therefore generates 1.37 times more 2050 capacity, 512 Mt more cumulative removals, and materially lower cost per unit of long-run capacity. Even after discounting, the early case remains more cost-effective. A five-year delay is also consequential: the mid scenario reaches roughly 132.8 $MtCO_2$ per year by 2050, about 3% below early action in 2050 but well above the late scenario. These findings hold across the sensitivity tests. Within the scenarios modelled here, early investment is a credible and cost-effective pathway to meeting the EU's own durable CDR ambition by 2050. Under any delayed-action scenario modelled, 2050 capacity falls well short of the Commission's 119 $MtCO_2$/year industrial removal trajectory (and further still below the 233-256 $MtCO_2$/year recommended by the European Scientific Advisory Board on Climate Change). The delayed frontloading (starting in 2038) scenario reached only 35% of the 2040 ambition and 84% of the 2050 ambition. Within the scenarios modelled here, only early action converges with these objectives by mid-century, because it unlocks the budget needed to fund CDR through the high-cost early phase and so captures the greatest learning-curve cost degression and compounding runway. This conclusion concerns the modelled pathways and does not assert that no other route could succeed. Frontloading matters not because it is the only possible mechanism but because it is the institutionally realistic one in the current EU window, because it matches the timing of the present policy debate and converts already-legislated future carbon revenues into present investment without requiring new fiscal resources. The employment implications mirror this pattern: early action generates between roughly 16,000 and 49,000 additional jobs in 2050 under the central 10% scenario, and up to roughly 73,000 additional jobs under the ambitious 15% scenario, relative to the baseline trajectory, gains that are substantially eroded, alongside the capacity and cost advantages, whenever frontloading is delayed or scaled back.

That point is central to the paper's contribution. The main result does not depend on frontloading as such. It depends on making substantial funding available early enough for the sector to benefit from scale effects, cost decline, private crowd-in, supply-chain development, and accumulated deployment experience. But the same economic logic would apply if an equivalent amount of funding were mobilised through a diversity of instruments, whether an EU procurement facility, a dedicated Innovation Fund window, coordinated national procurement, or another budgetary channel. What matters for the long-run result is not the financing vessel in itself, but the early arrival of capital at sufficient scale.

The policy implication is therefore straightforward. Any future legislative proposal on ETS revenue use, and more broadly any serious European strategy for industrial carbon management, should include a dedicated durable CDR funding period from the outset. The narrow recommendation of this paper is to do so through a 5 to 15% allocation within the frontloading framework now under discussion. The broader recommendation is that Europe should not postpone the funding decision itself. If durable CDR is excluded during the present design phase, the Union will lose the first deployment cycle and with it the compounding advantage documented throughout this paper. In a sector that must scale rapidly from a very low base, that lost time is not recoverable later at equal cost.

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