BUILT ENVIRONMENT · STRATEGIC BRIEF

The Infrastructure Carbon Curve

Ten infrastructure build-outs, ten abatement-cost curves. The pattern is consistent: a slug of carbon can be cut at negative cost — recycled materials that are cheaper, not dearer — before any premium tonne is bought.

A plain-language MACC analysis across roads, bridges, water, wastewater, grids, power, rail, ports, data centers & buildings — built & operational carbon, $/tCO₂e, cost per functional unit, and seven regions (US, EU, Asia, Australia, India, Japan, Brazil). Built on Infrastructure Australia, Carbon Leadership Forum/RMI, GCCA, IEA & Ember data (2022–2026)[1,2,3] — with CarbonSig research-tool notes.

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BOTTOM LINE UP FRONT

The cheapest carbon is the carbon you don't buy

> **The argument in one breath.** Across all ten infrastructure types, the abatement-cost curves share a shape: a band of **cost-negative levers** (recycled aggregate, reclaimed asphalt, lower-clinker concrete, structural lightweighting) sits below the

> zero line — cutting carbon while *saving* money — followed by a rising premium for the deeper cuts (electrified fleets, green steel, bio-fuels, CCS). Infrastructure Australia found **four of eleven material strategies are net cost-saving and one is cost-neutral**;[5] RMI/CLF reach the same verdict for buildings.[4] The strategic implication: most of the early abatement is a *procurement decision*, not a cost. Two numbers set the scale: embodied carbon is already **~10% of national emissions** in a developed economy,[5] and it is **locked in the day the asset is built** — unlike operational carbon, it cannot be cleaned up later by a greener grid.[5]

10%	~15–25%	5×	30–70%
embodied carbon as share of national emissions (Australia, 2023)[5]	typical abatement available at zero or negative cost via recycled materials[5]	grid-intensity spread driving operational carbon: Brazil ~103 vs Asia ~573 gCO_2/kWh[92]	embodied-carbon cut from commercial low-carbon cements vs OPC[86]

This brief gives each of ten build-out types its **own marginal abatement cost curve (MACC)**: levers ranked cheapest-first, bar width proportional to how much carbon each can cut, with the zero line separating money-saving moves from premium ones. Each curve is paired with the **functional units stakeholders actually budget in** — $/km, $/MW, $\$/m^3$, $\$/m^2$ — and both **embodied (built) and operational** carbon. A closing regional map shows how the same asset's footprint shifts across the US, EU, Asia, Australia, India, Japan and Brazil, and how CarbonSig is used to model any of it at the project level.

The framing treats *carbon as money*. Where embodied carbon is priced — Buy Clean procurement, CBAM on materials, low-carbon-concrete mandates — the MACC stops being an environmental chart and becomes a **cost curve a project engineer optimizes against**, exactly like a bill of materials.

METHOD · HOW TO READ THIS REPORT

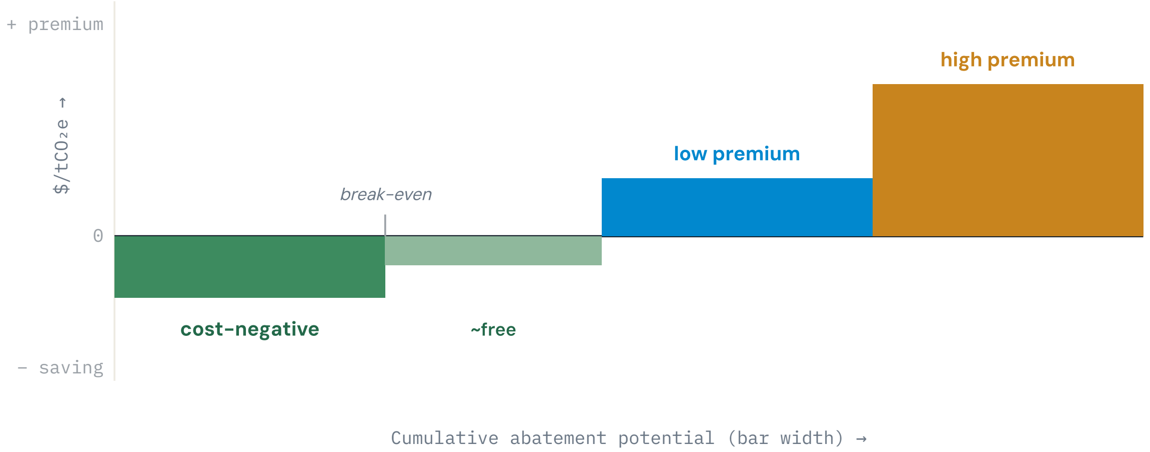
How to read a MACC — and what's in each cost

A **marginal abatement cost curve** ranks every carbon-cutting lever by its cost per tonne avoided (**$\$/tCO_2e$**), cheapest first, with each bar's **width** showing how much carbon that lever can cut. Levers below the zero line are **net cost-saving**; above it, they carry a premium that rises steeply for the last tonnes. McKinsey originated the format in 2007;[72] it is now standard in net-zero roadmaps.

METHOD — ANATOMY OF THE ABATEMENT-COST CURVES IN THIS REPORT

Reading the curve

Each infrastructure section uses this same layout: cheapest levers left, bar width = abatement potential, zero line = the break-even between saving and spending.



Read: Work left-to-right and stop where the curve crosses your carbon price. Everything left of that point pays for itself or beats your price; everything right of it is a deliberate premium for deeper cuts. **Cost basis:** each curve covers *both* embodied (materials + construction) and operational (energy + maintenance over the asset life) carbon; $/tCO$_2$e is the lever's net lifecycle cost per tonne avoided. Values are indicative syntheses of the cited sources, normalized for comparability across sectors.

THE TWO COST BASES, KEPT SEPARATE

Embodied (built) carbon is fixed the day the asset completes — it can only be designed out, never retrofitted away. **Operational** carbon (pumping, lighting, traction, cooling, 40-year maintenance) depends on the grid and decays as electricity decarbonizes. The split matters: embodied-dominated assets (roads, bridges) reward *material* choices; operational-dominated assets (water pumping, data centers) reward *energy* choices. Each section flags which kind it is.

CROSS-SECTOR OVERVIEW

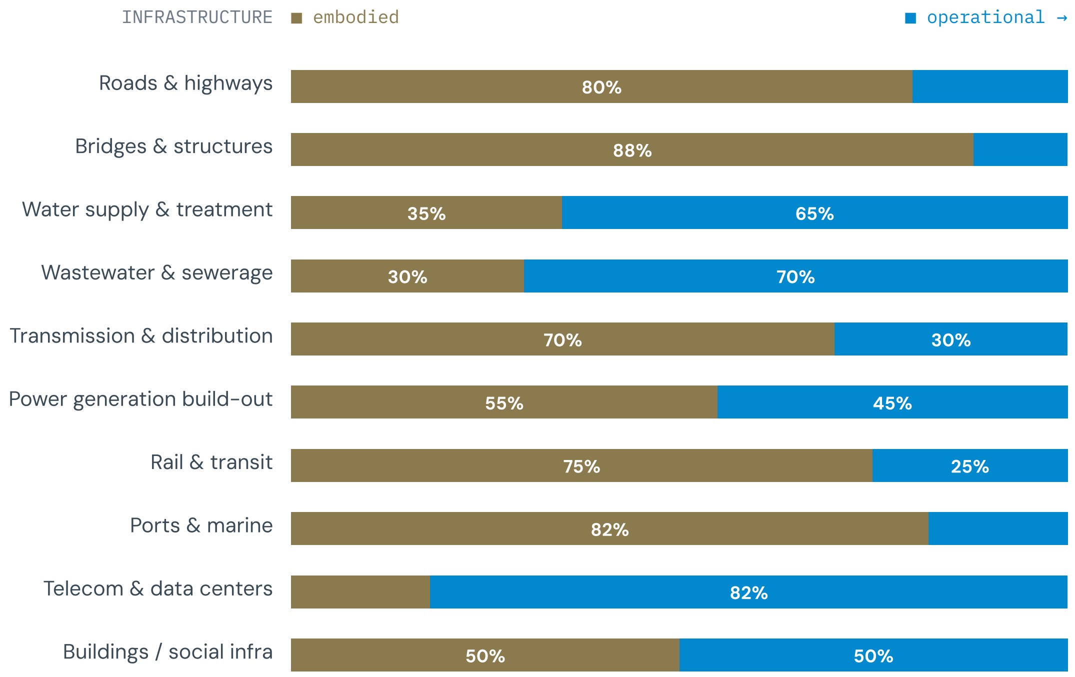
Where the carbon — and the free savings — sit

Before the ten curves, one orienting picture: infrastructure types differ sharply in whether their carbon is **embodied** (locked in materials) or **operational** (burned over decades of use). That split decides which levers matter and how much free abatement is on the table.

CROSS-SECTOR — EMBODIED VS. OPERATIONAL CARBON SPLIT BY INFRASTRUCTURE TYPE

Embodied or operational? The split decides the strategy

Left bar = share of whole-life carbon that is embodied (material/build); right = operational (energy/maintenance over life). Indicative.



Read: Embodied-dominated assets (bridges 88%, ports 82%, roads 80%, rail 75%) are won or lost at the *material-procurement* stage — recycled steel, low-clinker concrete, lightweighting. **Operational-dominated** assets (data centers ~82% operational, wastewater ~70%, water ~65%) are won at the *energy* stage — clean power and pump/process efficiency. Buildings and power-plant builds sit in the middle. **Source:** Infrastructure Australia (embodied locked at build);[5] IEEE/Schneider (data-center ~60% operational, ~40% embodied including devices);[105] CLF benchmarks.[81] Splits indicative.

WHY THIS ORDERING MATTERS FOR SPEND

For the embodied-heavy four, the cost-negative levers (recycled materials) capture real abatement on day one with no grid dependency — the fastest, cheapest wins in the whole report. For the operational-heavy assets, the lever is a power contract and an efficiency design, and the payoff compounds as the grid cleans up. CarbonSig models both in one canvas (see closing section).

INFRASTRUCTURE 01

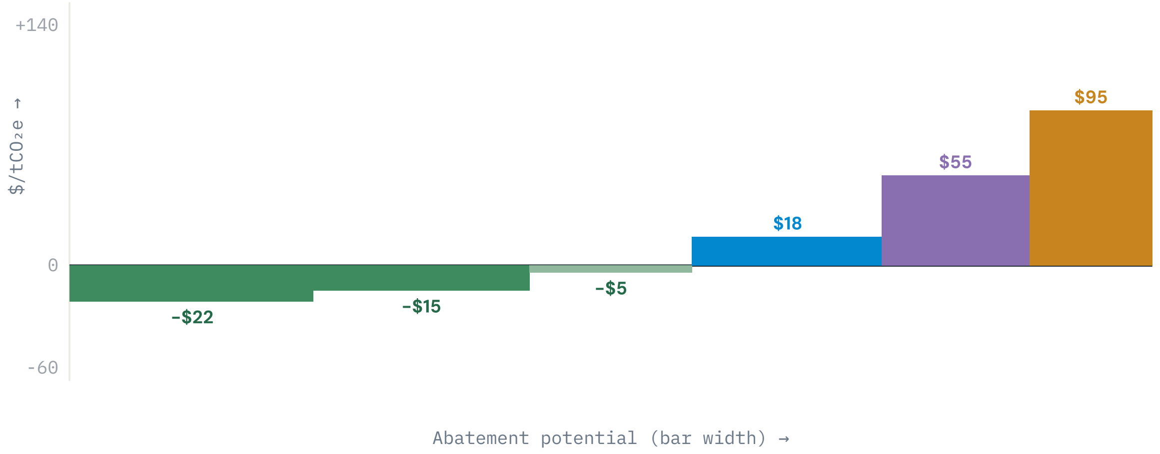
Roads & highways

Roads are **embodied-dominated**: most whole-life carbon is in pavement materials and earthworks, with operational carbon from lighting and 40-year maintenance cycles. Whole-life carbon runs **~800–2,700 tCO_2e/km** depending on scale (single-2-lane to dual-3).[76] The cheapest cuts — reclaimed asphalt and recycled aggregate — are *cost-negative*.

INFRASTRUCTURE 01 — ASPHALT & CONCRETE PAVEMENT, EARTHWORKS, LIGHTING

MACC: Roads & highways

Levers ordered cheapest-first. Below the line = net cost-saving; above = $\$/tCO_2e$ premium. Bar width ≈ abatement potential. Values indicative.



🟩 Reclaimed asphalt pavement **-$22** 🟩 Recycled aggregate sub-base **-$15**

🟩 Warm-mix asphalt **-$5** 🟦 Lower-clinker concrete **+$18** 🟪 Electrified paving fleet **+$55**

🟧 Bio/HVO plant fuel **+$95**

WHOLE-LIFE CARBON

800–2,700 tCO_2e/km

single-2 to dual-3 lane

BUILD COST

$2–10 M/km

varies by lanes & terrain

ABATEMENT AT NO COST

~15–25%

via recycled materials

Read: Roads are the clearest **cost-negative** case: reclaimed asphalt and recycled crushed concrete *reduce* material spend while cutting carbon (Infrastructure Australia).[5] The premium tonnes (fleet electrification, bio-fuels) wait until grids and HVO supply mature.

INFRASTRUCTURE 02

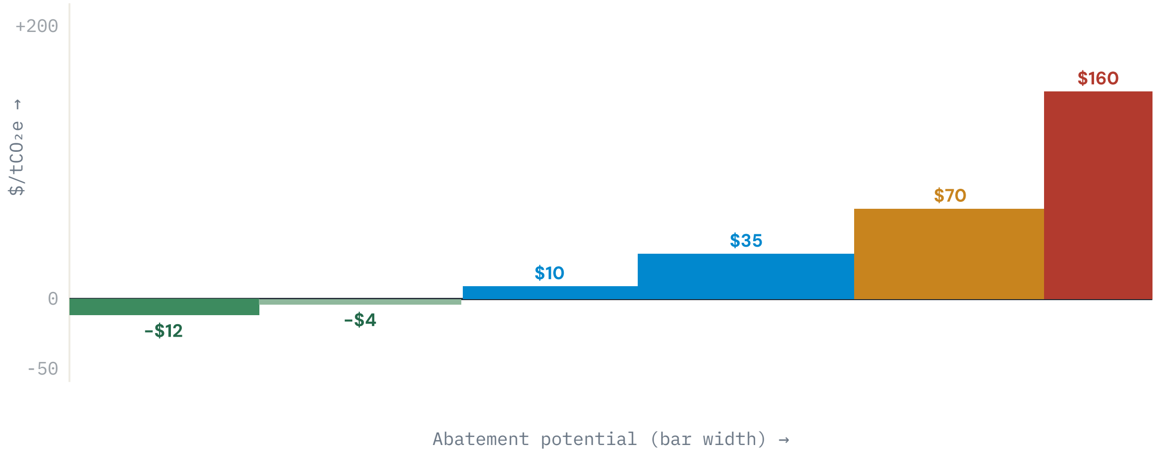
Bridges & elevated structures

Bridges are the most **embodied-dominated** infrastructure — nearly all carbon is in structural concrete and steel, with negligible operational energy. Span choice and material strength dominate: lower concrete grades and steel right-sizing cut carbon at little or no cost; green steel and low-carbon concrete carry a modest premium.[82]

INFRASTRUCTURE 02 — STEEL/CONCRETE SPANS, PIERS, DECKS

MACC: Bridges & elevated structures

Levers ordered cheapest-first. Below the line = net cost-saving; above = $/$tCO_2e$ premium. Bar width ≈ abatement potential. Values indicative.



🟩 Structural-steel right-sizing **-$12** 🟩 Optimized concrete grade **-$4**

🟦 Recycled-content rebar **+$10** 🟦 Low-carbon concrete mix **+$35** 🟧 Green ($H_2$/EAF) steel **+$70**
🟥 Novel cement / CCS **+$160**

EMBODIED CARBON	BUILD COST	DESIGN-STAGE SAVING
~0.5–2.5 tCO_2e/m^2 deck	**$1,000–4,000/m² deck**	**~10–20%**
span & type dependent	steel vs concrete	material optimization

Read: Because operational carbon is near zero, a bridge's whole-life answer is set **entirely at design**. Site/span selection alone can swing embodied carbon materially (BSCES);[82] green steel is the big-ticket residual lever.

INFRASTRUCTURE 03

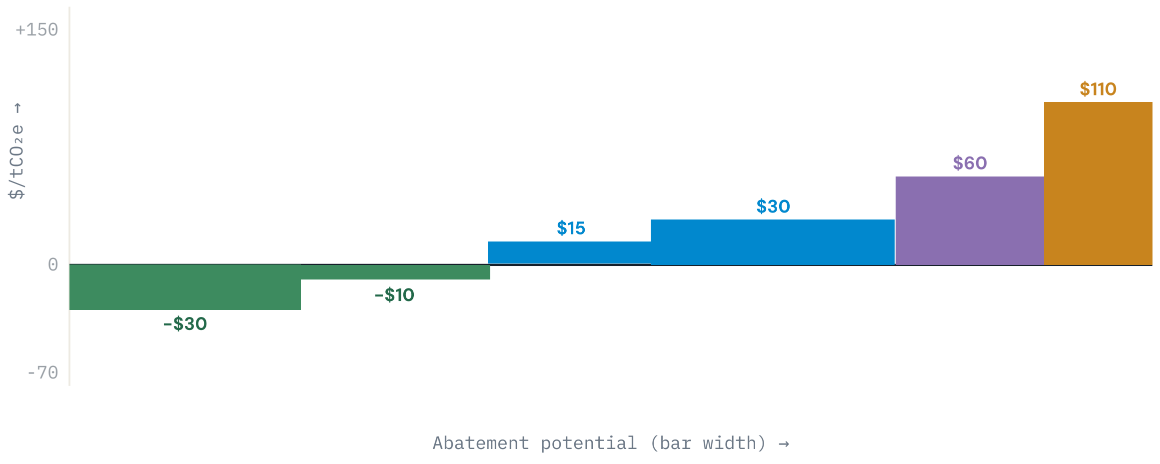
Water supply & treatment

Water shifts toward **operational dominance**: pumping and treatment electricity over decades outweigh the embodied carbon of pipes and plant concrete. The master lever is therefore **clean grid power + pump efficiency**; embodied cuts come from low-carbon pipe materials and concrete.[5]

INFRASTRUCTURE 03 — PIPES, PUMPS, TREATMENT PLANTS, RESERVOIRS

MACC: Water supply & treatment

Levers ordered cheapest-first. Below the line = net cost-saving; above = $/tCO_2e$ premium. Bar width ≈ abatement potential. Values indicative.



🟩 Pumps & system efficiency **−$30** 🟩 Pressure/leakage management **−$10**

🟦 Low-carbon pipe materials **+$15** 🟦 Clean grid power (PPA) **+$30** 🟪 On-site solar + storage **+$60**

🟧 Electrified process heat **+$110**

OPERATIONAL CARBON	TREATMENT COST	PLANT CAPEX
~0.3–0.7 $kgCO_2e/m^3$	**$0.3–1.5/$m^3$**	**$1–4 M/ML/day**
grid-dependent	source & standard	capacity dependent

Read: Efficiency is genuinely **cost-negative** — every kWh saved cuts both the power bill and the operational carbon. The grid factor is decisive: the same plant's operational carbon varies ~6× across regions (see regional exhibit).

INFRASTRUCTURE 04

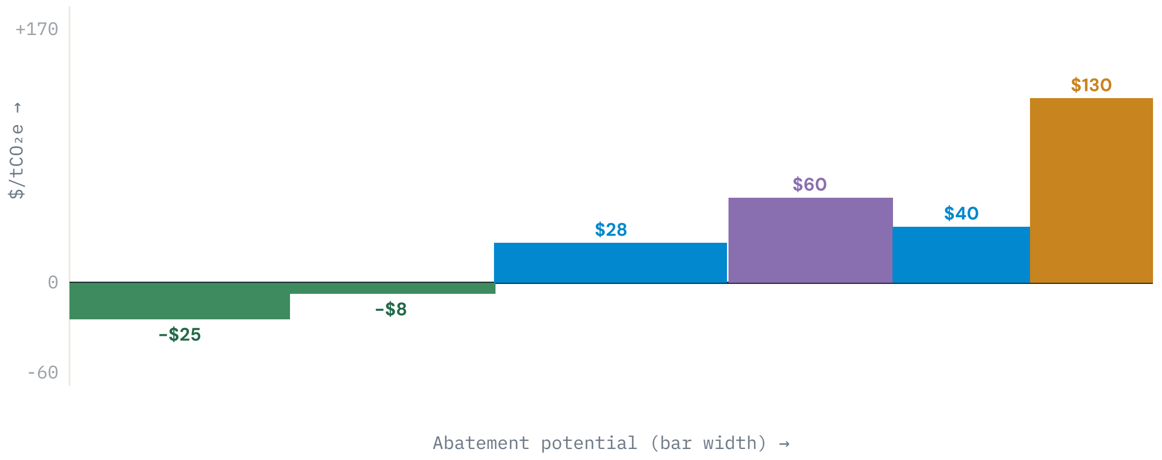
Wastewater & sewerage

Wastewater is strongly **operational-dominated**, with a twist: aeration electricity *and* direct **process emissions** (CH_2 and N_2O from treatment) that no grid greening touches. The curve mixes energy levers with process-control and biogas-capture levers.[5]

INFRASTRUCTURE 04 — COLLECTION, TREATMENT, BIOSOLIDS, AERATION

MACC: Wastewater & sewerage

Levers ordered cheapest-first. Below the line = net cost-saving; above = $/$tCO_2e$ premium. Bar width ≈ abatement potential. Values indicative.



🟩 Aeration control / efficiency **−$25** 🟩 Biogas capture & CHP **−$8** 🟦 Clean grid power (PPA) **+$28**

🟪 N_2O process optimization **+$60** 🟦 Low-carbon plant concrete **+$40**

🟧 Sludge-to-energy / pyrolysis **+$130**

OPERATIONAL CARBON	TREATMENT COST	ENERGY SELF-SUFFICIENCY
~0.5–1.2 $kgCO_2e/m^3$	**$0.5–2/m³**	**up to ~100%**
incl. process N_2O/CH_2	standard dependent	via biogas CHP

Read: Biogas capture can make a plant **energy-positive** — a cost-negative lever that also displaces grid power. Process N_2O is the hard residual: high GWP, no cheap fix, a prime target for measurement & control.

INFRASTRUCTURE 05

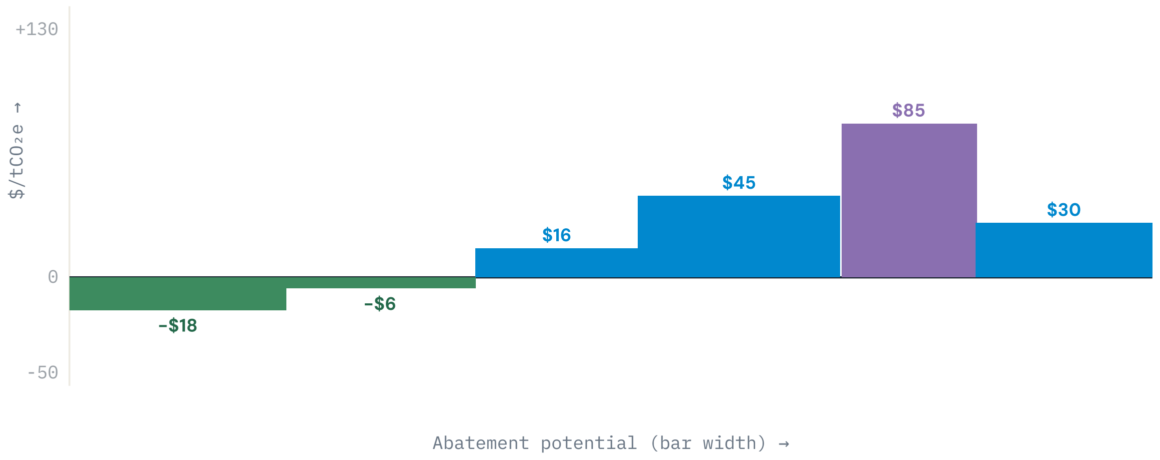
Electricity transmission & distribution

T&D is a **mixed** profile: embodied carbon in steel towers, aluminium conductor and concrete foundations, plus operational carbon from **line losses** (energy dissipated over decades, valued at the grid factor). Lower-loss conductors and recycled steel/aluminium lead the curve.[5]

INFRASTRUCTURE 05 — LINES, SUBSTATIONS, TRANSFORMERS, TOWERS

MACC: Electricity transmission & distribution

Levers ordered cheapest-first. Below the line = net cost-saving; above = $/tCO₂e premium. Bar width ≈ abatement potential. Values indicative.



🟩 Loss-optimized conductor sizing **-$18** 🟩 Recycled-content steel towers **-$6**

🟦 Low-carbon foundation concrete **+$16** 🟦 Low-carbon (recycled) aluminium **+$45**

🟪 SF_6-free switchgear **+$85** 🟦 Clean power for losses **+$30**

EMBODIED CARBON

~150–400 tCO_2e/km

voltage dependent

BUILD COST

$0.5–3 M/km

overhead vs underground

LOSS FACTOR

~2–6% of throughput

over line life

Read: Aluminium conductor is the embodied hotspot — recycled or renewable-powered aluminium is the key materials lever (ties to the aluminium brief). Line losses convert directly to operational carbon at the local grid factor, so low-loss design pays twice.

INFRASTRUCTURE 06

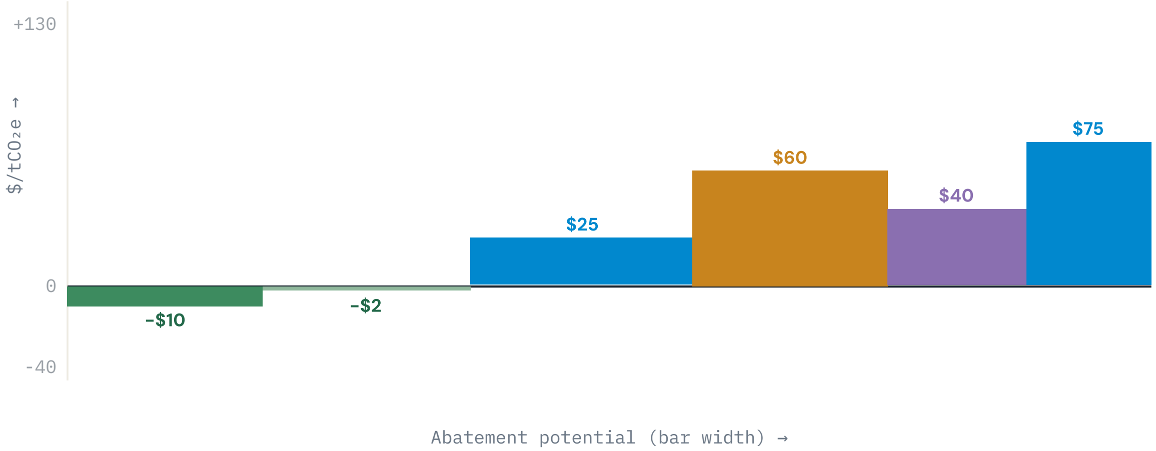
Power generation build-out

For the *physical build* of generation, carbon is **embodied** in foundations, towers and equipment — operational carbon belongs to the fuel, not the structure. Embodied intensity per kWh delivered: wind ~10–15 g, solar ~40–70 g (life-cycle), so the lever set is concrete, steel and panel/turbine supply chains.[102]

INFRASTRUCTURE 06 — TURBINES, FOUNDATIONS, SWITCHGEAR (THE PHYSICAL PLANT)

MACC: Power generation build-out

Levers ordered cheapest-first. Below the line = net cost-saving; above = $/$tCO_2e$ premium. Bar width ≈ abatement potential. Values indicative.



🟩 Foundation concrete optimization **-$10** 🟩 Recycled steel tower/rebar **-$2**

🟦 Low-carbon concrete mix **+$25** 🟧 Low-carbon module/turbine supply **+$60**

🟪 Circular end-of-life design **+$40** 🟦 On-site clean construction power **+$75**

EMBODIED (WIND)
~10–15 $\mathrm{gCO_2e}$/kWh
life-cycle

EMBODIED (SOLAR)
~40–70 $\mathrm{gCO_2e}$/kWh
life-cycle

BUILD COST
~$1,000–1,600/kW
onshore wind / utility PV

Read: The build-out's own footprint is small per kWh but scales with the gigawatts deployed for the transition. Foundation concrete is the single biggest embodied item — low-carbon mixes are the highest-leverage materials lever.

INFRASTRUCTURE 07

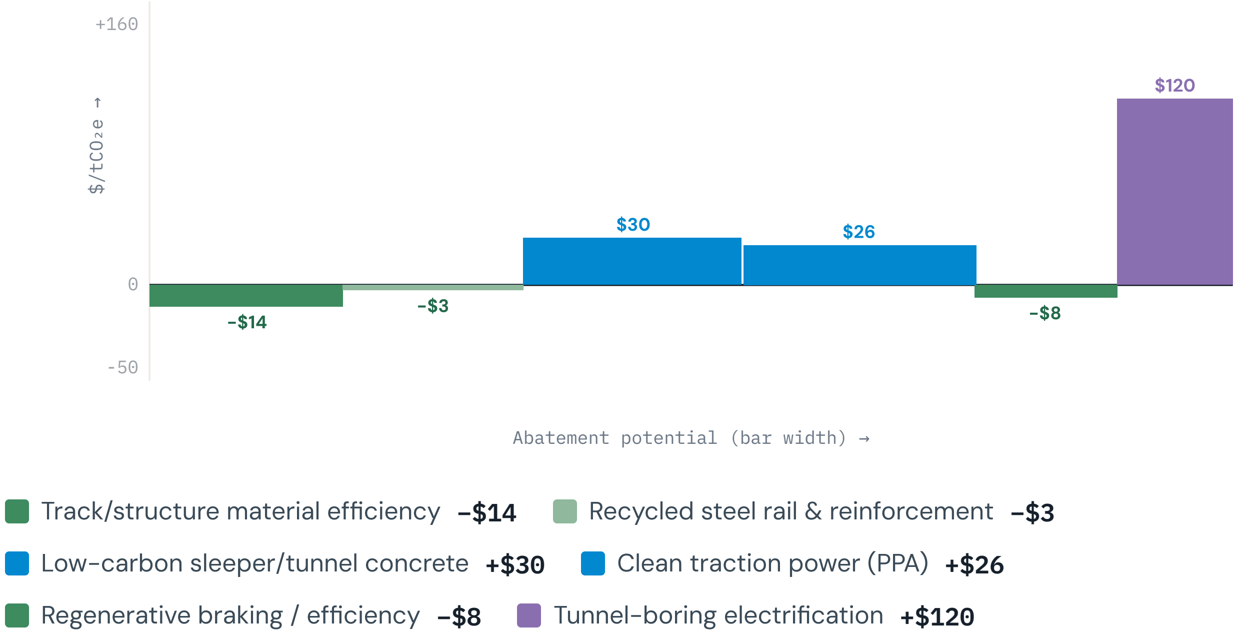
Rail & transit

Rail is **operational-leaning** once electrified (traction power over decades), but with heavy **embodied** carbon in track steel, concrete sleepers, ballast and especially tunnels/viaducts. The curve pairs materials levers with traction-power decarbonization.[78]

INFRASTRUCTURE 07 — TRACK, BALLAST, ELECTRIFICATION, DEPOTS, TUNNELS

MACC: Rail & transit

Levers ordered cheapest-first. Below the line = net cost-saving; above = $/tCO₂e premium. Bar width ≈ abatement potential. Values indicative.



EMBODIED CARBON

~1–5 ktCO$_2$e/km

at-grade to tunneled

BUILD COST

$10–200 M/km

at-grade vs tunnel

OPERATIONAL (ELECTRIC)

grid-factor × traction kWh

decades of use

Read: Tunnels and viaducts dominate embodied carbon — alignment choices (avoiding tunneling) are the largest single lever, set at planning. Electrified traction shifts the asset onto the grid's decarbonization curve.

INFRASTRUCTURE 08

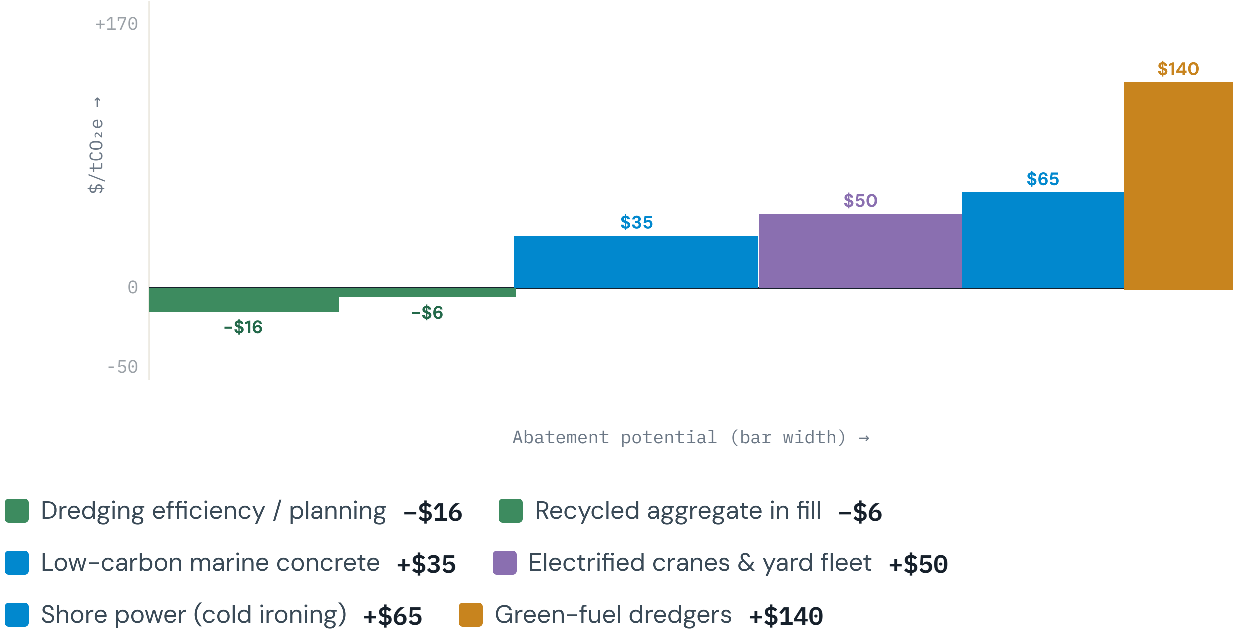
Ports & marine

Ports are **embodied-dominated** by huge volumes of marine concrete and steel sheet-piling, plus the fuel/energy of **dredging** and yard equipment. Marine concrete (durability-driven, high cement) is the hotspot; equipment electrification (cranes, yard tractors) leads the operational cuts.[5]

INFRASTRUCTURE 08 — QUAYS, BREAKWATERS, DREDGING, CONTAINER YARDS

MACC: Ports & marine

Levers ordered cheapest-first. Below the line = net cost-saving; above = $/tCO$_2$e premium. Bar width ≈ abatement potential. Values indicative.



EMBODIED CARBON

~0.3–0.8 $\text{tCO}_2\text{e/m}^2$ quay

marine concrete heavy

BUILD COST

$5,000–15,000/m quay

ground & depth dependent

ELECTRIFICATION

~40–60% of op. carbon

crane + yard fleet

Read: Marine concrete's durability requirement keeps cement content high — low-carbon marine mixes are technically harder but high-impact. Shore power moves berth emissions onto the grid, compounding with grid greening.

INFRASTRUCTURE 09

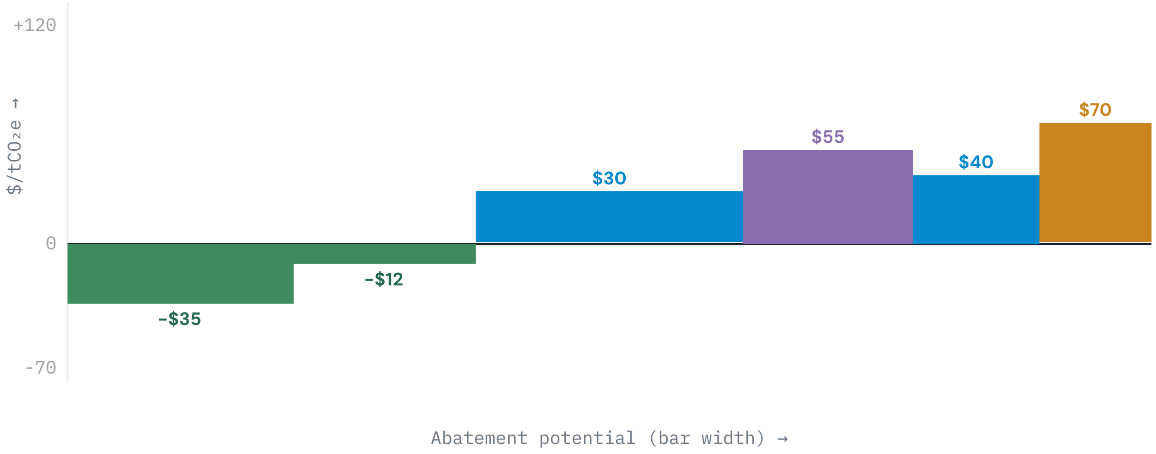
Telecom & data centers

Data centers are the extreme **operational-dominated** case — the building shell is only ~7% of lifetime emissions; the rest is **electricity** for compute and cooling.[105] The curve is overwhelmingly about clean power and efficiency (PUE), with embodied levers (low-carbon shell, server lifetime) as the minority.

INFRASTRUCTURE 09 — SERVER HALLS, COOLING, FIBER, TOWERS

MACC: Telecom & data centers

Levers ordered cheapest-first. Below the line = net cost-saving; above = \$/tCO_2e premium. Bar width ≈ abatement potential. Values indicative.



🟩 Cooling/PUE efficiency **-\$35** 🟩 Server lifetime extension **-\$12**

🟦 Clean power PPA / 24-7 CFE **+\$30** 🟪 On-site solar + storage **+\$55**

🟦 Low-carbon shell concrete/steel **+\$40** 🟧 Waste-heat reuse **+\$70**

OPERATIONAL CARBON

grid-factor × PUE × load

~1.1–1.5 PUE

BUILD COST

\$7–15 M/MW

Tier III, incl. M&E

EMBODIED SHARE

~7–12% of lifetime

shell + capital goods

Read: Because operational carbon dwarfs embodied, **where you site it** (the grid factor) is the dominant lever — the same MW emits ~6× more on a coal grid than on Brazil's or France's. Efficiency (PUE, server life) is cost-negative; clean-power procurement is the strategic spend.

INFRASTRUCTURE 10

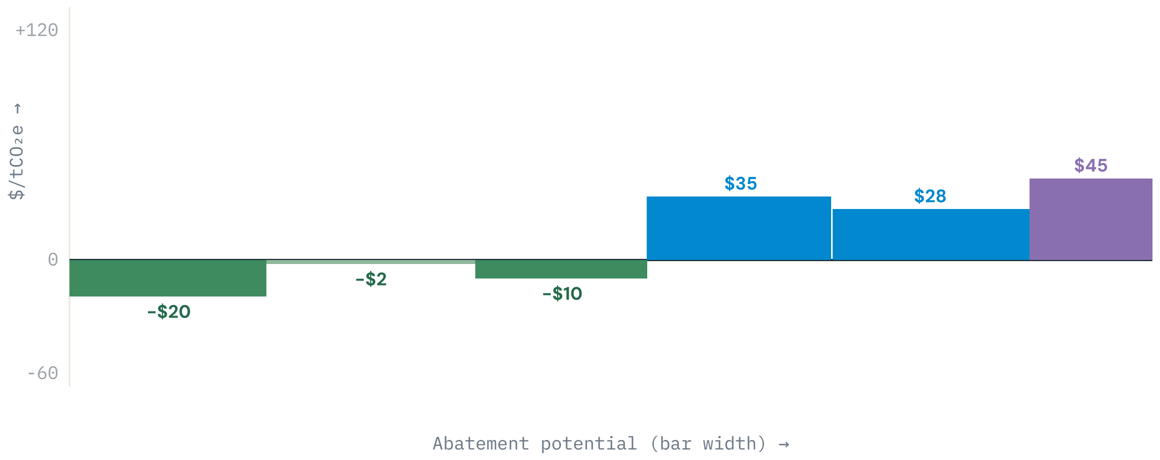
Buildings / social infrastructure

Social buildings are **balanced**: roughly half embodied (frame, envelope) and half operational (HVAC, lighting, plug loads) over a long life. RMI/CLF case studies show low-embodied-carbon design is often achievable at **no cost premium**; operational cuts come from efficiency and clean power.[80,83]

INFRASTRUCTURE 10 — SCHOOLS, HOSPITALS, PUBLIC STRUCTURES (CONCRETE + STEEL FRAME)

MACC: Buildings / social infrastructure

Levers ordered cheapest-first. Below the line = net cost-saving; above = \$/tCO$_2$e premium. Bar width ≈ abatement potential. Values indicative.



🟩 Structural material efficiency **-\$20** 🟩 Low-carbon concrete & recycled steel **-\$2**

🟩 Envelope / passive design **-\$10** 🟦 Heat-pump electrification **+\$35**

🟦 Clean grid power (PPA) **+\$28** 🟪 Mass timber substitution **+\$45**

EMBODIED CARBON

~300–700 kgCO$_2$e/m^2

frame & envelope

BUILD COST

\$2,000–6,000/m^2

hospital › school

OPERATIONAL

~10–40 kgCO$_2$e/m^2/yr

grid & efficiency

Read: The RMI finding is the headline: low-embodied-carbon buildings frequently cost **the same or less** when material efficiency is pursued early.[83] Heat-pump electrification plus clean power closes the operational half.

REGIONAL MULTIPLIER

The same asset, seven carbon footprints

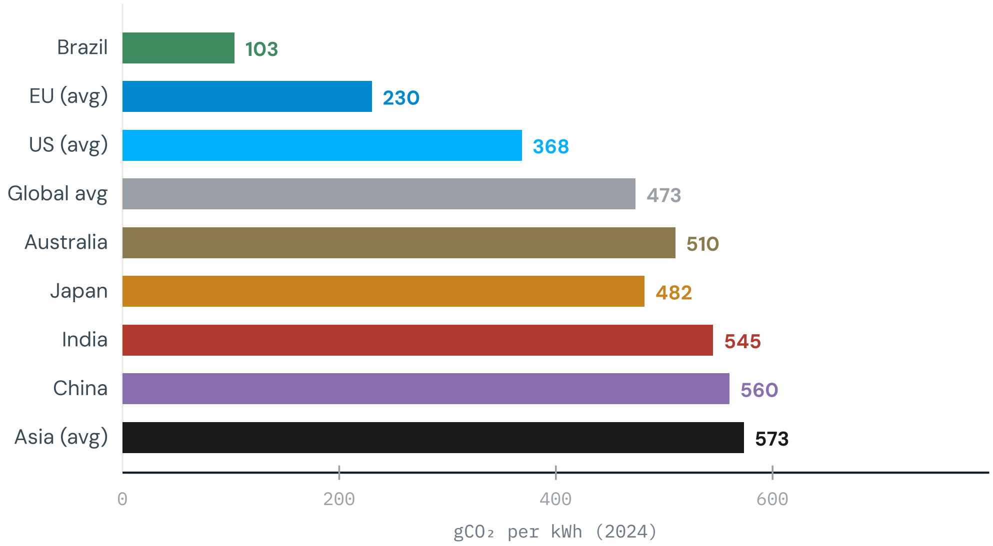
Identical infrastructure carries very different carbon depending on *where* it is built and operated. Two regional factors drive it: the **grid carbon intensity** (which sets operational carbon and the carbon of any electrified equipment) and the **material**

carbon intensity (local cement and steel, which set embodied carbon). A data center in Brazil and one in coal-heavy Asia can differ **5×** in operational carbon for the same design.

REGIONAL — GRID CARBON INTENSITY, 2024 (GCO₂/KWH)

The grid map: operational-carbon multiplier

Lower = cleaner operational carbon and cleaner electrified-equipment abatement. Global average ~473; falling ~3.6%/yr to ~400 by 2027.



Read: Operational carbon — and the carbon benefit of electrifying any fleet or process — scales directly with these numbers. The same electrified paving fleet or pumping station abates far more in **Brazil (~103)** or the **EU** than in **coal-heavy Asia (~573)**, where electrification can even *raise* emissions until the grid cleans up.

Source: Ember Global Electricity Review 2025 (Brazil 103, Japan 482, China 560, Asia 573, global 473);[92] IEA Electricity 2025 (global 445→400 by 2027);[95] US/EU/India/Australia from Ember & Enerdata.[92,97]

THE TWO-FACTOR REGIONAL RULE OF THUMB

Operational carbon follows the grid map above — build power-hungry assets (data centers, water/wastewater pumping, electrified rail) where the grid is clean (Brazil, EU, hydro-rich regions). **Embodied carbon** follows local cement and steel intensity — CBAM-style border pricing and Buy Clean rules are now making low-clinker concrete and recycled/green steel a procurement requirement in the EU and parts of the US, while India and parts of Asia carry higher default material intensities. The cost-negative recycled-material levers work *everywhere*, regardless of grid.

REGIONAL — HOW THE LEVERS SHIFT BY REGION

Which lever leads, by region

The cheapest high-impact lever differs by region's grid and material context. Recycled materials lead everywhere; electrification leads only where grids are clean.

REGION	GRID	LEADING LEVER
Brazil	clean (103)	Electrify everything + recycled materials
EU	low (~230)	Low-clinker concrete (CBAM) + electrify
US	moderate (~368)	Recycled materials (Buy Clean) + green steel
Japan	moderate (482)	Material efficiency + recycled steel
Australia	high (510)	Recycled aggregate/asphalt (cost-negative)
India	high (545)	Low-clinker (LC3) + material efficiency
Asia (coal)	high (573)	Recycled materials first; electrify later

Read: In clean-grid regions, electrifying fleets and processes is a top lever; in coal-heavy grids, the same move waits behind recycled materials and efficiency, which save carbon regardless of the grid. CBAM (EU) and Buy Clean (US) are turning low-carbon materials from option into requirement. **Source:** grid values per Ember;[92] lever logic per Infrastructure Australia & GCCA.[5,86]

RESEARCH TOOL

How CarbonSig is used as an infrastructure research tool

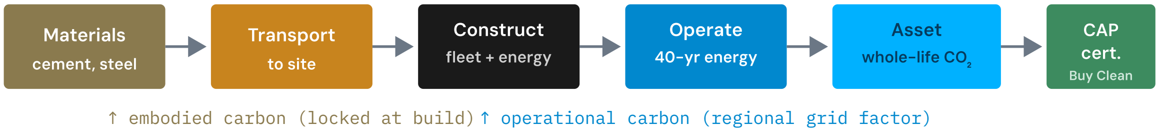
Every curve in this report is a *generic* answer. A real project — this highway, in this region, with this concrete supplier — needs its own curve. CarbonSig is the tool that builds it: a digital twin of the infrastructure asset where each material, fuel and process is a node carrying its own carbon factor, so a planner can **test a lever and watch carbon, cost and $/tCO_2e re-price instantly** — the MACC, computed live for the actual bill of materials.

RESEARCH TOOL — CARBONSIG MODELING STACK FOR AN INFRASTRUCTURE BUILD

From a generic MACC to your project's curve

A process-flow canvas mirroring the real build chain — resolved up from material to asset to portfolio and out to a verified certificate (CAP), with embodied + operational and regional grid factors captured natively.

PROCESS-FLOW CANVAS — materials & processes chain into the finished asset



FOUR RESOLUTIONS

MATERIAL / COMPONENT
Swap a concrete mix or steel grade (ISO 14067 / EPD) — compare OPC vs low-clinker, virgin vs recycled, per m³ or per tonne

ASSET / PROJECT
Build the whole road / bridge / data center; get its live MACC & whole-life carbon per functional unit ($/km, $/MW, $/m³)

PORTFOLIO / PROGRAM
Roll many assets into a capital program; rank projects by abatement-per-dollar; test against a regional grid & carbon-price path

MARKET / COMPLIANCE
Issue a verified CAP for the asset — the Buy Clean / CBAM / EPD evidence made auditable and tradable

Alternatives engine
Swap any node (OPC→low-clinker, virgin→recycled steel, diesel→electric fleet, grid by region) → re-price carbon, cost & $/t$CO_2$e.

How it maps to this report: every lever in the ten curves becomes an editable node; embodied vs operational (cross-sector exhibit) and the regional grid factor (regional map) are built in; the output is the project's own MACC plus an auditable, Buy-Clean/CBAM-ready certificate. **CarbonSig platform notes** — any value chain digitally twinned with PCF/CI, CAP certificates, scenario modeling & 3rd-party verification.[12]

What a planner, contractor or owner does with it

- **Build the asset model.** Assemble the materials→transport→construct→operate chain as connected nodes; enter the real concrete mix, steel source, fleet fuel and the *regional* grid factor; get whole-life carbon per functional unit ($/km, $/MW, $/m³, $/m²).

- **Generate the project's own MACC.** Toggle each lever — recycled aggregate, low-clinker concrete, green steel, electrified fleet, clean-power PPA — and watch carbon, cost and $/t$CO_2$e re-rank. The generic curves in this report become *your* curve for *your* bill of materials.

- **Rank a portfolio.** Compare projects by abatement-per-dollar; find the cost-negative tonnes first; stress-test against a carbon price or a Buy Clean threshold before procurement closes.
- **Issue the proof.** Turn the verified footprint into a Carbon Attested Product (CAP) — the EPD/Buy-Clean/CBAM evidence that wins low-carbon-procurement bids and survives third-party assurance.

> **The synthesis.** Every infrastructure type has a cost-negative band of carbon to cut before any premium is paid — but the exact curve depends on the asset, the materials and the region. CarbonSig is the research tool that computes that specific curve, turns the generic findings of this report into a project decision, and issues the certificate that makes a verified low-carbon asset worth more than its high-carbon twin.

CARBON-NEUTRAL INFRASTRUCTURE

Closing the gap: removals, ISO 14068, and the cost of neutral

The ten cost curves answer "how far can we cut?" They never reach zero — every asset has a **residual** of embodied carbon (calcination CO_2 in cement, process emissions in steel) that no material substitution removes. The correct accounting standard for closing that last gap is **ISO 14068-1:2023**, which defines carbon neutrality through a strict hierarchy: *reduce first, enhance removals second, and offset only the residual* — increasingly with durable **removal** credits, not avoidance offsets.[13,14] Pair the MACC (reduce) with a removal instrument (neutralize the residual) and an infrastructure asset can be made **verifiably carbon-neutral** — at a calculable, and falling, premium.

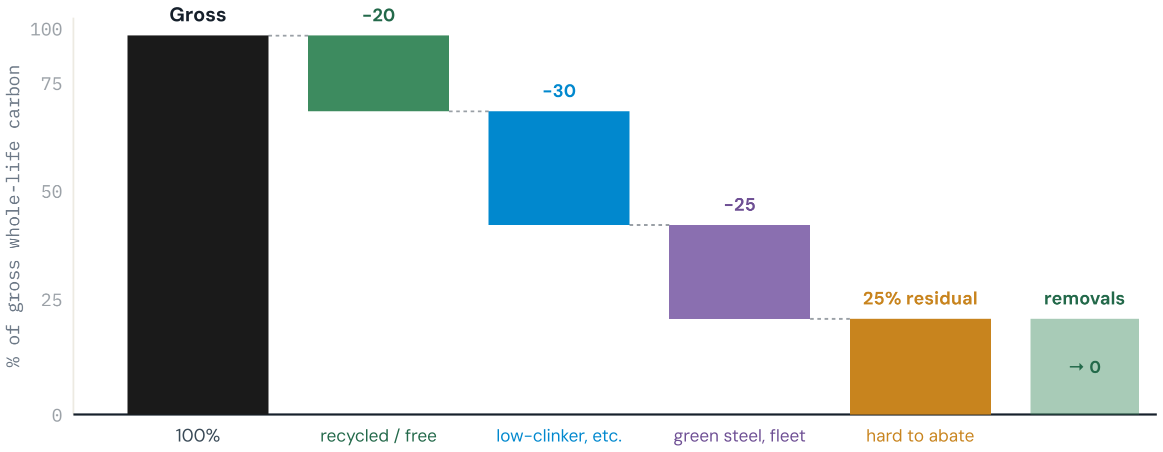
> **The argument in one breath.** A road, bridge or data center that has exhausted its cost-negative and low-premium levers still emits a residual. Under ISO 14068-1:2023 that residual may be neutralized with high-quality carbon credits — and the standard pushes buyers toward **permanent removals**. The cost depends entirely

> on the instrument: nature-based removals run **$6–50/t**, biochar **~$125–180/t**, enhanced weathering **~$200/t**, BECCS **~$390/t**, and **direct air capture (DAC) ~$300–600/t** today.[15,16,17] Because the residual after a good MACC is small, even premium DAC adds a *bounded, modelable* cost — and CarbonSig computes the least-cost blend of reduction + removal that reaches neutral.

VISUALIZATION 1 — THE PATH FROM GROSS TO NET-ZERO CARBON

The neutralization stack: reduce, then remove the residual

Gross embodied + operational carbon → MACC levers cut most of it → durable removals neutralize the residual → ISO 14068 carbon-neutral. Indicative shares.



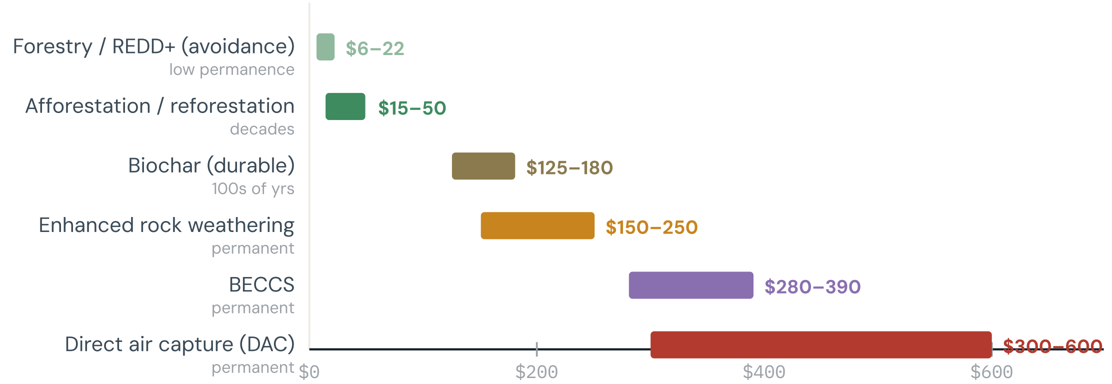
ISO 14068 hierarchy: reduce as far as the MACC allows, then remove the residual — offsetting is the last step, not the first.

Read: The MACC does the heavy lifting (here ~75% cut); durable removals neutralize only the ~25% residual that material and energy levers cannot reach. A smaller residual means a smaller removal bill — so spending on reduction first is what makes neutrality affordable. **Source:** ISO 14068-1:2023 hierarchy (iso.org);[13] cement calcination ~40–50% of concrete CO_2 is process-inherent.[86] Shares indicative.

VISUALIZATION 2 — COST PER TONNE OF CARBON REMOVED, BY INSTRUMENT (2025)

The removal cost ladder — where DAC sits

$/t$CO_2$e to neutralize a residual tonne. ISO 14068 favors permanent removals (biochar → DAC) over cheap avoidance offsets. DAC is the priciest but most durable & scalable.

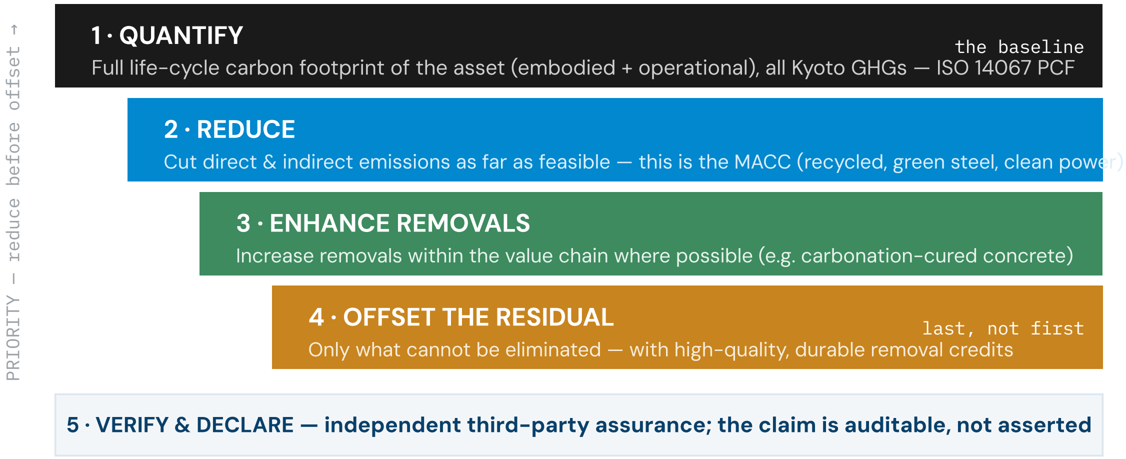


Read: Cheap nature-based offsets ($6–50) carry permanence risk; ISO 14068 steers neutrality claims toward *durable removals*. **DAC at ~$300–600/t** is the most expensive but offers permanence, scalability and verifiability — the gold-standard tonne for a credible carbon-neutral asset. **Sources:** Sylvera 2026 (ARR $22, biochar $177, ERW $200+, BECCS $389, DAC $500+);[17] IEA & ETH Zürich DAC $230–630 scaled (ETH 2024);[15,16] Puro.earth CORC biochar index ~$125–145 (2025).[17]

VISUALIZATION 3 — THE ISO 14068-1:2023 CARBON-NEUTRALITY HIERARCHY

The accounting standard that makes "neutral" mean something

ISO 14068-1:2023 (successor to PAS 2060) requires reductions and removals *before* offsetting, a full life-cycle boundary, and independent verification — the guardrail against greenwashed neutrality.



1 · QUANTIFY
Full life-cycle carbon footprint of the asset (embodied + operational), all Kyoto GHGs — ISO 14067 PCF
`the baseline`

2 · REDUCE
Cut direct & indirect emissions as far as feasible — this is the MACC (recycled, green steel, clean power)

3 · ENHANCE REMOVALS
Increase removals within the value chain where possible (e.g. carbonation-cured concrete)

4 · OFFSET THE RESIDUAL
Only what cannot be eliminated — with high-quality, durable removal credits
`last, not first`

5 · VERIFY & DECLARE — independent third-party assurance; the claim is auditable, not asserted

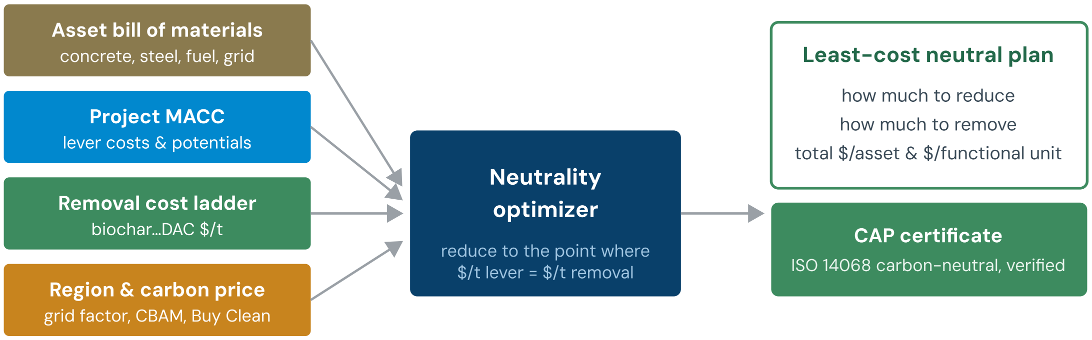
Read: ISO 14068 is what separates a defensible "carbon-neutral road" from a greenwash. Offsetting is permitted *only* for the residual that survives reduction and in-boundary removals, and the standard pushes the credit mix toward permanent removals over time. **Source:** ISO 14068-1:2023 (iso.org/standard/43279);[13] hierarchy & residual-only offsetting per ISO preview & Seedling/ECA summaries (Seedling 2026).[14]

VISUALIZATION 4 — HOW CARBONSIG MODELS THE COST OF REACHING NEUTRAL

CarbonSig: solving for the least-cost path to carbon-neutral

The platform stacks the project MACC against the removal cost ladder and finds the cheapest blend of reduction + removal that satisfies ISO 14068 — the "neutrality optimizer."

INPUTS → CARBONSIG MODEL → OPTIMIZED OUTPUT



The optimizer's rule: keep reducing while a lever is cheaper than the removal it displaces; remove the rest.

If DAC is $400/t and a green-steel lever abates at $250/t, reduce with steel first; send only the true residual to DAC.

Read: Neutrality is an optimization, not a checkbox. CarbonSig sets the project's marginal abatement cost against the marginal removal cost and solves for the cheapest mix that reaches zero under ISO 14068 — then issues the verified CAP. As DAC and biochar costs fall, the model re-balances toward removals automatically. **Source:** method follows the MACC-vs-backstop logic (McKinsey);[72] CarbonSig CaRMa platform capabilities (digital twin, scenario modeling, CAP, ISO 14067/14068 alignment).[12]

VISUALIZATION 5 — WORKED EXAMPLE: A CARBON-NEUTRAL HIGHWAY BRIDGE

What neutral actually costs — one bridge, three removal choices

A mid-size highway bridge: ~2,500 tCO_2e gross, ~$25M build. MACC cuts ~60%; the ~1,000 t residual is neutralized at three price points. Illustrative.

STEP 1 — REDUCE (MACC)

Gross: **2,500 tCO_2e** · cost-negative + low-premium levers remove the first 60% at little or no net cost

STEP 2 — NEUTRALIZE THE 1,000 t RESIDUAL (ISO 14068)

INSTRUMENT	$/t	RESIDUAL COST	% OF BUILD
Biochar (durable)	**$150**	$150,000	**~0.6%**
BECCS	**$390**	$390,000	**~1.6%**
Direct air capture (DAC)	**$300–600**	$300,000–600,000	**~1.2–2.4%**

The headline:

Even with premium **DAC at $300–600/t**, neutralizing the residual of a well-reduced bridge costs roughly **1–2.4% of build cost** — a small premium for a verifiably carbon-neutral asset, and falling as DAC scales.

Read: Because the MACC removes ~60% first, the residual sent to removals is small — so even the most expensive durable tonne (DAC) lands the whole-asset neutrality premium at ~1–2.4% of build cost. Reduce hard, and neutral becomes affordable. **Sources:** bridge carbon & cost from CLF/IStructE benchmarks;[80,81] DAC $300–600/t (IEA, ETH Zürich);[15,16] biochar/BECCS prices (Sylvera 2026).[17] Figures illustrative for a mid-size bridge.

WHY THIS MATTERS FOR THE CARBON-AS-MONEY THESIS

Once an asset can be made **verifiably carbon-neutral** under ISO 14068 at a known, single-digit-percent premium, neutrality becomes a *procurement option with a price tag* — not an aspiration. The reduced-plus-removed asset earns the low-carbon premium, qualifies for Buy Clean / CBAM-aligned tenders, and carries a CAP certificate proving it. CarbonSig is where the reduction MACC and the removal ladder meet, so an owner can price neutral before breaking ground.

SOURCES & AUTHORITIES

References

1. **Infrastructure Australia** — *Embodied Carbon Projections for Australian Infrastructure and Buildings*: embodied carbon ~10% of national emissions (2023, upfront 7%); four of eleven material strategies net cost-saving (recycled crushed concrete, reclaimed asphalt, structural steel lightweighting, hydrated lime), one cost-neutral; pipeline upfront 37–64 $MtCO_2e$/yr. link [ref 5]

2. **Carbon Leadership Forum / RMI / Univ. of Washington** — *Embodied Carbon Pathways to 2050 (US)*; WBLCA Benchmark Study V2 (292 projects); SE 2050 database (1,000+ LCAs); low embodied carbon often achievable without cost premium. link [refs 4, 81]
3. **Global Cement & Concrete Association (GCCA) / Sustainability Atlas (2025–26)** — construction materials ~15% of global CO_2 (cement ~8%, steel ~7%); low-carbon cement green premium 10–25%; commercial low-carbon cements achieve 30–70% reductions vs OPC (OPC ~600–900 kg CO_2/t). [refs 3, 86]
4. **Ember** — *Global Electricity Review 2025*: 2024 grid intensity gCO_2/kWh — Brazil 103, EU low/declining, global avg 473, Japan 482, China 560, Asia avg 573. link [refs 1, 92]
5. **IEA** — *Electricity 2025* (global CO_2 intensity 445→400 g/kWh by 2027, -3.6%/yr); *Emissions Factors 2025*; data centres & transmission embodied + operational guidance. link [refs 2, 95, 102]
6. **Univ. of Strathclyde / Univ. of Leeds / Transport for the North** — whole-life carbon of roads ~800–2,700 tCO_2eq/km (single-2-lane to dual-3), embodied + 40-yr operational (lighting, maintenance). link [ref 76]
7. **Arup / IStructE** — *Embodied Carbon Priority Actions*: C30/37 concrete mix breakdown; concrete ~7.5–8% of anthropogenic CO_2; design efficiency as the most effective lever; reinforcement carbon depends on recycled steel content. [ref 80, 83]
8. **Low Carbon Concrete (UNSDSN / Springer / One Click LCA)** — SCMs (GGBS, fly ash, calcined clay/LC3), RCA, carbonation curing; 80% of concrete emissions from cement, 40–50% from calcination (not abatable by renewables); clinker reduction often saves capital cost; lifecycle costs down up to 15%. [ref 86]
9. **IEEE Spectrum / Schneider Electric / IEA** — data-center carbon: operations ~60% / embodied ~40% (incl. devices); core & shell ~6.6% of pre-power Scope 3; whole-life (embodied + operational) accounting; renewable PPAs as primary operational lever. [refs 102, 105]
10. **Rio Tinto / ESG Today / Sustainability Directory** — construction-fleet decarbonization proof points: renewable diesel (drop-in), battery-electric and green-hydrogen haul trucks; fleet electrification as a Scope 1 lever. [ref 78]
11. **McKinsey** — origin of the marginal abatement cost curve (MACC), 2007; ~25% of 2030 reductions from negative/near-zero-cost levers. link [ref 72]
12. **Enerdata** — world CO_2-intensity trends by region (US, EU, China, India, Brazil, Japan, Australia), 2024. link [ref 97]
13. **CarbonSig** — CaRMa platform: digital twin of any value chain (materials→transport→construct→operate→asset); PCF/CI, CAP certificates, Scope 1–3, scenario modeling, EPD / Buy Clean / CBAM alignment, 3rd-party verification. (Project files.) [ref 12]
14. **ISO 14068-1:2023** — *Climate change management — Transition to net zero — Part 1: Carbon neutrality*: defines carbon neutrality via the hierarchy reduce → enhance removals → offset residual only; life-cycle boundary, all Kyoto GHGs, independent verification; successor to PAS 2060. iso.org/standard/43279 [ref 13]
15. **ISO 14068 explainers** — Seedling, ECA Business Energy, Sphera, Tunley: hierarchy, residual-only offsetting, durable-removal preference, anti-greenwash framing. Seedling (2026); ECA. [ref 14]
16. **IEA** — *Direct Air Capture*: scaled operational DAC cost ~$230–630/t$CO_2$, depending on energy cost; CDR need ~85 Mt (2030) → ~980 Mt (2050). iea.org/reports/direct-air-capture-2022 [ref 15]
17. **ETH Zürich (Sievert, Schmidt & Steffen, 2024)** — projected DAC costs ~$230–540/t$CO_2$ at scale (vs current ~$600–1,000); solid-sorbent ~$374/t, liquid-solvent ~$341/t at 1 Gt/yr. ScienceDaily summary; Carbon Herald. [ref 16]
18. **Sylvera (2026) & Puro.earth / CDR.fyi (2025)** — removal-instrument price benchmarks: ARR ~$22, REDD+ ~$6, biochar ~$125–180, ERW ~$200+, BECCS ~$389, DAC >$500; durable-CDR order prices ~$320/t (2024). sylvera.com; OTCflow market outlook. [ref 17]

All ten abatement-cost curves and the cross-sector split are **indicative syntheses** normalized for cross-sector comparability: lever orderings and the cost-negative-band finding are grounded in the cited sources (notably Infrastructure Australia and CLF/RMI), but specific \$/tCO₂e values and abatement widths are illustrative and will vary by project, supplier, region and year. Headline figures (embodied ~10% of national emissions; ~15–25% abatement at zero/negative cost; 30–70% cement reductions; the regional grid-intensity values) are sourced as cited. This is a strategic-planning aid, not a substitute for project-level LCA — which is precisely the gap the CarbonSig research tool fills. Reference numbering preserves the source IDs used across the CarbonSig brief series.

STRATEGIC BRIEF · The infrastructure carbon curve · Ten MECE build-out types, each with its own MACC · Synthesis of Infrastructure Australia, CLF/RMI, GCCA, IEA & Ember (2022–2026) · Prepared for CarbonSig · Carbon as currency: the cheapest tonne is the one you design out before you build.