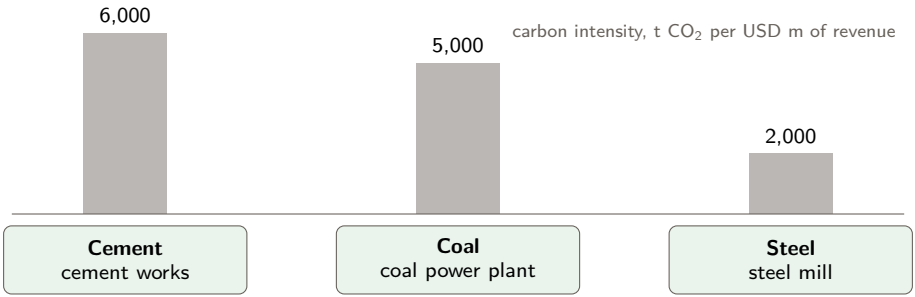
Portfolio decarbonisation at least tracking error

Mathematics of green finance risk management

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University of Twente

Cement, Coal and Steel by carbon intensity



The six-firm book holds six stylised firms, Coal, Cement, Steel, Port, Rice and Solar, each with emissions, revenue, EVIC and an equity volatility. An equal-weighted benchmark holds the six at 16.7 per cent each. A portfolio cuts the benchmark's WACI, its weighted average carbon intensity, by 50 per cent at the least tracking error, the volatility of its return over the benchmark's.

Rank Cement, Coal and Steel by the weight each one loses.

Stylised values.

Intensity, volatility and a target cut set a portfolio's weights

1. Compute a portfolio's financed emissions and WACI from holdings, EVIC, emissions and revenue
2. Compute the cut in WACI and the tracking error of a portfolio that excludes stocks
3. Derive the least-tracking-error weight change $\Delta w_i = -\kappa\,(c_i - m)/\sigma_i^2$ from the Lagrangian
4. Compute the intensity hurdle m and the least tracking error for a target cut
5. Explain why, of two stocks with the same intensity, the one of lower volatility loses more weight
6. Compute the intensity of a Paris-aligned path after t years and the year a long-only bound binds

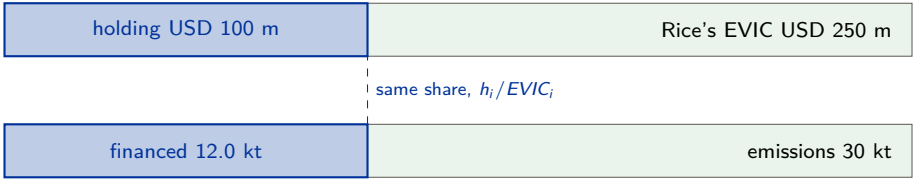
A portfolio's carbon intensity falls by a target at a cost in tracking error

1. How are a portfolio's emissions and carbon intensity counted?
2. How does a portfolio cut its WACI by half?
3. Which weights cut WACI at the least tracking error?
4. Which holdings pay as a Paris-aligned path compounds?

A portfolio's WACI is linear in its weights, so a target is one linear bound; the least-tracking-error weights solve a quadratic problem, and a Paris-aligned path tightens the bound yearly.

A holding finances its share of EVIC times the firm's emissions

1 2 3 4 **How are a portfolio's emissions and carbon intensity counted?**



PCAF attributes a listed firm's emissions to a holding by its share of the firm's EVIC, enterprise value including cash:

$$FE_i = \frac{h_i}{EVIC_i} E_i.$$

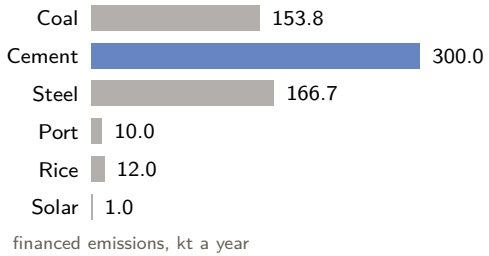
A private firm's share uses total equity and debt.

Stylised values.
PCAF (2025), Global GHG Accounting and Reporting Standard Part A, 3rd ed., section 5.2, p. 58, read 30 September 2026.

Cement has an EVIC of USD 1,000 m and emits 3.0 Mt a year. What does a holding of USD 100 m finance?

Financed emissions of the six holdings

firm	EVIC, USD m	E_i, Mt	$h_i E_i / EVIC_i$, kt
Coal	2,600	4.0	153.8
Cement	1,000	3.0	300.0
Steel	3,600	6.0	166.7
Port	1,500	0.15	10.0
Rice	250	0.03	12.0
Solar	400	0.004	1.0
six holdings of USD 100 m			644

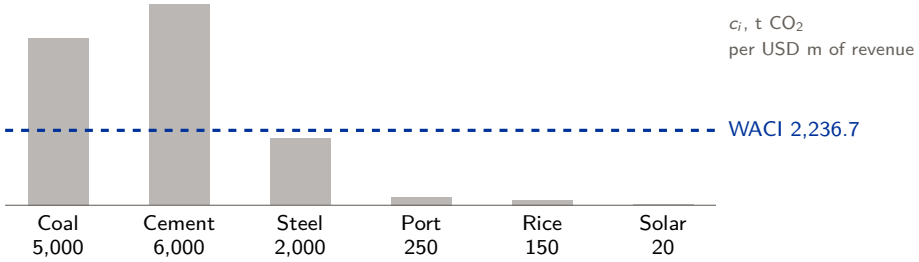


Each row is $h_i E_i / EVIC_i$ with h_i = USD 100 m. Cement finances the most, as a large share of a small EVIC.

Stylised values.

Coal's share price falls and its EVIC drops to USD 2,000 m, its emissions unchanged. What does the holding in Coal finance now?

WACI weights each firm's tonnes per USD m of revenue by its portfolio weight



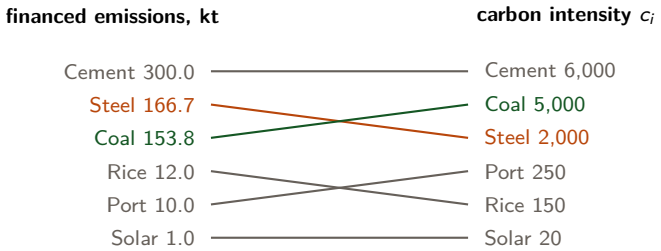
A firm's carbon intensity is $c_i = E_i/Rev_i$. TCFD allocates the tonnes by portfolio weights, so $\mathrm{WACI}(w) = \sum_i w_i c_i = c^\top w$. At 16.7 per cent each, the benchmark's WACI is the mean intensity: $13{,}420/6 = 2{,}236.7$.

Stylised values.

TCFD (2021), Implementing the Recommendations, Table 3, p. 52, read 30 September 2026.

A portfolio holds Steel, Port and Rice only, in equal weights. What is its WACI?

Financed emissions and carbon intensity rank Coal and Steel in opposite orders

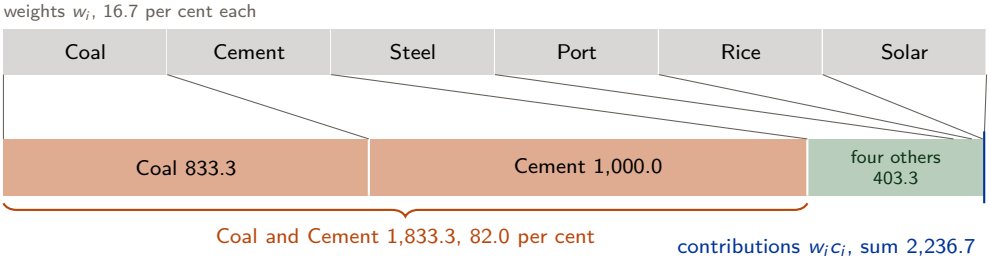


Financed emissions divide a firm's tonnes by its EVIC; intensity divides them by its revenue. Steel's EVIC of USD 3,600 m and revenue of USD 3,000 m put it second by tonnes financed and third by intensity, Coal the other way round. The orders answer two questions: how many tonnes the holdings pay for, and how carbon-heavy each dollar of sales is.

Stylised values.

Steel's revenue doubles at the same emissions and EVIC. Which of its two numbers changes, and to what value?

Cement and Coal contribute most of the benchmark's WACI between them



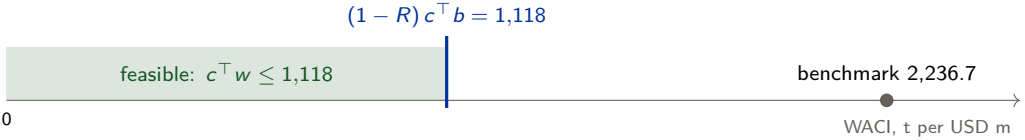
WACI is linear in the weights: firm i adds $w_i c_i$. At 16.7 per cent each, Cement adds 1,000.0 and Coal 833.3, together 1,833.3 of 2,236.7 t per USD m. A cut of half must come mostly out of these two.

Stylised values.

Sell Cement and leave the other five weights at 16.7 per cent. What do the five contributions add up to, and what do the weights sum to?

A target cut R turns WACI into a linear bound on the weights

1 2 3 4 **How does a portfolio cut its WACI by half?**



Roncalli writes the target as a constraint on the portfolio w against its benchmark b:

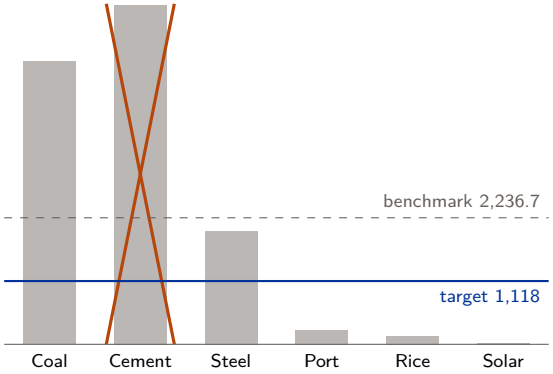
$$c^\top w \le (1-R)\,c^\top b.$$

The left side is linear in the weights w, so the portfolios that meet it fill a half-space.

Stylised values.
Roncalli, T. (2026), Handbook of Sustainable Finance, electronic version of 3 August 2026, CC BY 4.0, section 11.2 Portfolio decarbonization, p. 1063, read 1 October 2026.

What bound does a cut of 40 per cent set on the WACI of a portfolio against the book's benchmark?

WACI of the benchmark without Cement



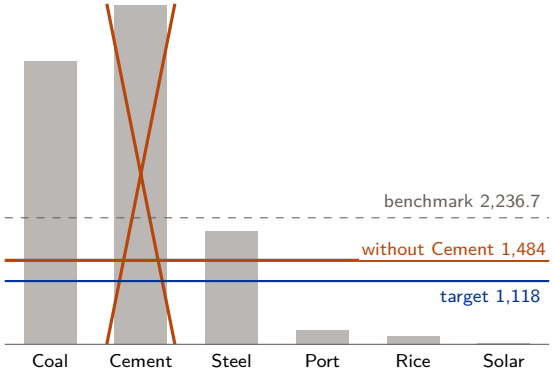
Cement is the most intensive of the six. Drop it and hold the other five at 20.0 per cent each.

Does the WACI fall by half?

Stylised values.

Drop Coal and hold the other five equally. What cut in WACI does that give?

WACI of the benchmark without Cement



Cement is the most intensive of the six. Drop it and hold the other five at 20.0 per cent each.

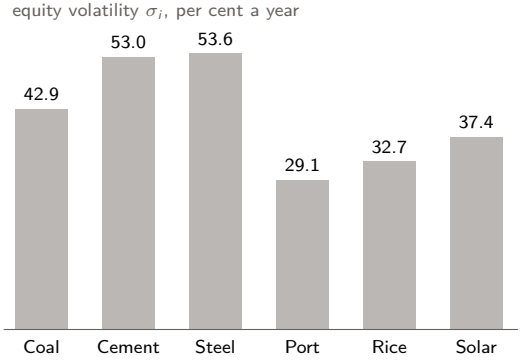
Does the WACI fall by half?

$c^\top w = (5{,}000 + 2{,}000 + 250 + 150 + 20)/5 = 1{,}484$, a cut of $1 - 1{,}484/2{,}236.7 = 33.7$ per cent against a target of 50.

Stylised values.

Drop Coal and hold the other five equally. What cut in WACI does that give?

Tracking error is the volatility of the portfolio's return over the benchmark's



Tracking error is the standard deviation of $r_w - r_b$:

$$TE = \sqrt{(w-b)^\top \Sigma\,(w-b)}.$$

With the six returns uncorrelated, Σ is diagonal and

$$TE^2 = \textstyle\sum_i \sigma_i^2\,(w_i - b_i)^2.$$

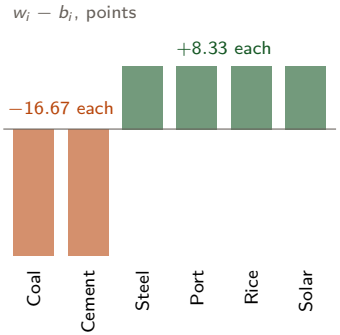
Each σ_i is a stock's equity volatility σ_E in the Merton (1974) model, $E\,\sigma_E = \Phi(d_1)\,\sigma_A V$, with V the firm's assets, σ_A their volatility and E its equity.

Stylised values.

A portfolio moves 10 points of weight from Port to Rice, the rest as the benchmark. What is its tracking error?

Tracking error of the benchmark without Cement and Coal

$$
\begin{aligned}
c^{\top} w &= (2{,}000 + 250 + 150 + 20)/4 = 605 \\
R &= 1 - 605/2{,}236.7 = 73.0\% \\
TE^2 &= 0.1667^2\,(0.429^2 + 0.530^2) \\
&\quad + 0.0833^2\,(0.536^2 + 0.291^2 + 0.327^2 + 0.374^2) \\
&= 0.1667^2 \times 0.4649 + 0.0833^2 \times 0.6188 \\
&= 0.01292 + 0.00429 = 0.01721 \\
TE &= 13.1\%
\end{aligned}
$$

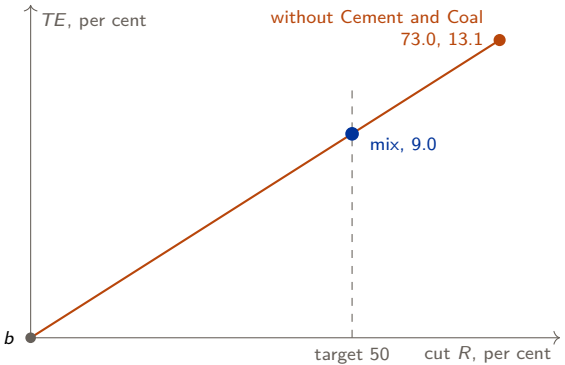


The four remaining stocks rise from the benchmark's 16.7 to 25.0 per cent each. The cut of 73.0 per cent passes the target of 50.

Stylised values.

What tracking error does dropping Cement alone give, with the other five at 20.0 per cent each?

A mix of benchmark and exclusion meets the target at lower tracking error



Hold a share t of the exclusion portfolio w_x and the rest in the benchmark: $w = b + t\,(w_x - b)$. Each weight change scales by t, and so do the cut, $t \times 73.0$ per cent, and the tracking error, $t \times 13.1$. Half needs $t = 50/73.0 = 0.685$, at a tracking error of 9.0 per cent.

Stylised values.
Exclusion of the worst issuers by carbon intensity: Andersson, Bolton and Samama (2016), in Roncalli (2026), section 11.2.

What share t of the exclusion portfolio cuts WACI by 30 per cent, and at what tracking error?

WACI and tracking error of four stocks and of the three without Gas

firm		EVIC USD m	emissions Mt a year	revenue USD m	equity volatility, %
Gas	gas power plant	1,200	2.4	600	30
Glass	glass works	400	0.6	200	40
Paper	paper mill	750	0.3	300	25
Wind	wind farm	600	0.012	150	35

USD 50 m in each of the four stocks, weights 25 per cent each; returns uncorrelated.

In pairs, eight minutes:

1. the financed emissions of each holding, and of the four together;
2. the benchmark's WACI;
3. the WACI and the cut R without Gas, the other three held equally;
4. the tracking error of that portfolio.

Stylised values.

Excluding Gas cuts WACI by less than half and costs tracking error

firm	financed, kt	c_i
Gas	$50 \times 2.4/1{,}200 = 100.0$	4,000
Glass	$50 \times 0.6/400 = 75.0$	3,000
Paper	$50 \times 0.3/750 = 20.0$	1,000
Wind	$50 \times 0.012/600 = 1.0$	80
four holdings	**196.0**	

$$c^\top b = (4{,}000 + 3{,}000 + 1{,}000 + 80)/4 = 2{,}020$$

$$c^\top w = (3{,}000 + 1{,}000 + 80)/3 = 1{,}360$$

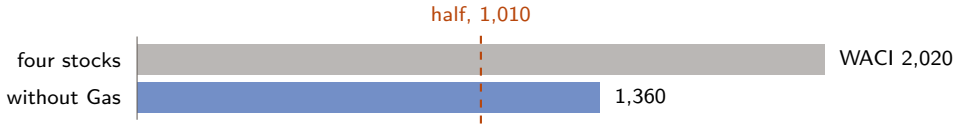
$$R = 1 - 1{,}360/2{,}020 = 32.7\%$$

$$TE^2 = 0.25^2 \times 0.30^2 + 0.0833^2\,(0.40^2 + 0.25^2 + 0.35^2)$$

$$= 0.005625 + 0.002394 = 0.008019$$

$$TE = 9.0\%$$

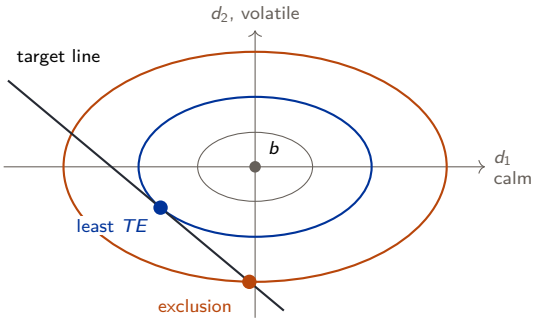
Gas finances 100.0 of the 196.0 kt and adds 1,000 to the WACI of 2,020, yet dropping it cuts WACI by 32.7 per cent, to 1,360 against half at 1,010: the three remaining weights rise to 33.3 per cent each, and Glass's rise adds back intensity. Their tracking error is 9.0 per cent.



Stylised values.

The portfolio of least tracking error touches the target line on the smallest ellipse

1 2 **3** 4 **Which weights cut WACI at the least tracking error?**



Minimise $(w-b)^\top \Sigma (w-b)$ subject to $\mathbf{1}^\top w = 1$ and $c^\top w = (1-R)\, c^\top b$. The axes are two directions of weight change that keep $\mathbf{1}^\top \Delta w = 0$: d_1 moves weight into a calm stock, d_2 into a volatile one. Each ellipse holds the portfolios of one tracking error; the least lies on the smallest ellipse touching the target line.

Stylised positions.
Roncalli (2026), equation (11.9).

Uncorrelated stocks at 20 and 60 per cent volatility: how many times as long is an ellipse along the calm one's weight?

Minimising tracking error moves each weight by intensity above m over variance

$$\Delta w = w - b: \quad \mathbf{1}^\top \Delta w = 0, \quad c^\top \Delta w = -R\, c^\top b \qquad \text{subtract } b$$

$$\mathcal{L} = \tfrac{1}{2}\, \Delta w^\top \Sigma\, \Delta w + \eta\, \mathbf{1}^\top \Delta w + \kappa\, (c^\top \Delta w + R\, c^\top b) \qquad \text{Lagrangian}$$

$$0 = \sigma_i^2\, \Delta w_i + \eta + \kappa\, c_i \qquad \partial / \partial \Delta w_i,\ \Sigma \text{ diagonal}$$

$$\Delta w_i = -(\eta + \kappa\, c_i)/\sigma_i^2 \qquad \text{solve}$$

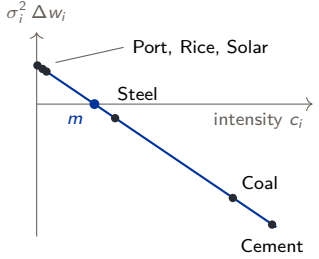
$$\eta = -\kappa\, m, \quad m = \textstyle\sum_j (c_j/\sigma_j^2) \big/ \sum_j (1/\sigma_j^2) \qquad \sum_i \Delta w_i = 0$$

$$\Delta w_i = -\kappa\, (c_i - m)/\sigma_i^2 \qquad \text{insert } \eta$$

$$c^\top \Delta w = -\kappa \textstyle\sum_i c_i (c_i - m)/\sigma_i^2 = -\kappa\, S \qquad \sum_i (c_i - m)/\sigma_i^2 = 0$$

$$\kappa = R\, c^\top b / S, \quad S = \textstyle\sum_i (c_i - m)^2/\sigma_i^2 \qquad \text{target}$$

$$TE = \kappa \sqrt{S} = R\, c^\top b / \sqrt{S} \qquad \text{tracking error}$$



Above m a weight falls, below it rises; variance σ_i^2 sets how far.

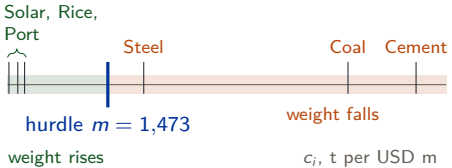
Steel: $c_i - m = 527$, $\sigma_i^2 = 0.2878$, *and* $\sqrt{S} = 13{,}812$. *What is its* Δw_i *at a 30 per cent cut?*

Intensity hurdle m of the six firms

firm	c_i	σ_i	$1/\sigma_i^2$	c_i/σ_i^2
Coal	5,000	0.4287	5.441	27,206
Cement	6,000	0.5297	3.564	21,384
Steel	2,000	0.5365	3.474	6,948
Port	250	0.2914	11.777	2,944
Rice	150	0.3269	9.358	1,404
Solar	20	0.3740	7.149	143
sum			40.763	60,029

$m = 60{,}029/40.763 = 1{,}473$ t per USD m.

Stylised values.



m averages the intensities with weights $1/\sigma_i^2$, so a calm stock counts more. Stocks above m lose weight.

Coal's volatility rises to 60 per cent, the others unchanged. Does m rise or fall, and to what value?

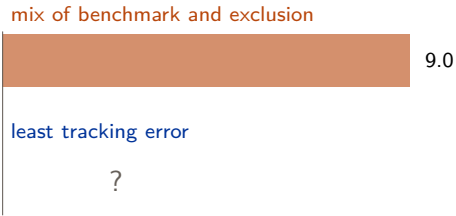
Tracking error at a cut of half

firm	$c_i - m$	σ_i	$z_i = (c_i - m)/\sigma_i$
Coal	3,527	0.4287	8,227
Cement	4,527	0.5297	8,546
Steel	527	0.5365	982
Port	−1,223	0.2914	−4,197
Rice	−1,323	0.3269	−4,047
Solar	−1,453	0.3740	−3,885

$$\sqrt{S} = \sqrt{\sum_i z_i^2} = 13{,}812$$

$$TE = \frac{R\, c^\top b}{\sqrt{S}} = \frac{50\% \times 2{,}236.7}{13{,}812} =$$

Stylised values.



TE in per cent at half, a cut of 50 per cent

Guess first: how far under the mix's 9.0 per cent does the least tracking error go?

What tracking error does the least-tracking-error portfolio need for a cut of 30 per cent?

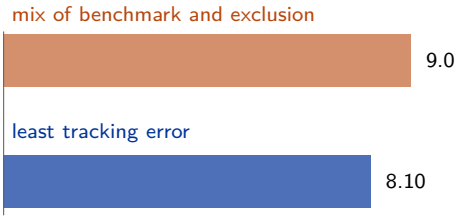
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$$\sqrt{S} = \sqrt{\sum_i z_i^2} = 13{,}812$$

$$TE = \frac{R\, c^\top b}{\sqrt{S}} = \frac{50\% \times 2{,}236.7}{13{,}812} = 8.10\%$$

Stylised values.

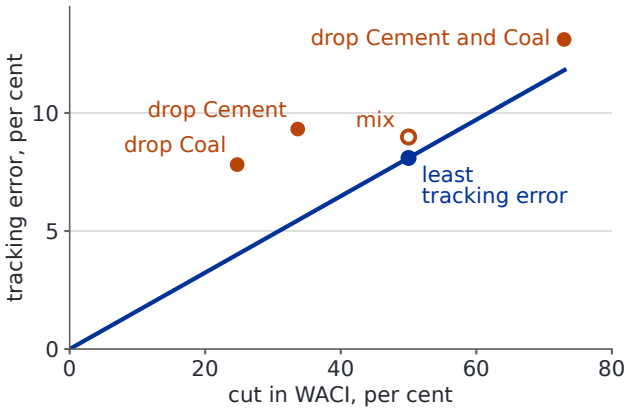


TE in per cent at half, a cut of 50 per cent

Guess first: how far under the mix's 9.0 per cent does the least tracking error go?

What tracking error does the least-tracking-error portfolio need for a cut of 30 per cent?

Tracking error grows in proportion to the cut, and exclusions lie above the line



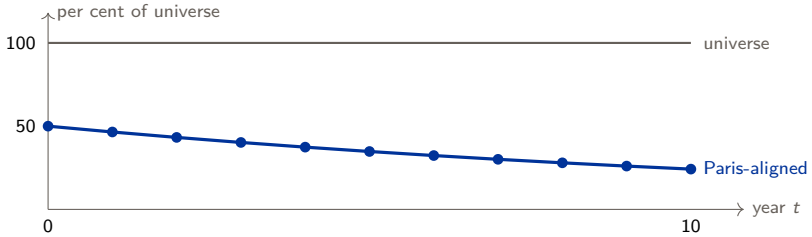
The least tracking error at a cut R is $Rc^\top b/\sqrt{S}$, in proportion to R: a straight line through the benchmark. Without Cement the cut is 33.7 per cent at a tracking error of 9.3; the line gives 5.5 at that cut.

Stylised values.
Portfolio construction with climate risk measures: Le Guenedal and Roncalli (2022).

Which of the three exclusions lies closest to the line per point of cut, and what in its weight changes brings it close?

A Paris-aligned benchmark's intensity starts at least half below its universe's and falls yearly

1 2 3 **4** **Which holdings pay as a Paris-aligned path compounds?**



A Paris-aligned benchmark's intensity starts at least 50% below its investable universe's and falls at least 7% a year on average, calculated geometrically. The regulation's GHG intensity is absolute GHG emissions divided by millions of euros in enterprise value including cash, Scope 1 to 3; the book's WACI divides Scope 1 and 2 by revenue.

Commission Delegated Regulation (EU) 2020/1818 of 17 July 2020 (EU Climate Transition and Paris-aligned Benchmarks), OJ L 406, 3.12.2020, p. 17, Article 11, first subparagraph, read 1 October 2026; Articles 1(c) and 7.

What share of the universe's intensity does the path reach after 5 years?

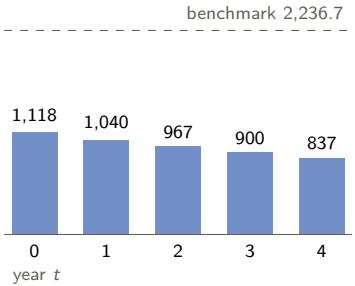
Intensity and cut of the book's Paris-aligned path in its first years

$$c_t = (1 - 50\%)\,(1 - 7\%)^t\, c_0, \quad c_0 = 2{,}236.7$$

$$R_t = 1 - c_t / c_0 = 1 - (1 - 50\%)\,(1 - 7\%)^t$$

$$TE_t = R_t\, c^\top b / \sqrt{S} = R_t \times 2{,}236.7 / 13{,}812$$

year t	0	1	2	3	4
c_t	1,118	1,040	967	900	837
cut R_t, %	50.0	53.5	56.8	59.8	62.6
TE_t, %	8.10	8.66	9.20	9.68	10.14



The universe's intensities are held fixed, so the path tightens only the target. The least-tracking-error portfolio follows it with R_t.

Stylised values.

What is the intensity of the book's Paris-aligned path in year 8?

Coal loses more weight than Cement because its equity is less volatile

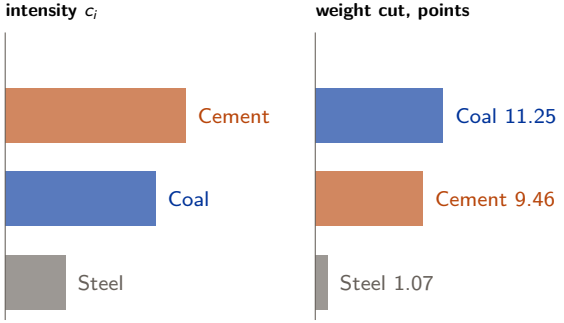
With σ_i the equity volatility and $\kappa = TE/\sqrt{S}$, the cut of stock i in points is

$$-\Delta w_i = \kappa \frac{c_i - m}{\sigma_i^2} = 8.10 \times \frac{(c_i - m)/\sigma_i^2}{13{,}812}.$$

firm	$c_i - m$	σ_i^2	$(c_i - m)/\sigma_i^2$	cut
Coal	3,527	0.1838	19,189	11.25
Cement	4,527	0.2806	16,133	9.46
Steel	527	0.2878	1,831	1.07

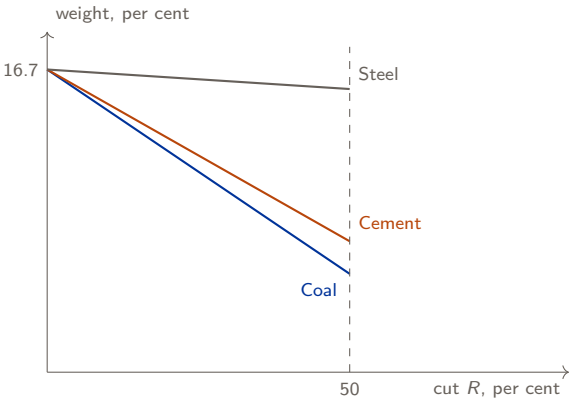
Cement lies further above m, but its variance divides by more: the squared volatility leaves Coal 19,189 against Cement's 16,133. Weights after: Coal 5.4, Cement 7.2, Steel 15.6 per cent, at a WACI of 1,118.

Stylised values.



Two stocks lie the same distance above m, and one has 2 times the other's volatility. Which loses more weight, and how many times as much?

Cut at which Coal's weight reaches zero

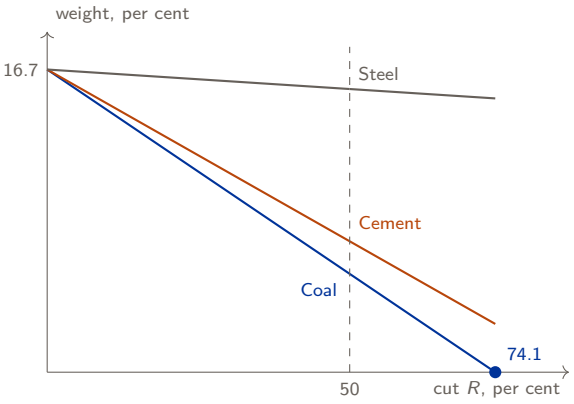


Each weight is linear in the cut: $w_i(R) = b_i - (R/50\%)\,\text{cut}_i$, with Coal's cut of 11.25 points at the first step. Guess the cut at which Coal's weight reaches zero.

Stylised values.

In which year does the book's Paris-aligned path first cut WACI by 80 per cent or more?

Cut at which Coal's weight reaches zero



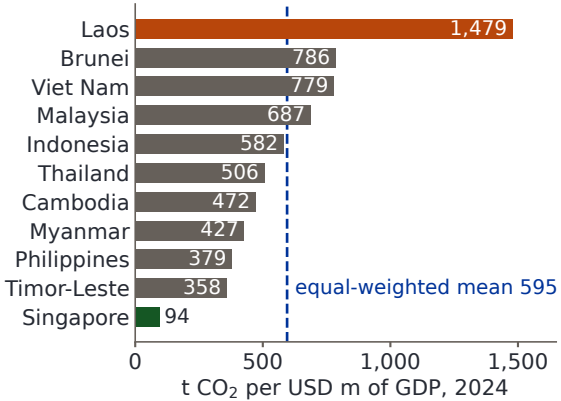
Each weight is linear in the cut: $w_i(R) = b_i - (R/50\%)\,\text{cut}_i$, with Coal's cut of 11.25 points at the first step. Guess the cut at which Coal's weight reaches zero.

$R_0 = 50\% \times 16.67/11.25 = 74.1\%$. The path's cut is 74.0 per cent in year 9 and 75.8 in year 10, so Coal leaves in year 10, the universe's intensities held fixed.

Stylised values.

In which year does the book's Paris-aligned path first cut WACI by 80 per cent or more?

Laos has the highest and Singapore the lowest carbon intensity of GDP in ASEAN



Carbon intensity in 2024, fossil CO_2 per USD m of GDP: Laos 1,479 t, Singapore 94, so Laos emits 15.7 times as much. ASEAN has 11 members since Timor-Leste joined on 26 October 2025.

Computed: Global Carbon Project, National Fossil Carbon Emissions 2025 v1.0, territorial fossil CO2 2024; World Bank WDI, GDP (current US$) 2024, last updated 13 July 2026, read 1 October 2026. Members: Agence Kampuchea Presse (AKP), Phnom Penh, 26 October 2025, read 1 October 2026.

With equal volatilities for the eleven bonds, how many times Brunei's weight cut does a least-tracking-error portfolio take from Laos?

Weights that move by intensity over variance cut WACI at least tracking error

1	How are a portfolio's emissions and carbon intensity counted?	Holding over EVIC times emissions: 644 kt in all. WACI is $c^\top w$, 2,236.7 for the benchmark, 82.0 per cent from Cement and Coal.
2	How does a portfolio cut its WACI by half?	By the bound $(1 - R)\, c^\top b$. Excluding Cement cuts 33.7 per cent; without Cement and Coal, 73.0 at a tracking error of 13.1, and a mix reaches half at 9.0.
3	Which weights cut WACI at the least tracking error?	$\Delta w_i = -\kappa\,(c_i - m)/\sigma_i^2$: intensity above $m = 1{,}473$ over variance. Tracking error $R\, c^\top b/\sqrt{S}$: 8.10 per cent at half.
4	Which holdings pay as a Paris-aligned path compounds?	At half Coal loses 11.25 points, Cement 9.46, Steel 1.07; Coal's weight reaches zero at a cut of 74.1 per cent, passed in year 10.

Stylised values.

Sources on financed emissions, carbon intensity and portfolio decarbonisation

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Read on 1 and 2 October 2026; PCAF and TCFD on 30 September 2026.

Declarations

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Checkpoint: decarbonising a portfolio

1. USD 40 m in a firm with EVIC USD 800 m, 1.2 Mt, revenue USD 600 m; USD 60 m in one with EVIC USD 300 m, 0.15 Mt, revenue USD 250 m. Give financed emissions and WACI.
2. Three uncorrelated stocks held equally: intensities 3,600, 1,200, 300; volatilities 40, 30, 20 per cent. Give the cut and tracking error without the first.
3. For these stocks, derive m and Δw_1 at a cut of 30 per cent from the first-order condition.
4. Give their least tracking error at a cut of 30 per cent.
5. Two stocks lie equally far above m, one 1.5 times as volatile. Which loses more weight, and how many times as much?
6. A stock at 20 per cent loses 15 points at a cut of 50. In which year of the Paris-aligned path does its weight reach zero, and what is a WACI of 1,600 then?

Stylised values.



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Portfolio decarbonisation at least tracking error - Mathematics of Green Finance Risk Management, Lecture 6

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