Course 2021-2022 in ESG and Climate Risks
Lecture 5. Climate Investing

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February 2022

[1] The opinions expressed in this presentation are those of the authors and are not meant to represent the opinions or official positions of Amundi Asset Management.

Agenda

- **Lecture 1: Introduction**
  - *Definition, Actors, the Market of ESG Investing* (42 slides)
- **Lecture 2: ESG Investing**
  - *ESG Scoring, ESG Ratings, Performance of ESG Investing, ESG Financing, ESG Premium* (132 slides)
- **Lecture 3: Other ESG Topics**
  - *Sustainable Financing Products, Impact Investing, Voting Policy & Engagement, ESG and Climate Accounting* (82 slides)
- **Lecture 4: Climate Risk**
  - *Definition, Global Warming, Economic Modeling, Risk Measures* (176 slides)
- **Lecture 5: Climate Investing**
  - *Portfolio Decarbonization, Net Zero Carbon Metrics, Portfolio Alignment* (164 slides)
- **Lecture 6: Mathematical Methods, Technical Tools and Exercises**
  - *Scoring System, Trend Modeling, Geolocation Data, Numerical Computations, Optimization* (150+ slides)

General information

1. **Overview**
   The objective of this course is to understand the concepts of sustainable finance from the viewpoint of asset owners and managers
2. **Prerequisites**
   M1 Finance or equivalent
3. **ECTS**
   3
4. **Keywords**
   Finance, Asset Management, ESG, Responsible Investing, Climate Change
5. **Hours**
   Lectures: 18h
6. **Evaluation**
   Project + oral examination
7. **Course website**
   `http://www.thierry-roncalli.com/SustainableFinance.html`

Class schedule

Course sessions

- Date 1 (6 hours, AM+PM)
- Date 2 (6 hours, AM+PM)
- Date 3 (6 hours, AM+PM)

Class times: Friday 9:00am-12:00pm, 1:00pm–4:00pm, Location: University of Evry

Additional materials

http://www.thierry-roncalli.com/SustainableFinance.html

- Slides
- Past examinations
- Exercises + Solutions
- LaTeX source of the slides + figures (in pdf format)
- Links to the references

Main references

Amundi publications on ESG Investing

1. Bennani *et al.* (2018), How ESG Investing Has Impacted the Asset Pricing in the Equity Market, DP-36-2018, 36 pages, November 2018
2. Drei *et al.* (2019), ESG Investing in Recent Years: New Insights from Old Challenges, DP-42-2019, 32 pages, December 2019
3. Ben Slimane *et al.* (2020), ESG Investing and Fixed Income: It's Time to Cross the Rubicon, DP-45-2019, 36 pages, January 2020
4. Roncalli, T. (2020), ESG & Factor Investing: A New Stage Has Been Reached, Amundi Viewpoint, May 2020

Available at `https://research-center.amundi.com` or `www.ssrn.com`

Main references

Amundi publications on Climate Investing

1. Le Guenedal, T. (2019), Economic Modeling of Climate Risk, WP-83-2019, 92 pages, April 2019
2. Bouchet, V., and Le Guenedal, T. (2020), Credit Risk Sensitivity to Carbon Price, WP-95-2020, 48 pages, May 2020
3. Le Guenedal *et al.* (2020), Trajectory Monitoring in Portfolio Management and Issuer Intentionality Scoring, WP-97-2020, 54 pages, May 2020
4. Roncalli *et al.* (2020), Measuring and Managing Carbon Risk in Investment Portfolios, WP-99-2020, 67 pages, August 2020
5. Ben Slimane, M., Da Fonseca, D., and Mahtani, V. (2020), Facts and Fantasies about the Green Bond Premium, WP-102-2020, 52 pages, December 2020
6. Le Guenedal, Drobinski, P., and Tankov, P. (2021), Measuring and Pricing Cyclone-Related Physical Risk under Changing Climate, WP-111-2021, 42 pages, June 2021
7. Adenot *et al.* (2022), Cascading Effects of Carbon Price through the Value Chain and their Impacts on Firm's Valuation, WP-122-2022, 82 pages, February 2022
8. Le Guenedal *et al.* (2022), Net Zero Carbon Metrics, WP-123-2022, 82 pages, February 2022

Available at `https://research-center.amundi.com` or `www.ssrn.com`

Main references

Amundi ESG Thema

1. Créhalet, E. (2021), Introduction to Net Zero, *Amundi ESG Thema #1*, `https://research-center.amundi.com`
2. Créhalet, E., Foll, J., Haustant, P., and Hessenberger, T. (2021), Carbon Offsetting: How Can It Contribute to the Net Zero Goal?, *Amundi ESG Thema #5*, `https://research-center.amundi.com`
3. Créhalet, E., and Talwar, S. (2021), Carbon-efficient Technologies in the Race to Net Zero, *Amundi ESG Thema #6*, `https://research-center.amundi.com`
4. Le Meaux, C., Le Berthe, T., Jaulin, T., Créhalet, E., Jouanneau, M., Pouget-Abadie, T., and Elbaz, J. (2021), How can Investors Contribute to Net Zero Efforts?, *Amundi ESG Thema #3*, `https://research-center.amundi.com`

Available at `https://research-center.amundi.com` or `www.ssrn.com`

Main references

Academic publications

1. Andersson, M., Bolton, P., and Samama, F. (2016), Hedging Climate Risk, *Financial Analysts Journal*, www.ssrn.com/abstract=2499628.
2. Ardia, D., Bluteau, K., Boudt, K., and Inghelbrecht, K. (2021), Climate Change Concerns and the Performance of Green versus Brown Stocks, *National Bank of Belgium, Working Paper*, www.ssrn.com/abstract=3717722.
3. Battiston, S., Mandel, A., Monasterolo, I., Schütze, F., and Visentin, G. (2017), A Climate Stress-test of the Financial System, *Nature Climate Change*, www.ssrn.com/abstract=2726076.
4. Berg, F. Koelbel, J.F., and Rigobon, R. (2019), Aggregate Confusion: The Divergence of ESG Ratings, *Working Paper*, www.ssrn.com/abstract=3438533
5. Berg, F., Fabisik, K., and Sautner, Z. (2021), Is History Repeating Itself? The (Un)predictable Past of ESG Ratings , *Working Paper*, www.ssrn.com/abstract=3722087
6. Bolton, P., and Kacperczyk, M. (2021), Do Investors Care about Carbon Risk?, *Journal of Financial Economics*, www.ssrn.com/abstract=3594189
7. Bolton, P., Kacperczyk, M., and Samama, F. (2021), Net-Zero Carbon Portfolio Alignment, *Working Paper*, www.ssrn.com/abstract=3922686
8. Coqueret, G. (2021), Perspectives in ESG Equity Investing, *Working Paper*, www.ssrn.com/abstract=3715753

Main references

Academic publications

9. Crifo, P., Diaye, M.A., and Oueghlissi, R. (2015), Measuring the Effect of Government ESG Performance on Sovereign Borrowing Cost, *Quarterly Review of Economics and Finance*, `hal.archives-ouvertes.fr/hal-00951304v3`
10. Dennig, F., Budolfson, M.B., Fleurbaey, M., Siebert, A., and Socolow, R.H. (2015), Inequality, Climate Impacts on the Future Poor, and Carbon Prices, *Proceedings of the National Academy of Sciences*, `www.pnas.org/content/112/52/15827`
11. Engle, R.F., Giglio, S., Kelly, B., Lee, H., and Stroebel, J. (2020), Hedging Climate Change News, *Review of Financial Studies*, `www.ssrn.com/abstract=3317570`
12. Görgen, M., Jacob, A., Nerlinger, M., Riordan, R., Rohleder, M., and Wilkens, M. (2020), Carbon Risk, *Working Paper*, `www.ssrn.com/abstract=2930897`
13. Harris, J. (2015), The Carbon Risk Factor, *Working Paper*, `www.ssrn.com/abstract=2666757`
14. Karydas, C., and Xepapadeas, A. (2021), Climate Change Financial Risks: Implications for Asset Pricing and Interest Rates, *Working Paper*
15. Le Guenedal, T., and Roncalli, T. (2022), Portfolio Construction and Climate Risk Measures, *Climate Investing*, `www.ssrn.com/abstract=3999971`

Main references

Academic publications

16. Martellini, L., and Vallée, L. (2021), Measuring and Managing ESG Risks in Sovereign Bond Portfolios and Implications for Sovereign Debt Investing, *Journal of Portfolio Management*, www.risk.edhec.edu/measuring-and-managing-esg-risks-sovereign-bond
17. Pedersen, L.H., Fitzgibbons, S., and Pomorski, L. (2021), Responsible Investing: The ESG-Efficient Frontier, *Journal of Financial Economics*, www.ssrn.com/abstract=3466417
18. Pástor, L., Stambaugh, R.F., and Taylor, L.A. (2021), Sustainable Investing in Equilibrium, *Journal of Financial Economics*, www.ssrn.com/abstract=3498354
19. Roncalli, T., Le Guenedal, T., Lepetit, F., Roncalli, T., and Sekine, T. (2021), The Market Measure of Carbon Risk and its Impact on the Minimum Variance Portfolio, *Journal of Portfolio Management*, www.ssrn.com/abstract=3772707
20. Van der Beck, P. (2021), Flow-driven ESG returns, *Working Paper*, www.ssrn.com/abstract=3929359

Portfolio decarbonization

Two approaches:

- Portfolio optimization by minimizing the tracking error and imposing a reduction in terms of carbon intensity (max-threshold approach)
- Elimination of the worst performers in terms of carbon intensity (order-statistic approach)

Portfolio optimization with a benchmark

The γ-optimization problem is:

$$
\begin{aligned}
x^\star & = \arg\min \frac{1}{2}\sigma^2(x \mid b) - \gamma\mu(x \mid b) \\
\text{u.c.} & \quad \left\{ \begin{array}{ll} \mathbf{1}_n^\top x = 1 & \\ \mathbf{0}_n \leq x \leq \mathbf{1}_n & \qquad \text{(no short selling)} \\ x \in \Omega & \end{array} \right.
\end{aligned}
$$

where $x = (x_1, \ldots, x_n)$ is the portfolio, $b = (b_1, \ldots, b_n)$ is the benchmark, $\sigma(x \mid b) = \sqrt{(x - b)^\top \Sigma (x - b)}$ is the volatility of the tracking error, $\mu(x \mid b) = (x - b)^\top \mu$ is the expected excess return and $x \in \Omega$ corresponds to additional constraints

Portfolio optimization with a benchmark

We have:

$$
\begin{aligned}
(*) &= \frac{1}{2}\sigma^2(x \mid b) - \gamma\mu(x \mid b) \\
&= \frac{1}{2}(x-b)^\top \Sigma (x-b) - \gamma (x-b)^\top \mu \\
&= \frac{1}{2}x^\top \Sigma x - x^\top(\gamma\mu + \Sigma b) + \left(\frac{1}{2}b^\top \Sigma b + \gamma b^\top \mu\right) \\
&= \frac{1}{2}x^\top \Sigma x - x^\top(\gamma\mu + \Sigma b) + \mathrm{constant}
\end{aligned}
$$

Remark

The objective function can be cast into a QP problem:

$$x^\star = \arg\min \frac{1}{2}x^\top \Sigma x - x^\top(\gamma\mu + \Sigma b)$$

Quadratic programming problem

Definition

The formulation of a standard QP problem is:

$$\begin{aligned} x^\star &= \arg\min \frac{1}{2} x^\top Q x - x^\top R \\ &\text{u.c.} \quad \left\{ \begin{array}{l} Ax = B \\ Cx \leq D \\ x^- \leq x \leq x^+ \end{array} \right. \end{aligned}$$

Portfolio decarbonization

Some examples of portfolio decarbonization:

- Limiting the carbon emissions

$$\mathcal{CE}_j(x) \leq \mathcal{CE}_j^+$$

- Limiting the carbon intensity

$$\mathcal{CI}_j(x) \leq \mathcal{CI}_j^+$$

- Reducing the carbon emissions with respect to a benchmark:

$$\mathcal{CE}_j(x) \leq (1 - \mathcal{R})\,\mathcal{CE}_j(b)$$

  where $\mathcal{R} > 0$ is the reduction rate

- Reducing the carbon intensity with respect to a benchmark:

$$\mathcal{CI}_j(x) \leq (1 - \mathcal{R})\,\mathcal{CI}_j(b)$$

Portfolio decarbonization

Portfolio decarbonization is equivalent to add a new constraint:

$$\Omega = \left\{ x : \mathcal{C}(x) = \sum_{i=1}^{n} x_i \cdot \mathcal{C}_i \leq \mathcal{C}^+ \right\}$$

where $\mathcal{C}(x)$ is the climate risk measure

Max-threshold approach

In the sequel, we omit the subscript j that defines the scope to simplify the notations

- The carbon intensity of the benchmark is equal to:

$$\mathcal{CI}(b) = \sum_{i=1}^{n} b_i \cdot \mathcal{CI}_i = b^\top \mathcal{CI}$$

  where $\mathcal{CI} = (\mathcal{CI}_1, \ldots, \mathcal{CI}_n)$ is the vector of carbon intensities
- The carbon intensity of the portfolio is equal to:

$$\mathcal{CI}(x) = \sum_{i=1}^{n} x_i \cdot \mathcal{CI}_i = x^\top \mathcal{CI}$$

  $\mathcal{CI}(x)$ is also called the weighted average carbon intensity (WACI)

Remark

Until 2020, portfolio decarbonization is generally done using carbon intensity and not absolute carbon emissions

Max-threshold approach

- We deduce that the optimization problem is:

$$
\begin{aligned}
x^{\star}(\mathcal{R}) &= \arg\min \frac{1}{2}(x-b)^{\top}\Sigma(x-b) \\
&\text{s.t.} \quad \left\{
\begin{array}{l}
\mathbf{1}_n^{\top} x = 1 \\
x \geq \mathbf{0}_n \\
\sum_{i=1}^{n} x_i \cdot \mathcal{CI}_i \leq (1-\mathcal{R}) \cdot \mathcal{CI}(b)
\end{array}
\right.
\end{aligned}
$$

  where $\mathcal{R}$ is the reduction rate
- The underlying idea is to obtain a decarbonized portfolio $x^{\star}$ such that the tracking error with respect to the benchmark b is the lowest
- The benchmark b can be a current portfolio (active management) or an index portfolio (passive management)

Max-threshold approach

- Since the constraint on the carbon intensity is equivalent to:

$$\mathcal{CI}^\top x \leq (1 - \mathcal{R}) \cdot \mathcal{CI}(b)$$

We obtain the following QP problem:

$$\begin{aligned} x^\star &= \frac{1}{2} x^\top \Sigma x - x^\top \Sigma b \\ &\text{u.c.} \quad \left\{ \begin{array}{l} \mathbf{1}_n^\top x = 1 \\ \mathcal{CI}^\top x \leq (1 - \mathcal{R}) \cdot \left(b^\top \mathcal{CI} \right) \\ \mathbf{0}_n \leq x \leq \mathbf{1}_n \end{array} \right. \end{aligned}$$

Max-threshold approach

The QP problem is:

$$
\begin{aligned}
x^{\star} &= \arg\min \frac{1}{2} x^{\top} Q x - x^{\top} R \\
\text{u.c.} & \left\{ \begin{array}{l} Ax = B \\ Cx \leq D \\ x^{-} \leq x \leq x^{+} \end{array} \right.
\end{aligned}
$$

We have the following QP correspondences:

$$
\begin{aligned}
Q &= \Sigma \\
R &= \Sigma b \\
A &= \mathbf{1}_n^{\top} \\
B &= 1 \\
C &= \mathcal{CI}^{\top} \\
D &= \mathcal{CI}^{+} = (1 - \mathcal{R}) \cdot \left(b^{\top} \mathcal{CI} \right) \\
x^{-} &= \mathbf{0}_n \\
x^{+} &= \mathbf{1}_n
\end{aligned}
$$

Max-threshold approach

Example

We consider a capitalization-weighted equity index, which is composed of 8 stocks. The weights are equal to 23%, 19%, 17%, 13%, 9%, 8%, 6% and 5%. We assume that their volatilities are equal to 22%, 20%, 25%, 18%, 35%, 23%, 13% and 29%. The correlation matrix is given by:

$$\rho = \left(\begin{array}{rrrrrrrr} 100\% & & & & & & & \\ 80\% & 100\% & & & & & & \\ 70\% & 75\% & 100\% & & & & & \\ 60\% & 65\% & 80\% & 100\% & & & & \\ 70\% & 50\% & 70\% & 85\% & 100\% & & & \\ 50\% & 60\% & 70\% & 80\% & 60\% & 100\% & & \\ 70\% & 50\% & 70\% & 75\% & 80\% & 50\% & 100\% & \\ 60\% & 65\% & 70\% & 75\% & 65\% & 70\% & 80\% & 100\% \end{array} \right)$$

The carbon intensities (expressed in $tCO_2e/\$$ mn) are respectively equal to: 100.5, 57.2, 250.4, 352.3, 27.1, 54.2, 78.6 and 426.7.

Max-threshold approach

Table 1: Optimal decarbonization portfolios (max-threshold approach)

$\mathcal{R}$	0.00	0.10	0.20	0.30	0.40	0.50
$x_1^\star$	23.00	20.98	18.97	16.95	14.91	11.96
$x_2^\star$	19.00	21.15	23.30	25.46	28.25	33.40
$x_3^\star$	17.00	16.79	16.59	16.38	14.79	9.05
$x_4^\star$	13.00	9.12	5.24	1.36	0.00	0.00
$x_5^\star$	9.00	10.33	11.67	13.00	14.51	16.92
$x_6^\star$	8.00	9.18	10.37	11.55	12.63	13.59
$x_7^\star$	6.00	8.20	10.40	12.59	14.21	15.06
$x_8^\star$	5.00	4.23	3.47	2.70	0.70	0.00
$\sigma(x^\star \mid b)$ (in bps)	0.00	19.32	38.64	57.96	84.74	141.97
$\mathcal{CI}(x)$	155.18	139.66	124.14	108.62	93.11	77.59

- The carbon intensity of the index is equal to 155.18 tCO_2/\$ mn
- The tracking error of the portfolio is equal to 141.97 bps if we target a 50% reduction of the carbon intensity

Max-threshold approach

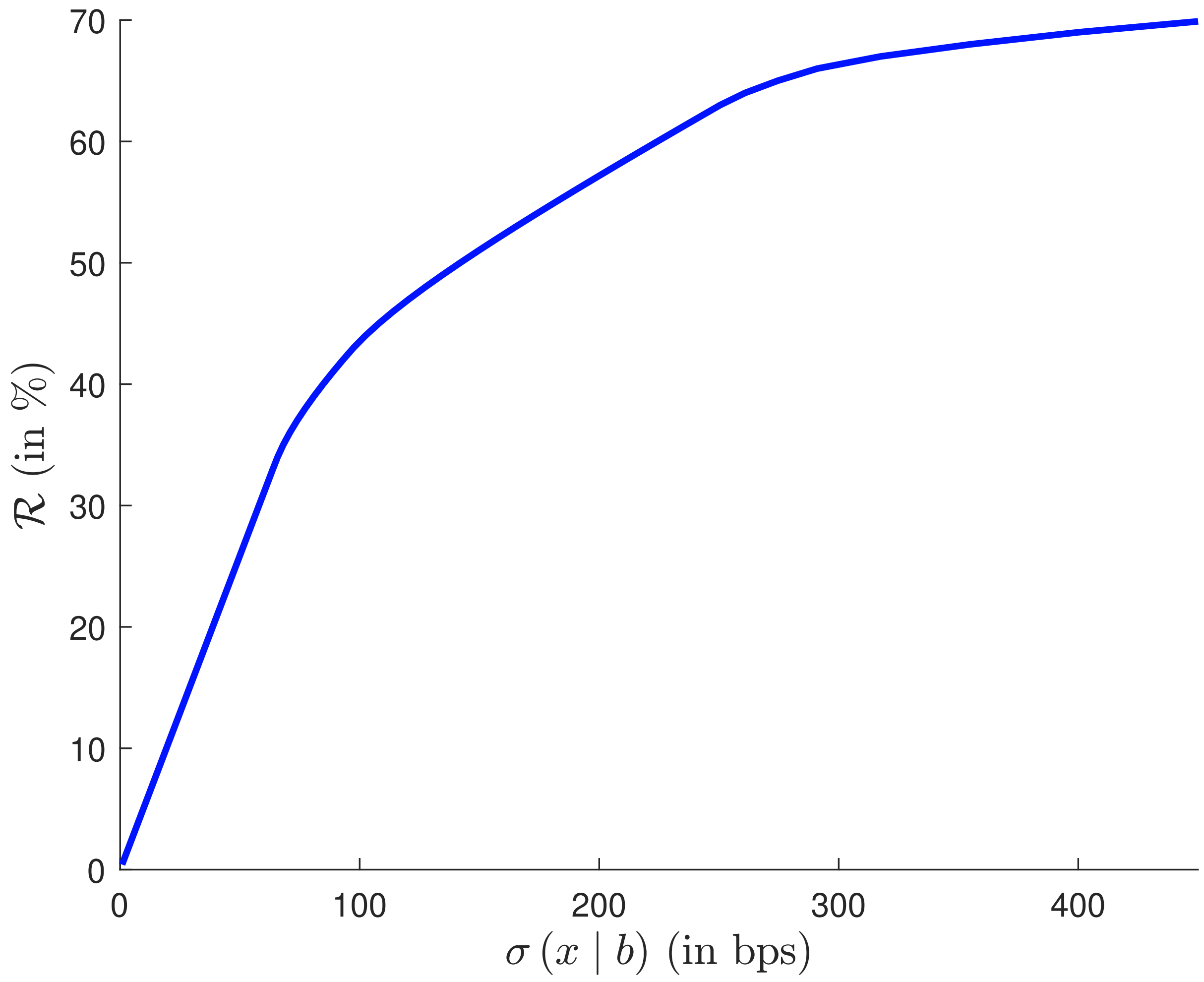


Figure 1: The efficient frontier of optimal decarbonization portfolios

Order-statistic approach

Andersson *et al.* (2016) propose a second portfolio decarbonization approach by eliminating the m worst performing issuers in terms of carbon intensity

- We note $\mathcal{CI}_{i:n}$ the order statistics of $(\mathcal{CI}_1, \ldots, \mathcal{CI}_n)$:

$$\min \mathcal{CI}_i = \mathcal{CI}_{1:n} \leq \mathcal{CI}_{2:n} \leq \cdots \leq \mathcal{CI}_{i:n} \leq \cdots \leq \mathcal{CI}_{n:n} = \max \mathcal{CI}_i$$

- The carbon intensity bound $\mathcal{CI}^{(m,n)}$ is defined as:

$$\mathcal{CI}^{(m,n)} = \mathcal{CI}_{n-m+1:n}$$

  where $\mathcal{CI}_{n-m+1:n}$ is the $(n-m+1)$-th order statistic of $(\mathcal{CI}_1, \ldots, \mathcal{CI}_n)$

- Eliminating the m worst performing assets is equivalent to imposing the following constraint:

$$\mathcal{CI}_i \geq \mathcal{CI}^{(m,n)} \Rightarrow x_i = 0$$

Order-statistic approach

- The optimization problem becomes:

$$\begin{aligned} x^{\star} &= \frac{1}{2} x^{\top} \Sigma x - x^{\top} \Sigma b \\ \text{u.c.} & \left\{ \begin{array}{l} \mathbf{1}_n^{\top} x = 1 \\ x_i \in \left\{ \begin{array}{ll} [0,1] & \text{if } \mathcal{CI}_i < \mathcal{CI}^{(m,n)} \\ \{0\} & \text{if } \mathcal{CI}_i \geq \mathcal{CI}^{(m,n)} \end{array} \right. \end{array} \right. \end{aligned}$$

- The last constraint can be written as:

$$\mathbf{0}_n \leq x \leq x^{+}$$

where:

$$x_i^{+} = \mathbb{1}\left\{ \mathcal{CI}_i < \mathcal{CI}^{(m,n)} \right\}$$

We obtain again a QP problem

Order-statistic approach

The QP problem is:

$$
\begin{aligned}
x^{\star}(m) &= \frac{1}{2} x^{\top} \Sigma x - x^{\top} \Sigma b \\
\text{s.t.} & \left\{
\begin{array}{l}
\mathbf{1}_n^{\top} x = 1 \\
\mathbf{0}_n \leq x \leq x^{+} \\
x_i^{+} = \mathbb{1}\left\{ \mathcal{CI}_i < \mathcal{CI}^{(m,n)} \right\}
\end{array}
\right.
\end{aligned}
$$

We have the following QP correspondences:

$$
\begin{aligned}
Q &= \Sigma \\
R &= \Sigma b \\
A &= \mathbf{1}_n^{\top} \\
B &= 1 \\
x^{-} &= \mathbf{0}_n \\
x^{+} &= \mathbb{1}\left\{ \mathcal{CI} < \mathcal{CI}^{(m,n)} \right\}
\end{aligned}
$$

Order-statistic approach

Table 2: Optimal decarbonization portfolios (order-statistic approach)

m	0	1	2	3	4	5	6	7	$\mathcal{CI}$
$x_1^\star$	23.00	18.68	15.94	14.00	**0.00**	0.00	0.00	0.00	100.5
$x_2^\star$	19.00	23.54	26.26	35.84	45.65	56.44	**0.00**	0.00	57.2
$x_3^\star$	17.00	17.46	17.50	**0.00**	0.00	0.00	0.00	0.00	250.4
$x_4^\star$	13.00	6.50	**0.00**	0.00	0.00	0.00	0.00	0.00	352.3
$x_5^\star$	9.00	11.88	13.63	17.98	21.18	26.14	34.73	100.00	27.1
$x_6^\star$	8.00	10.85	12.44	15.84	13.20	17.42	65.27	**0.00**	54.2
$x_7^\star$	6.00	11.11	14.23	16.34	19.98	**0.00**	0.00	0.00	78.6
$x_8^\star$	5.00	**0.00**	0.00	0.00	0.00	0.00	0.00	0.00	426.7
$\sigma(x^\star \mid b)$ (in bps)	0.00	77.78	84.51	240.71	278.40	400.71	11.4%	21.6%	
$\mathcal{CI}(x)$	155.18	116.66	96.48	60.87	54.70	48.81	44.79	27.10	
$\mathcal{R}$ (in %)	0.00	24.82	37.82	60.77	64.75	68.55	71.14	82.54	

- The reduction of carbon intensity is equal to 24.82% if we eliminate the worst performer
- In this case, we obtain a tracking error of 77.78 bps

Order-statistic approach

The "*naive*" solution consists in re-weighting the remaining assets:

$$x_i = \frac{\mathbb{1}\left\{\mathcal{CI}_i < \mathcal{CI}^{(m,n)}\right\} \cdot b_i}{\sum_{k=1}^{n} \mathbb{1}\left\{\mathcal{CI}_k < \mathcal{CI}^{(m,n)}\right\} \cdot b_k}$$

Order-statistic approach

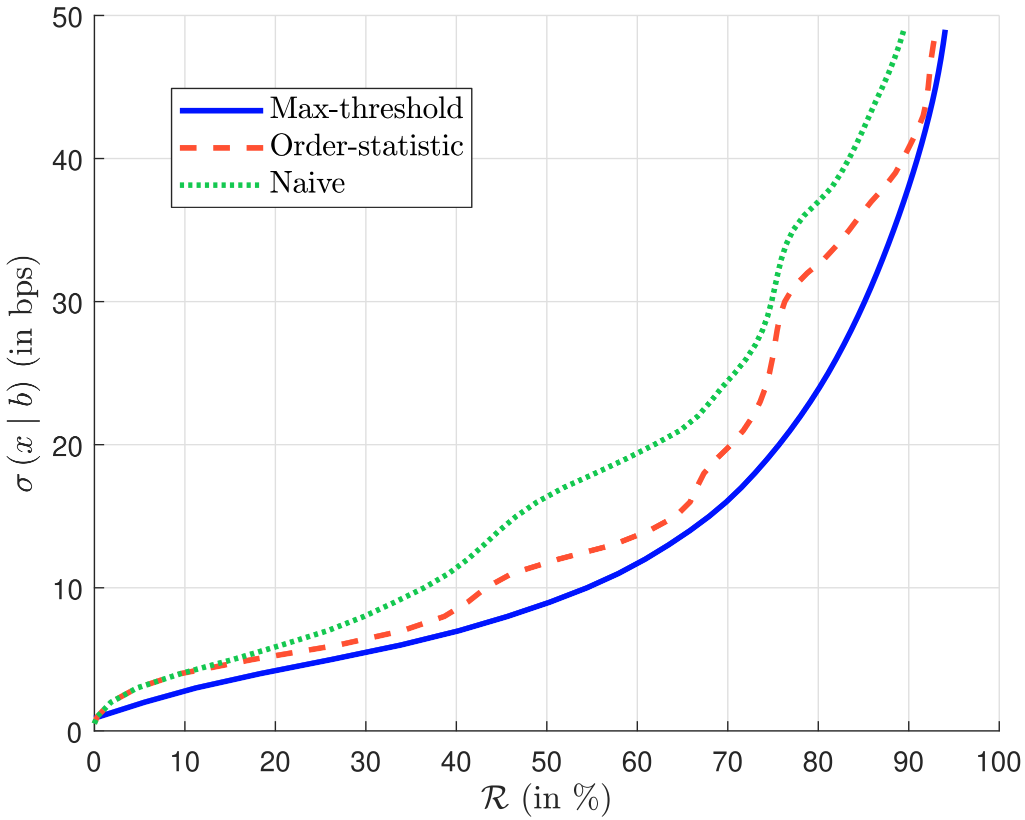
Table 3: Optimal decarbonization portfolios (order-statistic naive approach)

m	0	1	2	3	4	5	6	7	$\mathcal{CI}$
$x_1^\star$	23.00	24.21	28.05	35.38	**0.00**	0.00	0.00	0.00	100.50
$x_2^\star$	19.00	20.00	23.17	29.23	45.24	52.78	**0.00**	0.00	57.20
$x_3^\star$	17.00	17.89	20.73	**0.00**	0.00	0.00	0.00	0.00	250.40
$x_4^\star$	13.00	13.68	**0.00**	0.00	0.00	0.00	0.00	0.00	352.30
$x_5^\star$	9.00	9.47	10.98	13.85	21.43	25.00	52.94	100.00	27.10
$x_6^\star$	8.00	8.42	9.76	12.31	19.05	22.22	47.06	**0.00**	54.20
$x_7^\star$	6.00	6.32	7.32	9.23	14.29	**0.00**	0.00	0.00	78.60
$x_8^\star$	5.00	**0.00**	0.00	0.00	0.00	0.00	0.00	0.00	426.70
$\sigma(x^\star \mid b)$ (in bps)	0.00	92.73	186.22	355.15	301.43	409.44	12.5%	21.6%	
$\mathcal{CI}(x)$	55.18	140.89	107.37	69.96	53.24	49.01	39.85	27.10	
$\mathcal{R}$ (in %)	0.00	9.21	30.81	54.92	65.69	68.42	74.32	82.54	

- The reduction of carbon intensity is equal to 9.21% if we eliminate the worst performer
- In this case, we obtain a tracking error of 92.73 bps

Efficient frontier

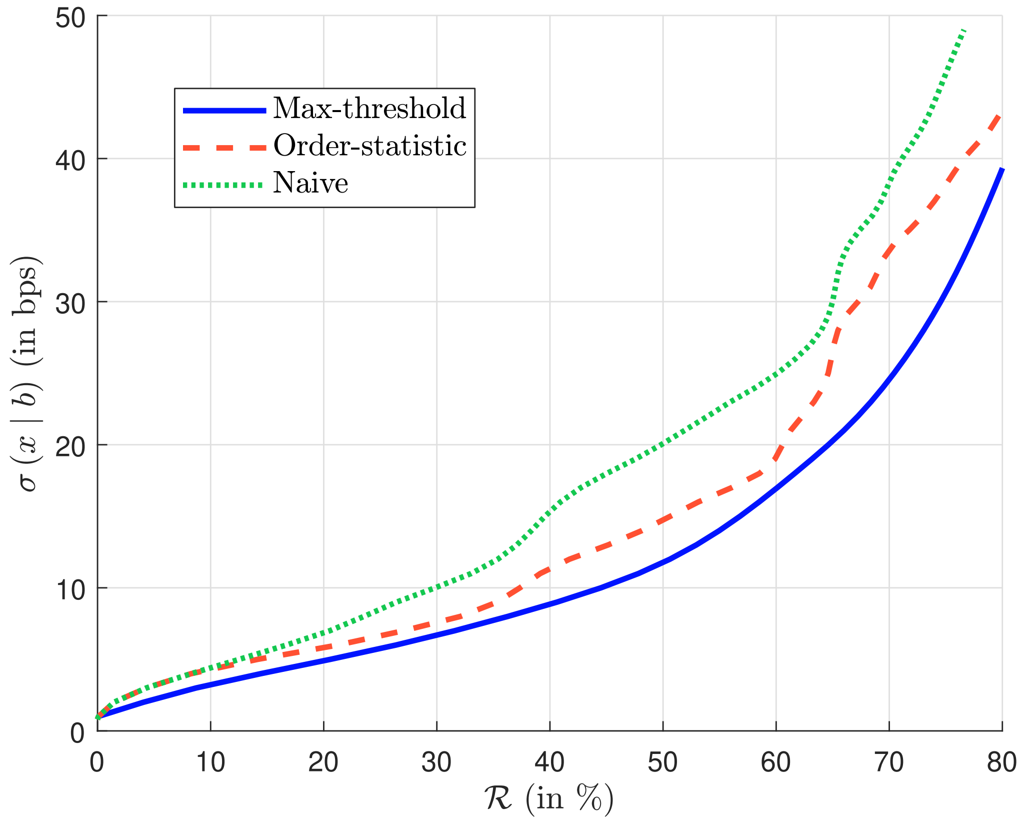
Figure 2: Efficient frontier of optimal decarbonization portfolios (S&P 500 index, October 2021, scope 1)



Source: Trucost reporting year 2020 & Le Guenedal and Roncalli (2022).

Efficient frontier

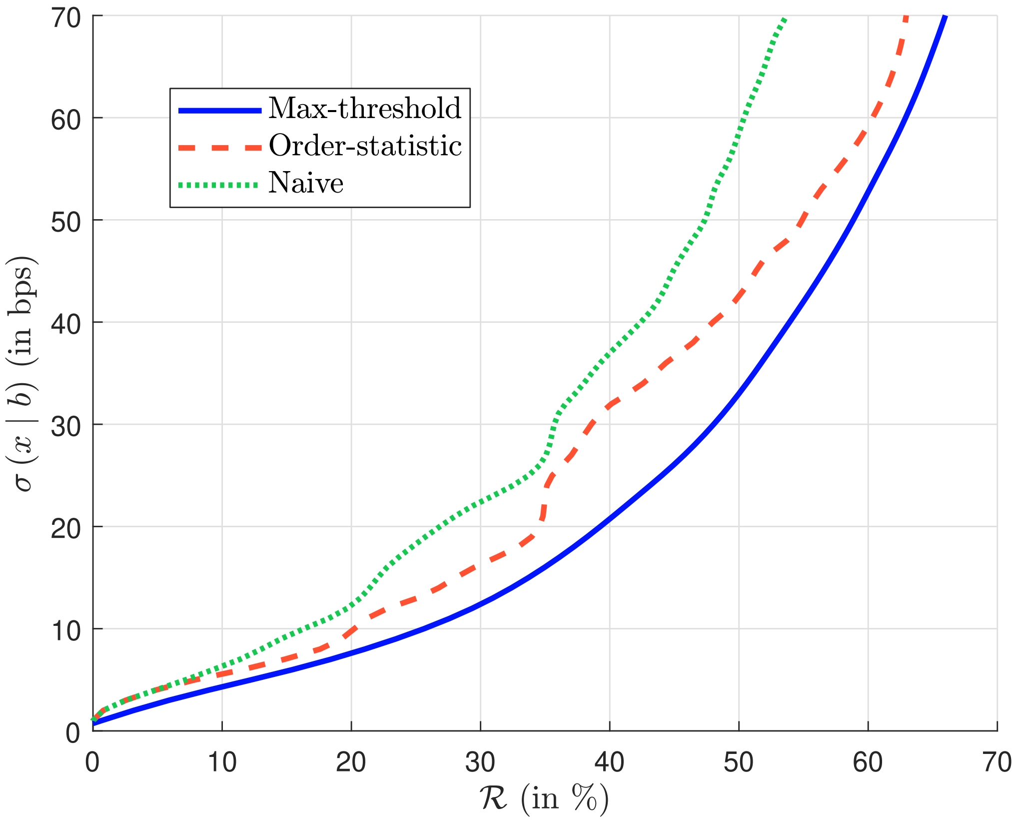
Figure 3: Efficient frontier of optimal decarbonization portfolios (S&P 500 index, October 2021, scope 1 + 2)



Source: Trucost reporting year 2020 & Le Guenedal and Roncalli (2022).

Efficient frontier

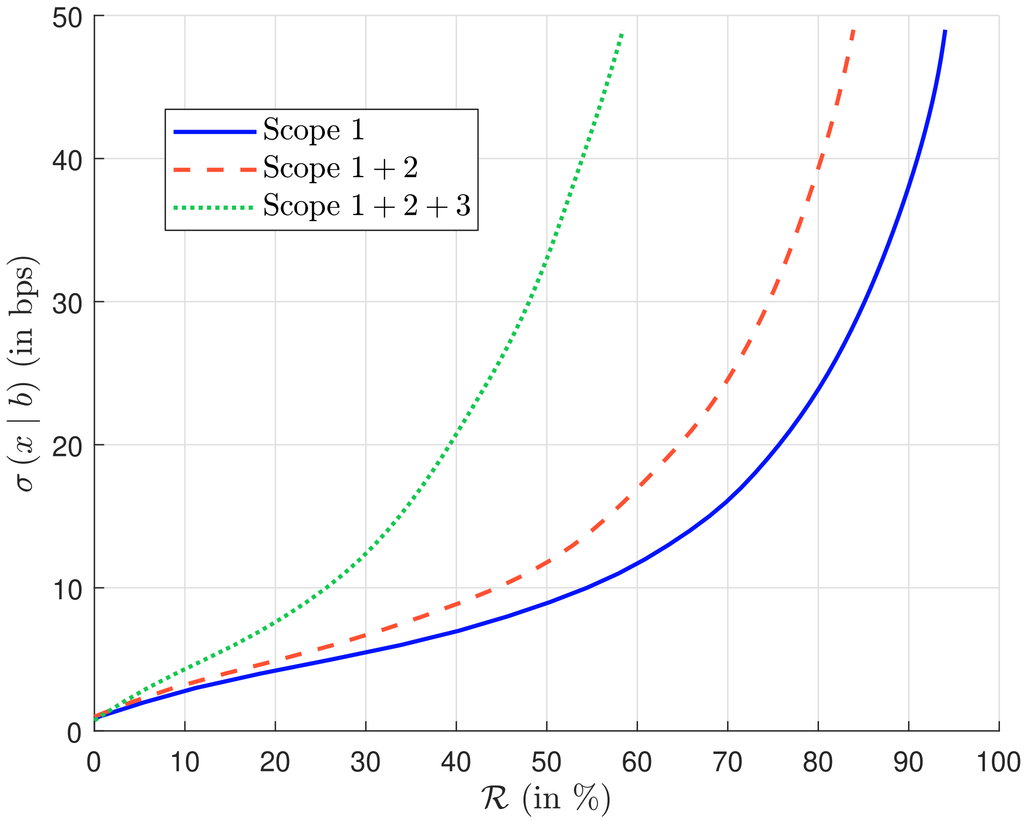
Figure 4: Efficient frontier of optimal decarbonization portfolios (S&P 500 index, October 2021, scope $1+2+3$)



Source: Trucost reporting year 2020 & Le Guenedal and Roncalli (2022).

Efficient frontier

Figure 5: Impact of the carbon scope on the tracking error volatility (S&P 500 index, October 2021, max-threshold approach)



Source: Trucost reporting year 2020 & Le Guenedal and Roncalli (2022).

Overlap statistics

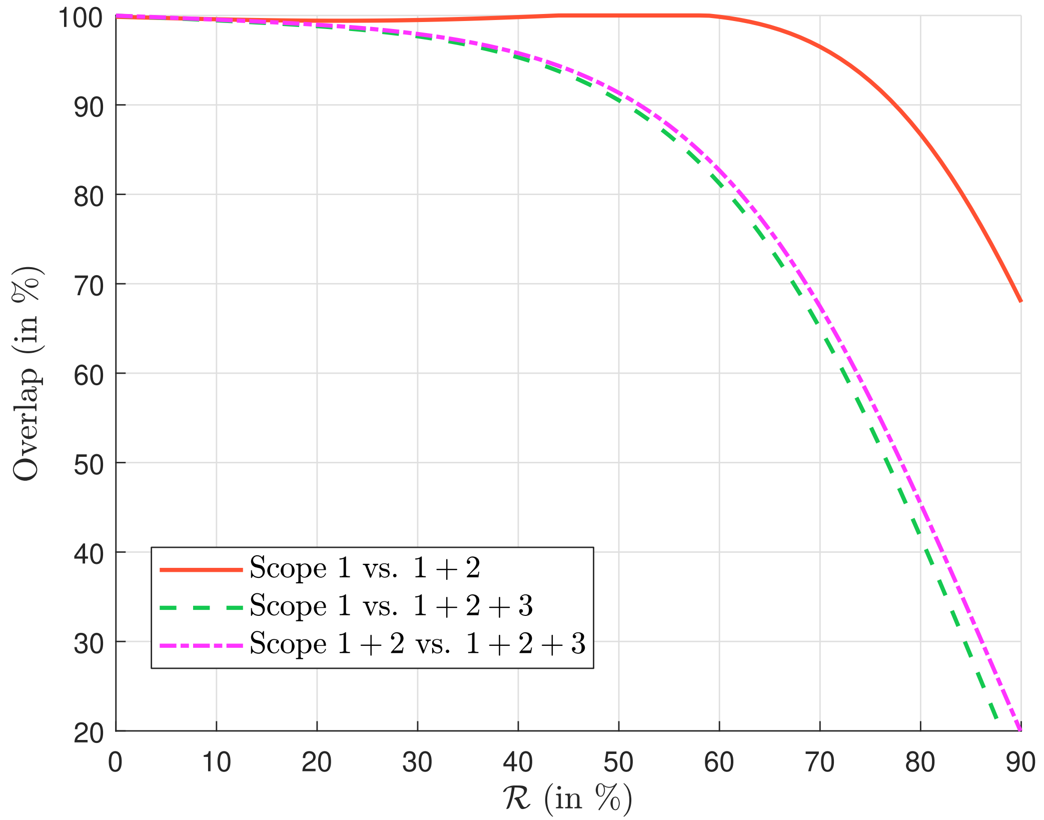
The overlap measure between two portfolios x and y is defined as:

$$\mathrm{overlap}\left(x, y\right) = 1 - \frac{1}{2}\sum_{i=1}^{n}\left|x_i - y_i\right| = \sum_{i=1}^{n}\min\left(x_i, y_i\right)$$

It is equal to 100% if the two portfolios are the same and 0% if the two portfolios have no common trading positions

Overlap statistics

Figure 6: Overlap of optimal decarbonization portfolios (S&P 500 index, October 2021, max-threshold approach)



Source: Trucost reporting year 2020 & Le Guenedal and Roncalli (2022).

Lessons from portfolio decarbonization

- 2010: Scope 1 $\Rightarrow$ 2015: Scope $1+2$ $\Rightarrow$ 2020's: Scope $1+2+3$
- Big differences between Scope $1+2$ and Scope $1+2+3$
  - High tracking error risk
  - Measurement uncertainty
  - Less diversification?

Carbon emissions contribution

- The carbon emissions contribution of a nominal exposure W_i to the stock i is equal to:

$$\boldsymbol{\mathcal{CEC}}_i(W_i) = \frac{W_i}{\mathcal{MC}_i} \cdot (\mathcal{FP}_i \cdot \boldsymbol{\mathcal{CE}}_i)$$

  where $\mathcal{FP}_i$ is the float percentage associated with the stock i and $\mathcal{MC}_i$ is the free-float market capitalization
- $\mathcal{FP}_i \cdot \boldsymbol{\mathcal{CE}}_i$ is the quantity of carbon emissions emitted by the issuer i that is attributed to public investors
- We normalize the carbon emissions amount $\mathcal{FP}_i \cdot \boldsymbol{\mathcal{CE}}_i$ by the holding ratio $W_i / \mathcal{MC}_i$

If we assume that $\mathcal{FP}_i = 90\%$, $\mathcal{MC}_i = \$20$ bn, $\boldsymbol{\mathcal{CE}}_i = 3\,116\,272$ tCO_2e and $W_i = \$100$ mn, we obtain:

$$\boldsymbol{\mathcal{CEC}}_i(\$100 \text{ mn}) = \frac{100}{20 \times 10^3} \times (90\% \times 3\,116\,272) = 14\,023.22 \text{ tCO}_2\text{e}$$

Carbon emissions contribution

- The market value of the company is:

$$\mathcal{MV}_i = \frac{\mathcal{MC}_i}{\mathcal{FP}_i}$$

- The carbon emissions contribution of a nominal exposure W_i to the stock i is equal to:

$$\boldsymbol{\mathcal{CEC}}_i \left(W_i \right) = \varpi_i \cdot \boldsymbol{\mathcal{CE}}_i = \frac{W_i}{\mathcal{MV}_i} \cdot \boldsymbol{\mathcal{CE}}_i$$

where $\varpi_i = W_i / \mathcal{MV}_i$ is the ownership ratio of the company

If we assume that $\mathcal{FP}_i = 90\%$, $\mathcal{MC}_i = \$20$ bn, $\boldsymbol{\mathcal{CE}}_i = 3\,116\,272$ tCO_2e and $W_i = \$100$ mn, we obtain:

$$\mathcal{MV}_i = \frac{\mathcal{MC}_i}{\mathcal{FP}_i} = \$22.22\text{bn}, \ \varpi_i = \frac{W_i}{\mathcal{MV}_i} = \frac{\$100 \text{ mn}}{\$22.22 \text{ bn}} = 0.45\%$$

$$\boldsymbol{\mathcal{CEC}}_i \left(\$100 \text{ mn} \right) = 0.45\% \times 3\,116\,272 = 14\,023.22 \text{ tCO}_2\text{e}$$

Carbon emissions contribution

- We have:

$$\boldsymbol{\mathcal{CI}}_i^{\mathcal{MV}} = \frac{\boldsymbol{\mathcal{CE}}_i}{\mathcal{MV}_i}$$

- It follows that:

$$\boldsymbol{\mathcal{CEC}}_i\left(W_i\right) = W_i \cdot \boldsymbol{\mathcal{CI}}_i^{\mathcal{MV}}$$

If we assume that $\mathcal{FP}_i = 90\%$, $\mathcal{MC}_i = \$20$ bn, $\boldsymbol{\mathcal{CE}}_i = 3\,116\,272$ tCO_2e and $W_i = \$100$ mn, we obtain:

$$\begin{aligned}
\mathcal{MV}_i &= \frac{\mathcal{MC}_i}{\mathcal{FP}_i} = \$22.22\text{bn} \\
\boldsymbol{\mathcal{CI}}_i^{\mathcal{MV}} &= \frac{\boldsymbol{\mathcal{CE}}_i}{\mathcal{MV}_i} = \frac{3\,116\,272}{22\,222.22} = 140.2322 \text{ tCO}_2\text{e}/\$\text{ mn} \\
\boldsymbol{\mathcal{CEC}}_i\left(\$100 \text{ mn}\right) &= 100 \times 140.2322 = 14\,023.22\text{tCO}_2\text{e}
\end{aligned}$$

Carbon emissions of a portfolio

- W is the nominal value of the portfolio
- $W_i = W \cdot x_i$ is the wealth invested in asset i
- The carbon emissions of the portfolio is the sum of the carbon emissions contributions:

$$\begin{aligned}\mathcal{CE}(x; W) &= \sum_{i=1}^{n} \mathcal{CEC}_i(W_i) \\ &= \sum_{i=1}^{n} \frac{W_i \cdot \mathcal{FP}_i}{\mathcal{MC}_i} \cdot \mathcal{CE}_i \\ &= W \cdot \overline{\mathcal{CE}}(x; W)\end{aligned}$$

  where $\overline{\mathcal{CE}}(x; W)$ is the normalized carbon emissions for a \$1 investment:

$$\overline{\mathcal{CE}}(x; W) = \sum_{i=1}^{n} \frac{x_i \cdot \mathcal{FP}_i}{\mathcal{MC}_i} \cdot \mathcal{CE}_i$$

- $\overline{\mathcal{CE}}(x; W)$ is generally expressed in tCO_2e per 1\$ mn invested

Carbon emissions of a portfolio

Remark

If we assume that $\mathcal{FP}_i = 100\%$ and the portfolio is an index ($x_i \propto \mathcal{MC}_i$), the carbon emissions of the portfolio is equal to the ownership ratio of the index portfolio times the sum of carbon emissions of all constituents times:

$$\mathcal{CE}(x; W) = \frac{W}{\sum_{i=1}^{n} \mathcal{MC}_i} \sum_{i=1}^{n} \mathcal{CE}_i$$

Carbon intensity of a portfolio

- We have:

$$\mathcal{CI}^{\mathrm{direct}}(x) = \sum_{i=1}^{n} x_i \cdot \mathcal{CI}_i$$

- The carbon intensity of the portfolio is:

$$\mathcal{CI}^{\mathrm{exact}}(x; W) = \frac{\mathcal{CE}(x; W)}{Y(x; W)}$$

where:

$$Y(x; W) = \sum_{i=1}^{n} \frac{W_i \cdot \mathcal{FP}_i}{\mathcal{MC}_i} \cdot Y_i$$

Computation of the portfolio's carbon emissions

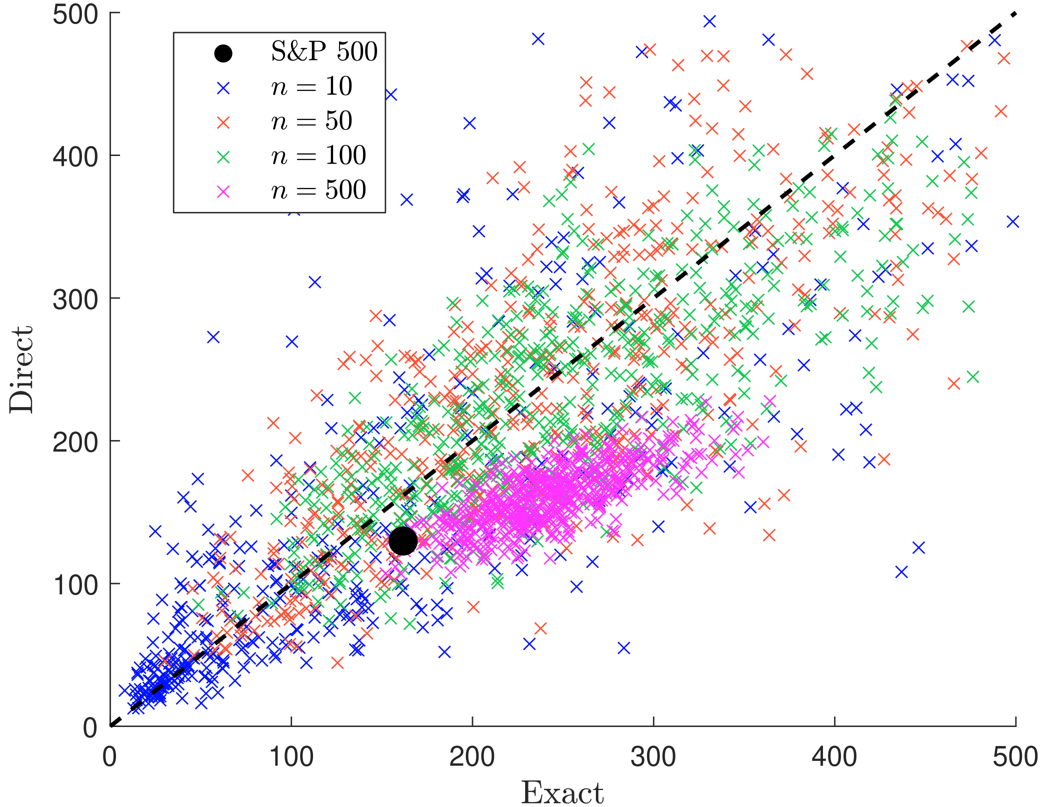
Table 4: Carbon emission (in tCO_2e) and intensity (tCO_2e/$ mn) of S&P 500 index portfolios

Scope	$\mathcal{CE}(x; W)$ S&P 500	$\mathcal{CE}(x; W)$ \$1 bn	$\mathcal{CE}(x; W)$ \$5 bn	$\mathcal{CI}(x)$ Exact	$\mathcal{CI}(x)$ Direct
1	1.66×10^9	40.5×10^3	202.5×10^3	133.8	99.2
$1+2$	2.01×10^9	48.9×10^3	244.7×10^3	161.7	129.8
$1+2+3$	3.75×10^9	91.4×10^3	457.2×10^3	302.1	245.2

Source: Trucost reporting year 2020 & Le Guenedal and Roncalli (2022).

Computation of the portfolio's carbon emissions

Figure 7: Exact vs. direct computation of scope $1+2$ carbon intensity (S&P 500 index, October 2021)



Source: Trucost reporting year 2020 & Le Guenedal and Roncalli (2022).

Portfolio optimization with carbon emissions

- We have:

$$\mathcal{CE}(x; W) \leq \mathcal{CE}^+ \Leftrightarrow \sum_{i=1}^{n} \frac{W_i \cdot \mathcal{FP}_i}{\mathcal{MC}_i} \cdot \mathcal{CE}_i \leq \mathcal{CE}^+$$
$$= \sum_{i=1}^{n} x_i \cdot \mathcal{CI}_i^{\mathcal{MV}} \leq \frac{\mathcal{CE}^+}{W}$$

where $\mathcal{CI}_i^{\mathcal{MV}}$ is the carbon intensity measure normalized by the market value of the company i:

$$\mathcal{CI}_i^{\mathcal{MV}} = \frac{\mathcal{FP}_i}{\mathcal{MC}_i} \cdot \mathcal{CE}_i = \frac{\mathcal{CE}_i}{\mathcal{MV}_i}$$

- In the case where $\mathcal{CE}^+ = (1 - \mathcal{R}) \cdot \mathcal{CE}(b; W)$, we obtain:

$$\frac{\mathcal{CE}^+}{W} = (1 - \mathcal{R}) \cdot \sum_{i=1}^{n} b_i \cdot \mathcal{CI}_i^{\mathcal{MV}}$$

Portfolio optimization with carbon emissions

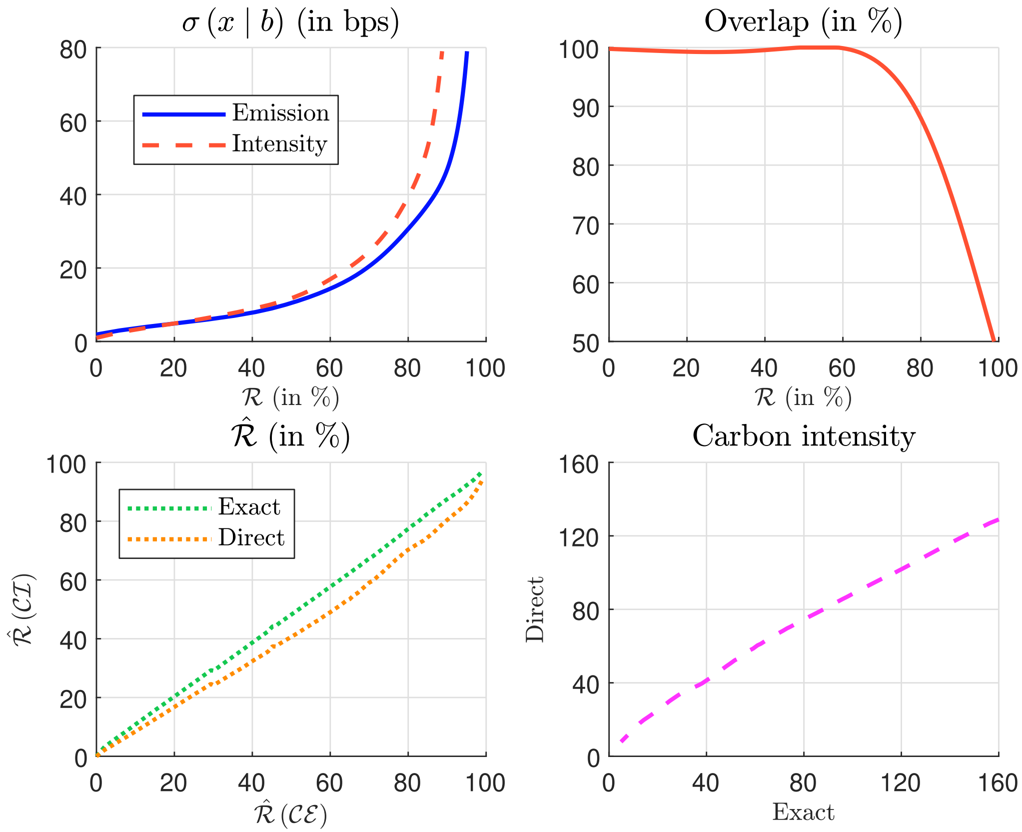
- The optimization problem becomes:

$$
\begin{array}{rcl}
x^{\star}\left(\mathcal{R}\right) & = & \arg\min \dfrac{1}{2}\left(x-b\right)^{\top}\Sigma\left(x-b\right) \\
 & \text{s.t.} & \left\{\begin{array}{l}
\mathbf{1}_n^{\top}x = 1 \\
x \geq \mathbf{0}_n \\
\sum_{i=1}^{n} x_i \cdot \mathcal{CI}_i^{\mathcal{MV}} \leq \left(1-\mathcal{R}\right)\cdot\left(\sum_{i=1}^{n} b_i \cdot \mathcal{CI}_i^{\mathcal{MV}}\right)
\end{array}\right.
\end{array}
$$

- The implied reduction rates are $\hat{\mathcal{R}}\left(\mathcal{CE}\right) = 1 - \mathcal{CE}\left(x^{\star}\right)/\mathcal{CE}\left(b\right)$ and $\hat{\mathcal{R}}\left(\mathcal{CI}\right) = 1 - \mathcal{CI}\left(x^{\star}\right)/\mathcal{CI}\left(b\right)$

Portfolio optimization with carbon emissions

Figure 8: Portfolio decarbonization with carbon emissions (S&P 500 index, October 2021, scope $1+2$)



Source: Trucost reporting year 2020 & Le Guenedal and Roncalli (2022).

The arithmetic of net zero

"Using global mean surface air temperature, as in AR5, gives an estimate of the remaining carbon budget of 580 GtCO$_2$e for a 50% probability of limiting warming to $1.5°\mathrm{C}$, and 420 GtCO$_2$e for a 66% probability (medium confidence)" (IPCC, 2018).

$$\Pr\left\{\mathcal{T} \leq 1.5°\mathrm{C} \mid \mathcal{CB}(2019, 2050) \leq 580 \text{ GtCO}_2\text{e}\right\} \geq 50\%$$

$$\Pr\left\{\mathcal{T} \leq 1.5°\mathrm{C} \mid \mathcal{CB}(2019, 2050) \leq 420 \text{ GtCO}_2\text{e}\right\} \geq 66\%$$

$$\Pr\left\{\mathcal{T} \leq 1.5°\mathrm{C} \mid \mathcal{CB}(2019, 2050) \leq 300 \text{ GtCO}_2\text{e}\right\} \geq 83\%$$

NZE framework

Net zero emission tools

- **Absolute carbon emissions**
- Carbon target
- Carbon trend
- Carbon budget

Carbon budget

- The carbon budget defines the amount of GHG emissions that a country, a company or an organization produces over the time period $[t_0, t]$.
- The gross carbon budget is equal to:

$$\mathcal{CB}_i(t_0, t) = \int_{t_0}^{t} \mathcal{CE}_i(s)\,\mathrm{d}s$$

- The net carbon budget is equal to:

$$\begin{aligned}\mathcal{CB}_i(t_0, t) &= \int_{t_0}^{t} \left(\mathcal{CE}_i(s) - \mathcal{CE}_i^{\star}\right)\mathrm{d}s \\ &= -(t - t_0)\cdot\mathcal{CE}_i^{\star} + \int_{t_0}^{t} \mathcal{CE}_i(s)\,\mathrm{d}s\end{aligned}$$

Carbon budget

We assume that $\mathcal{CE}_i(t)$ is known for $t \in \{t_0, t_1, \ldots, t_m\}$ and $\mathcal{CE}_i(t)$ is linear between two consecutive dates:

$$\mathcal{CE}_i(t) = \mathcal{CE}_i(t_{k-1}) + \frac{\mathcal{CE}_i(t_k) - \mathcal{CE}_i(t_{k-1})}{t_k - t_{k-1}}(t - t_{k-1}) \qquad \text{if } t \in [t_{k-1}, t_k]$$

We can show that:

$$\begin{aligned}
\mathcal{CB}_i(t_0, t) \quad = \quad & \frac{1}{2}\sum_{k=1}^{k(t)} \left(\mathcal{CE}_i(t_k) - \mathcal{CE}_i(t_{k-1})\right)(t_k + t_{k-1}) + \\
& \sum_{k=1}^{k(t)} \left(\mathcal{CE}_i(t_{k-1}) - \mathcal{CE}_i^{\star}\right) t_k - \sum_{k=1}^{k(t)} \left(\mathcal{CE}_i(t_k) - \mathcal{CE}_i^{\star}\right) t_{k-1} + \\
& \frac{1}{2}\left(\mathcal{CE}_i(t) - \mathcal{CE}_i\left(t_{k(t)}\right)\right)\left(t + t_{k(t)}\right) + \\
& \left(\mathcal{CE}_i\left(t_{k(t)}\right) - \mathcal{CE}_i^{\star}\right) t - \sum_{k=1}^{k(t)} \left(\mathcal{CE}_i(t) - \mathcal{CE}_i^{\star}\right) t_{k(t)}
\end{aligned}$$

Carbon budget

Example 1

The data corresponds to observed values before 2019, and estimated values after this date. After year 2020, we assume that the carbon emissions are linear between two dates.

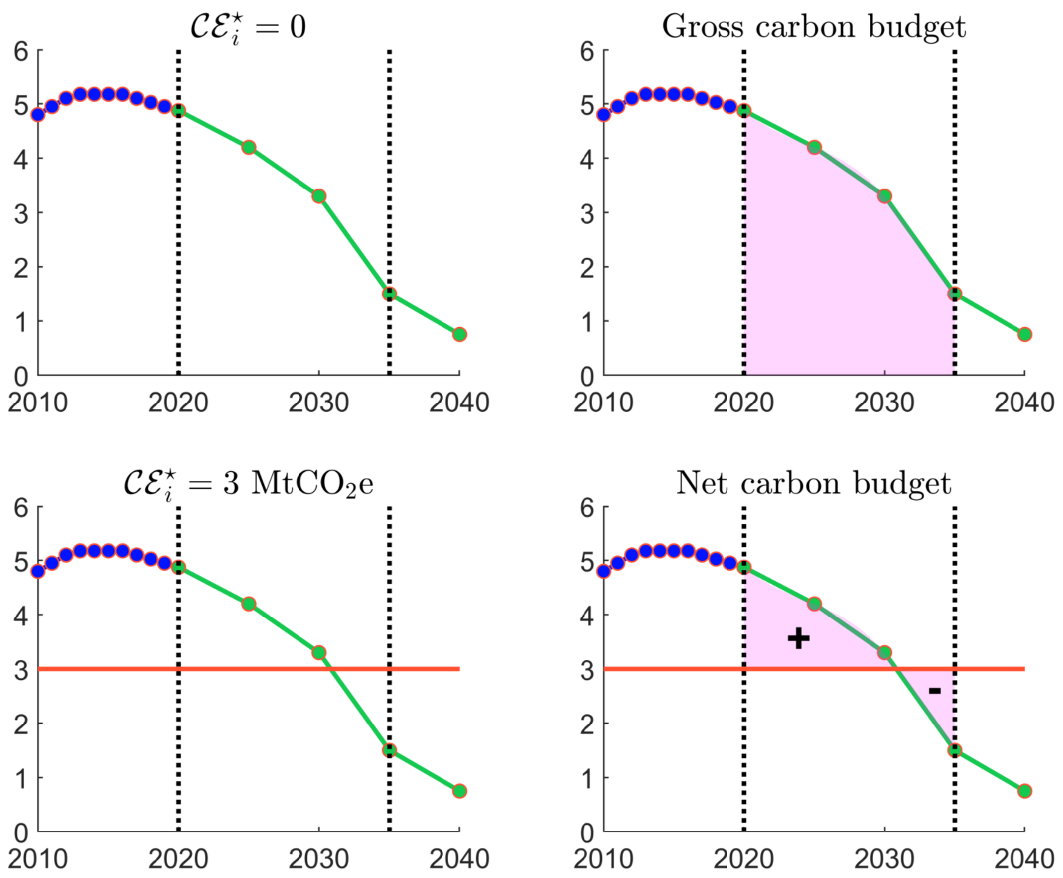
Table 5: Carbon emissions in $MtCO_2e$

Year	2010	2011	2012	2013	2014	2015	2016	2017
$\mathcal{CE}_i$	4.800	4.950	5.100	5.175	5.175	5.175	5.175	5.100
Year	2018	2019	2020*	2025*	2030*	2035*	2040*	2050*
$\mathcal{CE}_i$	5.025	4.950	4.875	4.200	3.300	1.500	0.750	0.150

Source: Le Guenedal *et al.* (2022).

Carbon budget

Figure 9: The gross carbon budget $\mathcal{CB}_i\,(2020, 2035)$ is equal to 53.4375 $MtCO_2e$ whereas the net carbon budget is equal to 8.4375 $MtCO_2e$



Source: Le Guenedal *et al.* (2022).

Carbon reduction

- $t_{\mathcal{L}ast}$ is the last reporting date.
- The estimated carbon emissions are:

$$\mathcal{CE}_i(t) := \widehat{\mathcal{CE}}_i(t) = (1 - \mathcal{R}_i(t_{\mathcal{L}ast}, t)) \cdot \mathcal{CE}_i(t_{\mathcal{L}ast})$$

where $\mathcal{R}_i(t_{\mathcal{L}ast}, t)$ is the carbon reduction between $t_{\mathcal{L}ast}$ and t

- We have

$$\begin{aligned}\mathcal{CB}_i(t_{\mathcal{L}ast}, t) &= (t - t_{\mathcal{L}ast})(\mathcal{CE}_i(t_{\mathcal{L}ast}) - \mathcal{CE}_i^{\star}) - \\ &\quad \mathcal{CE}_i(t_{\mathcal{L}ast}) \int_{t_{\mathcal{L}ast}}^{t} \mathcal{R}_i(t_{\mathcal{L}ast}, s)\,\mathrm{d}s\end{aligned}$$

Carbon reduction

1. Global approach

$$\mathcal{R}_i\left(t_{\mathcal{L}ast},t\right)=\mathcal{R}_{\mathcal{G}lobal}\left(t_{\mathcal{L}ast},t\right)$$

2. Country approach

$$\mathcal{R}_i\left(t_{\mathcal{L}ast},t\right)=\mathcal{R}_{\mathcal{C}ountry(c)}\left(t_{\mathcal{L}ast},t\right)\qquad \text{if } i\in\mathcal{C}ountry\left(c\right)$$

3. Sector approach

$$\mathcal{R}_i\left(t_{\mathcal{L}ast},t\right)=\mathcal{R}_{\mathcal{S}ector(s)}\left(t_{\mathcal{L}ast},t\right)\qquad \text{if } i\in\mathcal{S}ector\left(s\right)$$

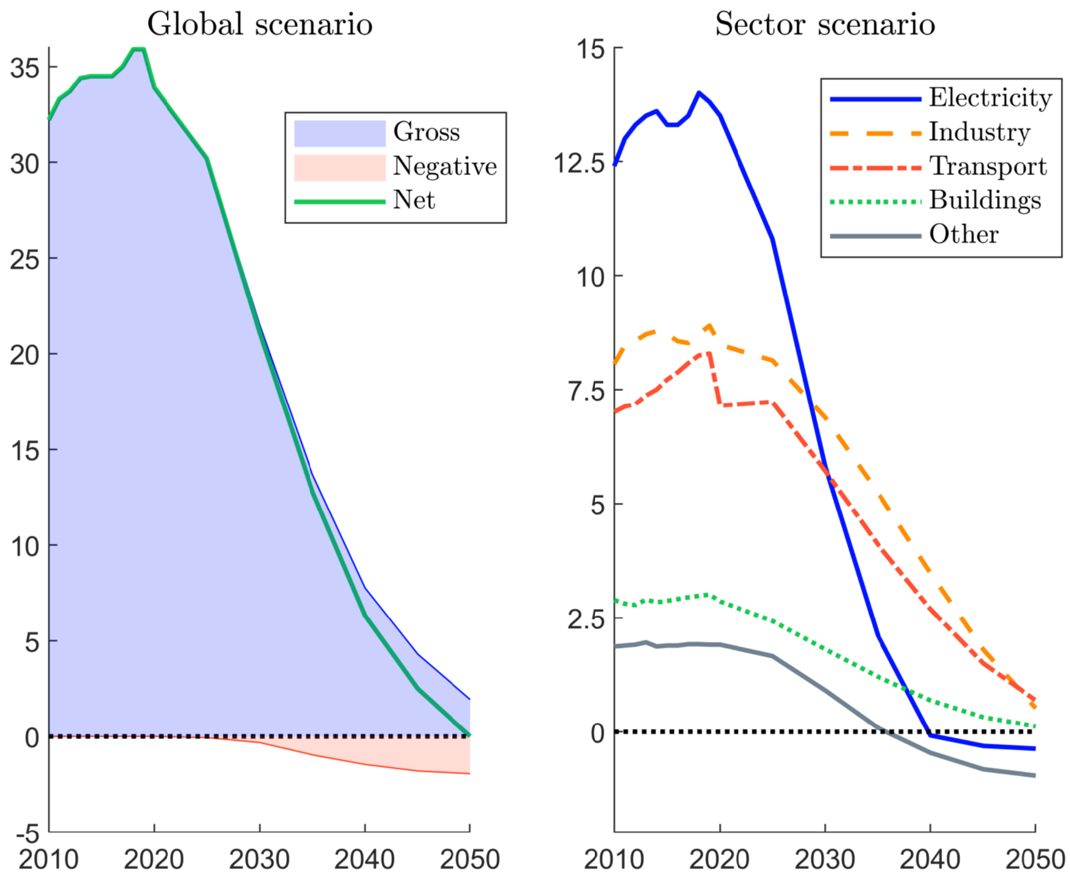
4. Issuer approach

$$\mathcal{R}_i\left(t_{\mathcal{L}ast},t\right)=\hat{\mathcal{R}}_i\left(t_{\mathcal{L}ast},t\right)$$

where $\hat{\mathcal{R}}_i\left(t_{\mathcal{L}ast},t\right)$ is the estimated value by the issuer

Carbon reduction

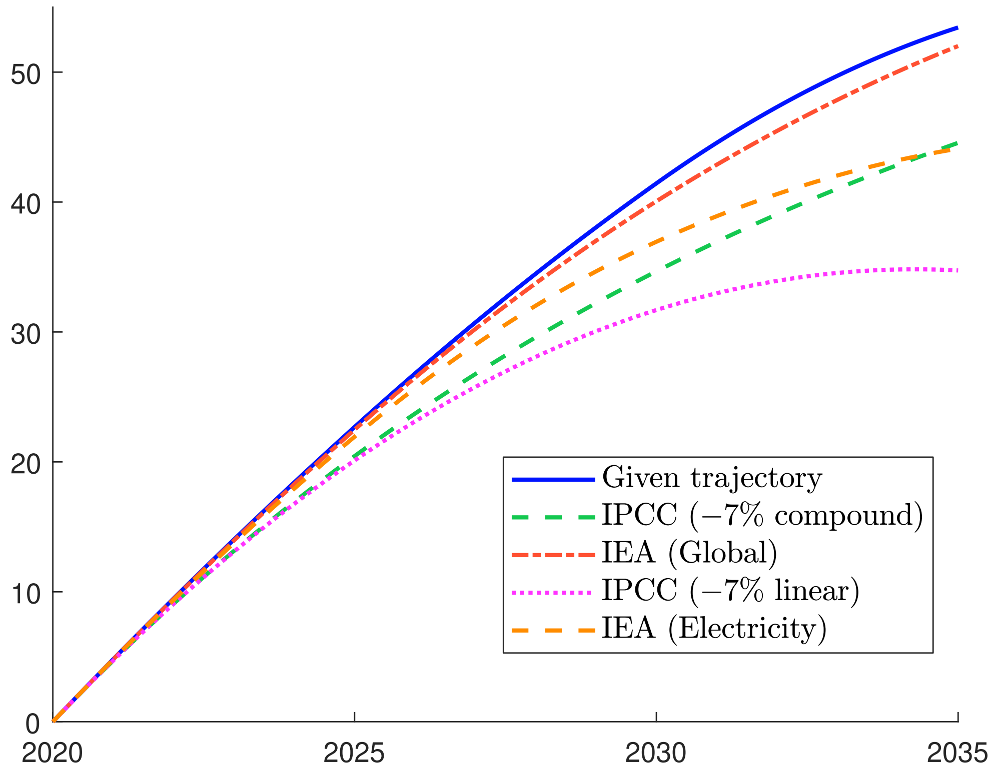
Figure 10: CO_2 emissions in the IEA NZE scenario



Source: IEA (2021).

Carbon reduction

Figure 11: Comparison of gross carbon budget with different scenarios*



Source: IEA (2021), IPCC (2018) & Le Guenedal *et al.* (2022).

*Reduction scenarios: given trajectory (Example 1), IPCC (−7% compound reduction), IEA (global scenario), IPCC (−7% linear reduction) and IEA (electricity sector scenario)

Carbon target

The carbon target setting is defined from the following space:

$$\mathcal{T} = \left\{k \in [1, m] : \left(i, j, t_1^k, t_2^k, \boldsymbol{\mathcal{R}}_{i,j}\left(t_1^k, t_2^k\right)\right)\right\}$$

where k is the target index, m is the number of historical targets, i is the issuer, j is the scope, t_1^k is the beginning of the target period, t_2^k is the end of the target period, and $\boldsymbol{\mathcal{R}}_{i,j}\left(t_1^k, t_2^k\right)$ is the carbon reduction between t_1^k and t_2^k for the scope j announced by issuer i

Carbon target

Here are the steps to compute the target trajectory

1. The linear annual reduction rate for scope j and target k is given by:

$$\mathcal{R}_{i,j}^{k}\left(t\right) = \mathbb{1}\left\{t \in \left[t_1^k, t_2^k\right]\right\} \cdot \frac{\mathcal{R}_{i,j}\left(t_1^k, t_2^k\right)}{t_2^k - t_1^k}$$

2. We aggregate the targets to obtain the annual reduction rate:

$$\mathcal{R}_{i,j}\left(t\right) = \sum_{k=1}^{m} \mathcal{R}_{i,j}^{k}(t)$$

3. We compute the global reduction at time t:

$$\mathcal{R}_{i}\left(t\right) = \frac{1}{\sum_{j=1}^{3} \mathcal{CE}_{i,j}\left(t_0\right)} \cdot \sum_{j=1}^{3} \mathcal{CE}_{i,j}\left(t_0\right) \cdot \mathcal{R}_{i,j}\left(t\right)$$

4. Finally, we have:

$$\mathcal{CE}_{i}^{\mathcal{T}arget}\left(t\right) := \widehat{\mathcal{CE}}_{i}\left(t\right) = \left(1 - \mathcal{R}_{i}\left(t_{\mathcal{L}ast}, t\right)\right) \cdot \mathcal{CE}_{i}\left(t_{\mathcal{L}ast}\right)$$

where $\mathcal{R}_{i}\left(t_{\mathcal{L}ast}, t\right) = \sum_{s=t_{\mathcal{L}ast}+1}^{t} \mathcal{R}_{i}\left(s\right)$

Carbon target

Example 2

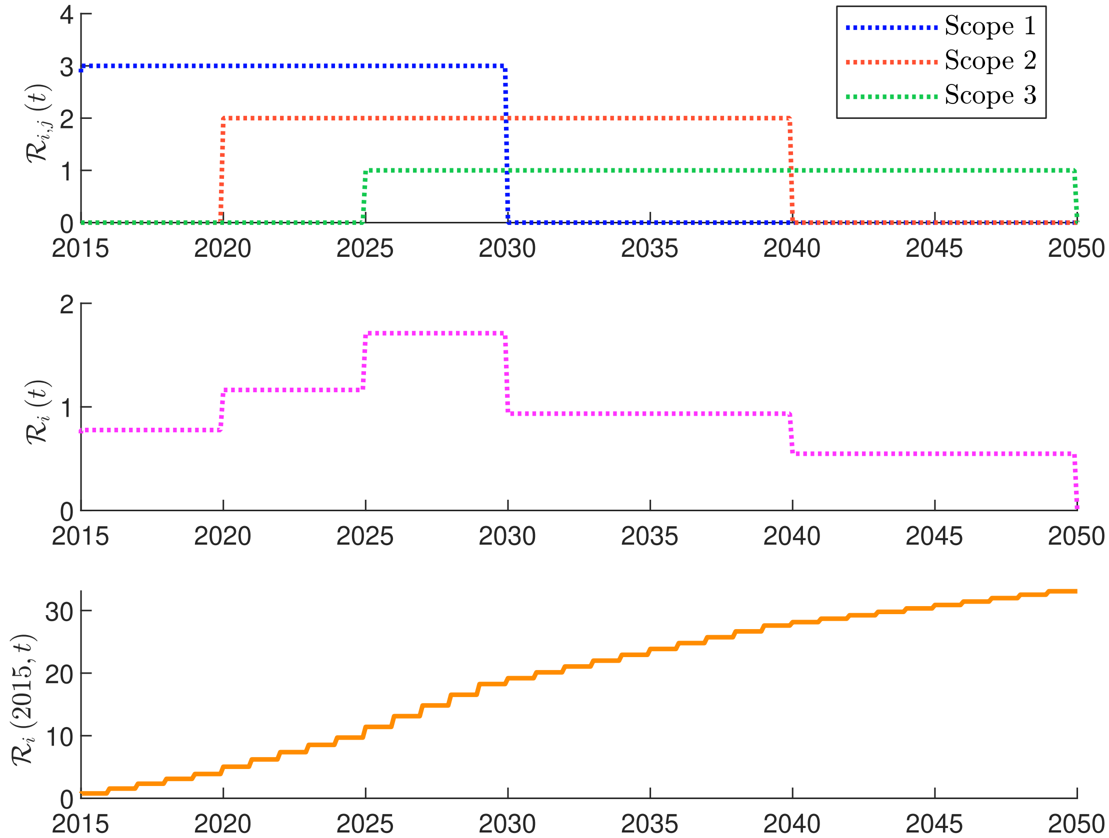
- The dates t_1^k and t_2^k correspond to the 1[st] January
- We assume that $\mathcal{CE}_{i,1}(2020) = 10.33$, $\mathcal{CE}_{i,2}(2020) = 7.72$ and $\mathcal{CE}_{i,3}(2020) = 21.86$

Table 6: Carbon reduction targets (Example 2)

k	Release Date	Scope	t_1^k	t_2^k	$\mathcal{R}(t_1^k, t_2^k)$
1	01/08/2013	$\mathcal{SC}_1$	2015	2030	45%
2	01/10/2019	$\mathcal{SC}_2$	2020	2040	40%
3	01/01/2019	$\mathcal{SC}_3$	2025	2050	25%

Carbon target

Figure 12: Reduction of the carbon emissions deduced from the three targets (Example 2)



Source: Le Guenedal *et al.* (2022).

Carbon trend

We define the carbon trend by considering a linear constant trend model:

$$\mathcal{CE}_i(t) = \beta_{i,0} + \beta_{i,1} t + u_i(t)$$

where $t \in [t_{\mathcal{F}irst}, t_{\mathcal{L}ast}]$

The carbon trajectory implied by the current trend is given by:

$$\mathcal{CE}_i^{\mathcal{T}rend}(t) := \widehat{\mathcal{CE}}_i(t) = \hat{\beta}_{i,0} + \hat{\beta}_{i,1} t$$

for $t > t_{\mathcal{L}ast}$

Carbon trend

Example 4

Table 7: Carbon emissions in $MtCO_2e$

Year	2007	2008	2009	2010	2011	2012	2013
$\mathcal{CE}_i(t)$	57.82	58.36	57.70	55.03	51.73	46.44	47.19
Year	2014	2015	2016	2017	2018	2019	2020
$\mathcal{CE}_i(t)$	46.18	45.37	40.75	39.40	36.16	38.71	39.91

We obtain:

$$\begin{aligned}\mathcal{CE}_i^{\mathcal{T}rend}(t) &= 3\,637.73 - 1.7832 \cdot t \\ &= 35.61 - 1.7822 \cdot (t - 2020)\end{aligned}$$

The rescaled trend model is:

$$\mathcal{CE}_i^{\mathcal{T}rend}(t) = 39.91 - 1.7822 \cdot (t - 2020)$$

NZE metrics

Net zero emission metrics

Static NZE metrics

- Gap
- Slope
- Budget
- Duration
  - Gap
  - Budget

Dynamic NZE metrics

- Time contribution
  - Error contribution
  - Revision contribution
- Velocity
- Scenarios
  - Zero-velocity scenario
  - Burn-out scenario

Static NZE measures

- t_0 is the current date
- $t^\star$ is the time/target horizon
- $\mathcal{CE}_i^{\mathrm{nze}}(t^\star)$ is the net zero emission scenario for issuer i
  - It can be computed using the targets of the issuer
  - It can be calculated using a market-based consensus scenario:

$$\mathcal{CE}_i^{\mathrm{nze}}(t^\star) = (1 - \mathcal{R}^\star(t_0, t^\star)) \cdot \mathcal{CE}_i(t_0)$$

    where $\mathcal{R}^\star(t_0, t^\star)$ is the carbon reduction between t_0 and $t^\star$ expected by the market for this issuer
- We use the generic notation $\widehat{\mathcal{CE}}_i(t)$ to name $\mathcal{CE}_i^{\mathcal{T}arget}(t)$ and $\mathcal{CE}_i^{\mathcal{T}rend}(t)$

The NZE duration

The time to reach the NZE scenario (or NZE duration) is defined as follows:

$$\tau_i = \left\{ \inf t : \widehat{\mathcal{CE}}_i(t) \leq \mathcal{CE}_i^{\mathrm{nze}}(t^\star) \right\}$$

- If $\widehat{\mathcal{CE}}_i(t) = \mathcal{CE}_i^{\mathcal{T}arget}(t)$, we obtain the NZE duration $\tau_i^{\mathcal{T}arget}$ $\Rightarrow$This measure indicates if the carbon targets announced by the company are in line with the consensus scenario $\mathcal{CE}_i^{\mathrm{nze}}(t^\star)$
- If $\widehat{\mathcal{CE}}_i(t) = \mathcal{CE}_i^{\mathcal{T}rend}(t)$, we obtain the NZE duration $\tau_i^{\mathcal{T}rend}$ $\Rightarrow$ This measure indicates if the track record of the issuer is in line with its targets or the consensus scenario

The NZE duration

For the trend approach, we remind that:

$$\mathcal{CE}_i^{\mathcal{T}rend}(t) = \hat{\beta}_{i,0} + \hat{\beta}_{i,1} t$$

We distinguish two cases:

1. If the slope $\hat{\beta}_{i,1}$ is positive, we have:

$$\tau_i^{\mathcal{T}rend} = \begin{cases} t_0 & \text{if } \mathcal{CE}_i(t_0) \leq \mathcal{CE}_i^{\mathrm{nze}}(t^\star) \\ +\infty & \text{otherwise} \end{cases}$$

2. If the slope $\hat{\beta}_1$ is negative, we have:

$$\tau_i^{\mathcal{T}rend} = t_0 + \frac{\mathcal{CE}_i^{\mathrm{nze}}(t^\star) - \hat{\beta}'_{i,0}}{\hat{\beta}_{i,1}}$$

where $\hat{\beta}'_{i,0} = \hat{\beta}_{i,0} + \hat{\beta}_{i,1} t_0$ is the intercept of the trend model when we use t_0 as the pivot date

The NZE duration

Proof.

$$
\begin{aligned}
\mathcal{CE}_i^{Trend}(t) \leq \mathcal{CE}_i^{\mathrm{nze}}(t^\star) & \Leftrightarrow \quad \hat{\beta}_{i,0} + \hat{\beta}_{i,1} t \leq \mathcal{CE}_i^{\mathrm{nze}}(t^\star) \\
& \Leftrightarrow \quad t \geq \frac{\mathcal{CE}_i^{\mathrm{nze}}(t^\star) - \hat{\beta}_{i,0}}{\hat{\beta}_{i,1}} \\
& \Leftrightarrow \quad t \geq t_0 + \frac{\mathcal{CE}_i^{\mathrm{nze}}(t^\star) - \left(\hat{\beta}_{i,0} + \hat{\beta}_{i,1} t_0\right)}{\hat{\beta}_{i,1}} \\
& \Leftrightarrow \quad t \geq t_0 + \frac{\mathcal{CE}_i^{\mathrm{nze}}(t^\star) - \hat{\beta}'_{i,0}}{\hat{\beta}_{i,1}}
\end{aligned}
$$

The NZE duration

Example 5 is the combination of Example 2 + Example 4

Table 8: Carbon reduction targets (Example 2)

k	Release Date	Scope	t_1^k	t_2^k	$\mathcal{R}\left(t_1^k, t_2^k\right)$
1	01/08/2013	$\mathcal{SC}_1$	2015	2030	45%
2	01/10/2019	$\mathcal{SC}_2$	2020	2040	40%
3	01/01/2019	$\mathcal{SC}_3$	2025	2050	25%

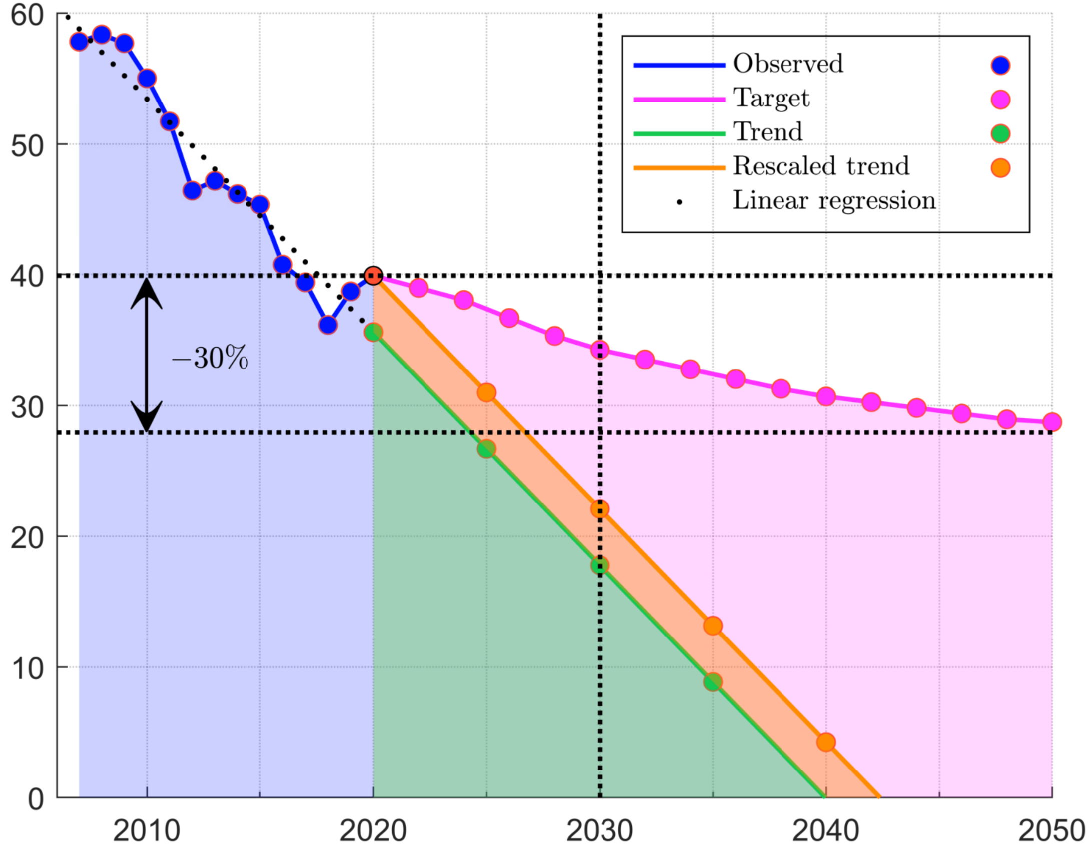
Table 9: Carbon emissions in $MtCO_2e$ (Example 4)

Year	2007	2008	2009	2010	2011	2012	2013
$\mathcal{CE}_i(t)$	57.82	58.36	57.70	55.03	51.73	46.44	47.19
Year	2014	2015	2016	2017	2018	2019	2020
$\mathcal{CE}_i(t)$	46.18	45.37	40.75	39.40	36.16	38.71	39.91

The market-based NZE scenario for 2030 is a reduction of carbon emissions by 30%: $\mathcal{CE}_i^{\mathrm{nze}}(2030) = 39.91 \times (1 - 30\%) = 27.94$ $MtCO_2e$

The NZE duration

Figure 13: $\tau_i^{Target} = +\infty$, $\tau_i^{Trend} = 2024.3$ (2026.7 if rescaled) (Example 5)



Source: Le Guenedal *et al.* (2022).

The NZE duration

- A special case of NZE scenario is to set $\mathcal{CE}_i^{\mathrm{nze}} = 0$
- In this case, $\boldsymbol{\tau}_i$ corresponds to the date when the company is expected to emit zero carbon emissions
- For the rescaled trend, if $\hat{\beta}_1 < 0$, we have

$$\boldsymbol{\tau}_i^{\mathcal{T}rend} = t_0 - \frac{\mathcal{CE}_i(t_0)}{\hat{\beta}_1}$$

- For instance, we obtain $\boldsymbol{\tau}_i^{\mathcal{T}rend} = 2042.38$, meaning that the company can reach a carbon neutrality by 2043 if it continues the same effort of carbon emissions reduction as observed during the period 2007–2020

The NZE gap

- The NZE gap is the expected distance between the estimated carbon emissions and the NZE scenario:

$$\mathcal{G}ap_i(t^\star) = \widehat{\mathcal{CE}}_i(t^\star) - \mathcal{CE}_i^{\mathrm{nze}}(t^\star)$$

- Again, we can use the target scenario:

$$\mathcal{G}ap_i^{\mathcal{T}arget}(t^\star) = \mathcal{CE}_i^{\mathcal{T}arget}(t^\star) - \mathcal{CE}_i^{\mathrm{nze}}(t^\star)$$

or the trend model:

$$\mathcal{G}ap_i^{\mathcal{T}rend}(t^\star) = \mathcal{CE}_i^{\mathcal{T}rend}(t^\star) - \mathcal{CE}_i^{\mathrm{nze}}(t^\star)$$

The NZE gap

We consider Example 5:

- We have $\mathcal{CE}_i^{\mathrm{nze}}(2030) = 27.94$, $\mathcal{CE}_i^{\mathcal{T}arget}(2030) = 34.27$ and $\mathcal{CE}_i^{\mathcal{T}rend}(2030) = 22.08$ for the rescaled trend model
- We deduce that the NZE gaps are $\mathcal{G}ap_i^{\mathcal{T}arget}(2030) = 6.33$ and $\mathcal{G}ap_i^{\mathcal{T}rend}(2030) = -5.86$
- If we define the NZE scenario by the target scenario $\mathcal{CE}_i^{\mathrm{nze}}(2030) = \mathcal{CE}_i^{\mathcal{T}arget}(2030) = 34.27$, we obtain $\mathcal{G}ap_i^{\mathcal{T}rend}(2030) = -12.19$

The NZE slope

- The NZE slope is the value of $\hat{\beta}_{i,1}$ such that the NZE gap is closed, meaning that $\mathcal{G}ap_i^{\mathcal{T}rend}(t^\star) = 0$
- We have:

$$\mathcal{S}lope_i(t^\star) = \frac{\mathcal{CE}_i^{\text{nze}}(t^\star) - \mathcal{CE}_i(t_0)}{t^\star - t_0}$$

- The slope is generally negative because the gap is negative if the NZE scenario is not already reached

The NZE slope

Proof.

- This solution is not acceptable because it depends on $\hat{\beta}_{i,0}$:

$$\begin{aligned}\mathcal{G}ap_i^{\mathcal{T}rend}\left(t^{\star}\right)=0 \quad &\Leftrightarrow \quad \hat{\beta}_{i,0}+\hat{\beta}_{i,1}t^{\star}-\mathcal{CE}_i^{\mathrm{nze}}\left(t^{\star}\right)=0 \\ &\Leftrightarrow \quad \hat{\beta}_{i,1}=\frac{\mathcal{CE}_i^{\mathrm{nze}}\left(t^{\star}\right)-\hat{\beta}_{i,0}}{t^{\star}}\end{aligned}$$

- Using the rescaled trend model and the pivot date t_0, we obtain:

$$\begin{aligned}\mathcal{G}ap_i^{\mathcal{T}rend}\left(t^{\star}\right)=0 \quad &\Leftrightarrow \quad \hat{\beta}'_{i,0}+\hat{\beta}_{i,1}\left(t^{\star}-t_0\right)-\mathcal{CE}_i^{\mathrm{nze}}\left(t^{\star}\right)=0 \\ &\Leftrightarrow \quad \hat{\beta}_{i,1}=\frac{\mathcal{CE}_i^{\mathrm{nze}}\left(t^{\star}\right)-\hat{\beta}'_{i,0}}{t^{\star}-t_0} \\ &\Leftrightarrow \quad \mathcal{S}lope_i\left(t^{\star}\right)=\frac{\mathcal{CE}_i^{\mathrm{nze}}\left(t^{\star}\right)-\mathcal{CE}_i\left(t_0\right)}{t^{\star}-t_0}\end{aligned}$$

∎

The NZE slope

We can normalize the slope metric by the current carbon emissions:

$$\overline{\mathcal{S}lope}_i\left(t^\star\right) = \frac{\mathcal{S}lope_i\left(t^\star\right)}{\mathcal{CE}_i\left(t_0\right)}$$

Another normalization consists in using the current slope $\hat{\beta}_{i,1}$ of the trend model. In this case, we obtain the slope multiplier:

$$m_i^{\mathcal{S}lope} = \frac{\mathcal{S}lope_i\left(t^\star\right)}{\hat{\beta}_{i,1}}$$

The NZE slope

- If we consider Example 5, we obtain:

$$\mathcal{S}lope_i\,(2030) = \frac{27.94 - 39.91}{2030 - 2020} = -1.1973$$

- We have:

$$\left|\mathcal{S}lope_i\,(2030)\right| = 1.1973 \leq \left|\hat{\beta}_{i,1}\right| = 1.7832$$

- The slope multiplier is equal to 67.14%

The NZE budget

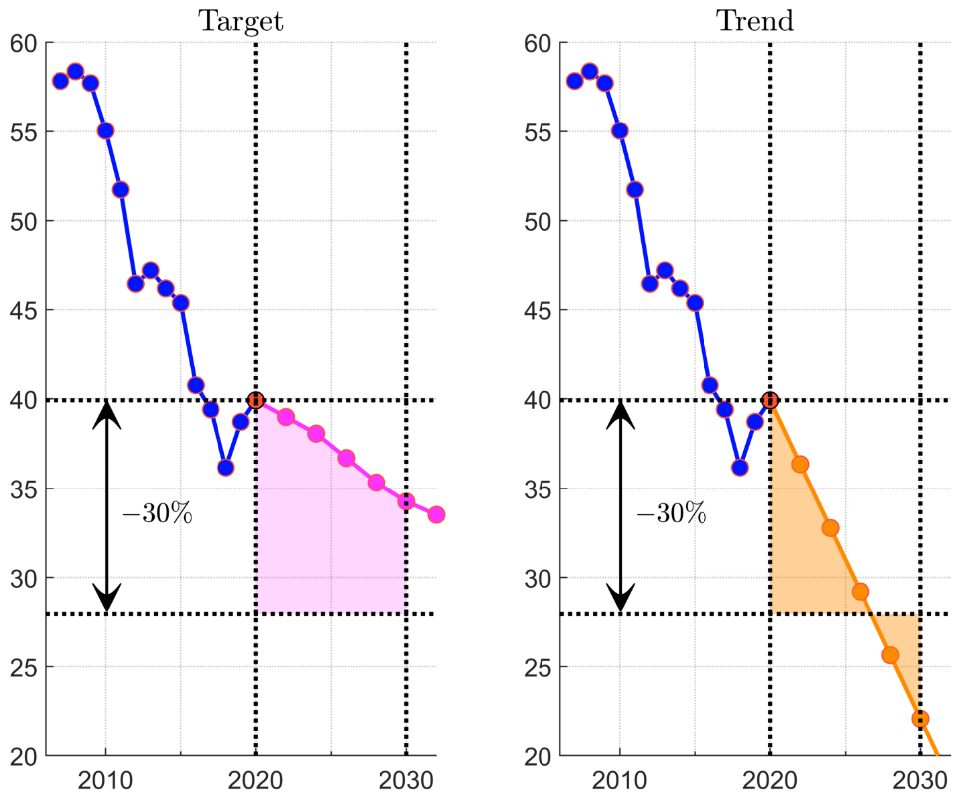
- The NZE budget corresponds to the carbon budget between the current date t_0 and the NZE date $t^\star$:

$$\mathcal{CB}_i\left(t_0, t^\star\right) = \int_{t_0}^{t^\star} \left(\widehat{\mathcal{CE}}_i\left(s\right) - \mathcal{CE}_i^{\mathrm{nze}}\left(t^\star\right)\right) \mathrm{d}s$$

- As previously, we can compute the carbon budget with respect to the target trajectory or the trend. We note them respectively by $\mathcal{CB}_i^{\mathcal{T}arget}\left(t_0, t^\star\right)$ and $\mathcal{CB}_i^{\mathcal{T}rend}\left(t_0, t^\star\right)$

The NZE budget

Figure 14: $\mathcal{CB}_i^{Target}(2020, 2030) = 92.735$ $MtCO_2e$ and $\mathcal{CB}_i^{Trend}(2020, 2030) = 30.568$ $MtCO_2e$ (Example 5)



Source: Le Guenedal *et al.* (2022).

The NZE (budget) duration

- We can define the duration with respect to the carbon budget:

$$\boldsymbol{\tau}_i = \inf \left\{ t : \mathcal{CB}_i \left(t_0, t \right) \leq 0 \right\}$$

- $\boldsymbol{\tau}_i$ indicates the time required to obtain a zero carbon budget since the current date t_0
- In the case of the trend model, we have:

$$\boldsymbol{\tau}_i^{\mathcal{T}rend} = t_0 + 2 \frac{\mathcal{CE}_i^{\star} - \hat{\beta}_0'}{\hat{\beta}_1}$$

- For instance, using the rescaled trend model of Example 5, we obtain $\boldsymbol{\tau}_i^{\mathcal{T}rend} = 2033.43$ when $\mathcal{CE}_i^{\star} = 27.94$ $MtCO_2e$.

Dynamic analysis of the track record

- Let $t_1 > t_0$ be a future reporting date. We have:

$$\mathcal{CB}_i(t_0, t^\star) = \int_{t_0}^{t_1} \left(\widehat{\mathcal{CE}}_i(s) - \mathcal{CE}_i^{\mathrm{nze}}(t^\star)\right) \mathrm{d}s + \int_{t_1}^{t^\star} \left(\widehat{\mathcal{CE}}_i(s) - \mathcal{CE}_i^{\mathrm{nze}}(t^\star)\right) \mathrm{d}s$$

When the current date becomes t_1, we obtain:

$$\mathcal{CB}_i(t_0, t^\star) = \underbrace{\mathcal{CB}_i(t_0, t_1)}_{\text{observed}} + \underbrace{\mathcal{CB}_i(t_1, t^\star)}_{\text{estimated}}$$

- A new reported value $\mathcal{CE}_i(t_1)$ of carbon emissions can change the expectations, meaning that:

$$\mathbb{E}\left[\mathcal{CE}_i(t) \mid \mathcal{F}_{t_0}\right] \neq \mathbb{E}\left[\mathcal{CE}_i(t) \mid \mathcal{F}_{t_1}\right] \qquad \text{for } t \geq t_1$$

Time contribution

- Let $\mathcal{CB}_i(t_0, t_1, t^\star)$ be the carbon budget between the starting date t_0 and the target date $t^\star$, which is evaluated at the current date t_1
- We have:

$$\mathcal{CB}_i(t_0, t_1, t^\star) = \mathcal{CB}_i(t_0, t_1, t_1) + \mathcal{CB}_i(t_1, t_1, t^\star)$$

- The contribution $\mathcal{TC}_i(t_1 \mid t_0, t^\star)$ of the new information observed at the date t_1 satisfies:

$$\mathcal{CB}_i(t_0, t_1, t^\star) = \mathcal{CB}_i(t_0, t_0, t^\star) + \mathcal{TC}_i(t_1 \mid t_0, t^\star)$$

- We have:

$$\mathcal{TC}_i(t_1 \mid t_0, t^\star) = \int_{t_0}^{t^\star} \left(\mathbb{E}\left[\mathcal{CE}_i(s) \mid \mathcal{F}_{t_1}\right] - \mathbb{E}\left[\mathcal{CE}_i(s) \mid \mathcal{F}_{t_0}\right]\right) \mathrm{d}s$$

Time contribution

The time contribution is made up of two components:

$$\mathcal{TC}_i\left(t_1 \mid t_0, t^\star\right) = \mathcal{TC}_i^{\mathrm{error}}\left(t_1 \mid t_0, t^\star\right) + \mathcal{TC}_i^{\mathrm{revision}}\left(t_1 \mid t_0, t^\star\right)$$

where:

1. $\mathcal{TC}_i^{\mathrm{error}}\left(t_1 \mid t_0, t^\star\right)$ measures the forecast error between the observed trajectory and the estimate done at time t_0:

$$\mathcal{TC}_i^{\mathrm{error}}\left(t_1 \mid t_0, t^\star\right) = \int_{t_0}^{t_1} \left(\mathcal{CE}_i\left(s\right) - \mathbb{E}\left[\mathcal{CE}_i\left(s\right) \middle| \mathcal{F}_{t_0}\right]\right) \mathrm{d}s$$

2. $\mathcal{TC}_i^{\mathrm{revision}}\left(t_1 \mid t_0, t^\star\right)$ measures the forecast revision:

$$\mathcal{TC}_i^{\mathrm{revision}}\left(t_1 \mid t_0, t^\star\right) = \int_{t_1}^{t^\star} \left(\mathbb{E}\left[\mathcal{CE}_i\left(s\right) \middle| \mathcal{F}_{t_1}\right] - \mathbb{E}\left[\mathcal{CE}_i\left(s\right) \middle| \mathcal{F}_{t_0}\right]\right) \mathrm{d}s$$

Time contribution

We can normalize the previous quantities by current carbon emissions and the corresponding time period:

$$\left\{\begin{array}{l}
\overline{\mathcal{TC}}_i\left(t_1 \mid t_0, t^\star\right) = \dfrac{\mathcal{TC}_i\left(t_1 \mid t_0, t^\star\right)}{\left(t^\star - t_0\right) \cdot \mathcal{CE}_i\left(t_0\right)} \\
\overline{\mathcal{TC}}_i^{\text{error}}\left(t_1 \mid t_0, t^\star\right) = \dfrac{\mathcal{TC}_i^{\text{error}}\left(t_1 \mid t_0, t^\star\right)}{\left(t_1 - t_0\right) \cdot \mathcal{CE}_i\left(t_0\right)} \\
\overline{\mathcal{TC}}_i^{\text{revision}}\left(t_1 \mid t_0, t^\star\right) = \dfrac{\mathcal{TC}_i^{\text{revision}}\left(t_1 \mid t_0, t^\star\right)}{\left(t^\star - t_1\right) \cdot \mathcal{CE}_i\left(t_0\right)}
\end{array}\right.$$

Application to the trend model

Let $\hat{\beta}_{i,0}(t)$ and $\hat{\beta}_{i,1}(t)$ be the intercept and the slope coefficient of the trend model that is estimated at time t. We have:

$$\begin{aligned}
\mathcal{TC}_i^{\mathrm{error}}(t_1 \mid t_0, t^\star) &= \int_{t_0}^{t_1} \left(\mathcal{CE}_i(s) - \left(\hat{\beta}_0(t_0) + \hat{\beta}_{i,1}(t_0)\, s\right)\right) \mathrm{d}s \\
&= -\frac{1}{2}\hat{\beta}_{i,1}(t_0)\left(t_1^2 - t_0^2\right) - \hat{\beta}_{i,0}(t_0)(t_1 - t_0) + \int_{t_0}^{t_1} \mathcal{CE}_i(s)\, \mathrm{d}s
\end{aligned}$$

and:

$$\begin{aligned}
\mathcal{TC}_i^{\mathrm{revision}}(t_1 \mid t_0, t^\star) &= \int_{t_1}^{t^\star} \left(\left(\hat{\beta}_{i,0}(t_1) + \hat{\beta}_{i,1}(t_1)\, s\right) - \left(\hat{\beta}_{i,0}(t_0) + \hat{\beta}_{i,1}(t_0)\, s\right)\right) \mathrm{d}s \\
&= \frac{1}{2}\left(\hat{\beta}_{i,1}(t_1) - \hat{\beta}_1(t_0)\right)\left(t^{\star 2} - t_1^2\right) + \\
&\quad \left(\hat{\beta}_{i,0}(t_1) - \hat{\beta}_{i,0}(t_0)\right)(t^\star - t_1)
\end{aligned}$$

Time contribution

Example 6

- Example 6 is a slight modification of Example 5
- **The company has reduced its carbon emissions from 2007 to 2018 by** 37.5%, **but it has also increased them in the last two years by** 10.4%
- Two scenarios:
  1. Black scenario: $\mathcal{CE}_i(2021) = 41$ $MtCO_2e$
  2. Green scenario: $\mathcal{CE}_i(2021) = 36$ $MtCO_2e$

Table 10: Carbon emissions in $MtCO_2e$

Year	2007	2008	2009	2010	2011	2012	2013	2014
$\mathcal{CE}_i(t)$	57.82	58.36	57.70	55.03	51.73	46.44	47.19	46.18
Year	2015	2016	2017	2018	2019	2020	2021	
Scenario							**Black**	**Green**
$\mathcal{CE}_i(t)$	45.37	40.75	39.40	36.16	38.71	39.91	**41**	**36**

Time contribution

Table 11: Estimation of the rescaled trend model (Example 6)

Scenario	$\hat{\beta}_{i,0}$	$\hat{\beta}_{i,1}$	t_p	$\mathcal{CE}_i(t_p)$	$\tilde{\beta}_{i,0}$
2020	3 637.7316	−1.7832	2020	39.91	3 642.0362
Black	3 276.8078	−1.6038	2021	41.00	3 282.2509
Green	3 578.5078	−1.7538	2021	35.00	3 579.4009

Source: Le Guenedal *et al.* (2022).

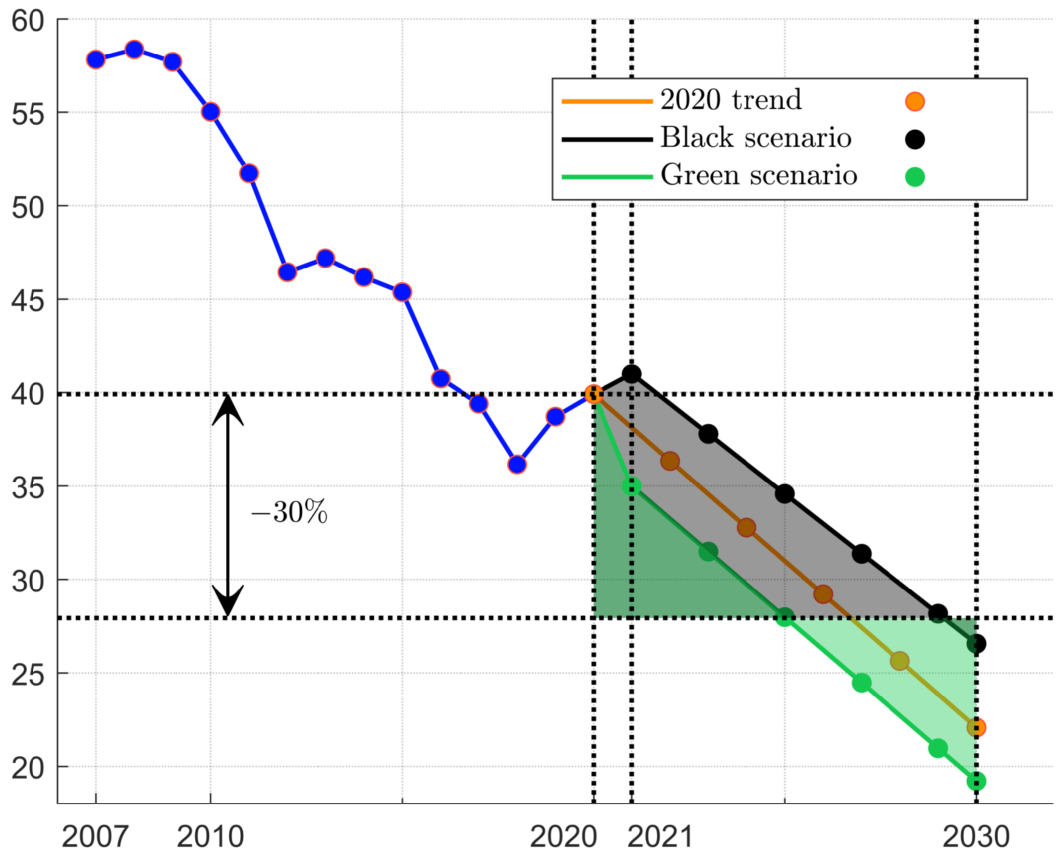
Table 12: Time contribution of 2021 black and green scenarios in $MtCO_2e$

Scenario	$\mathcal{CB}_i(t_0, t_1, t^\star)$	$\mathcal{CB}_i(t_0, t_1, t_1)$	$\mathcal{CB}_i(t_1, t_1, t^\star)$	$\mathcal{CB}_i(t_0, t_0, t^\star)$
2020	30.568	11.081	19.487	30.568
Black	65.132	12.518	52.614	30.568
Green	2.057	9.518	−7.461	30.568
Scenario	$\mathcal{CB}_i(t_0, t_1, t^\star)$	$\mathcal{TC}_i(t_1 \mid t_0, t^\star)$	$\mathcal{TC}_i^{\mathrm{error}}(t_1 \mid t_0, t^\star)$	$\mathcal{TC}_i^{\mathrm{revision}}(t_1 \mid t_0, t^\star)$
Black	65.132	34.563	1.437	33.127
Green	2.057	−28.512	−1.563	−26.948

Source: Le Guenedal *et al.* (2022).

Time contribution

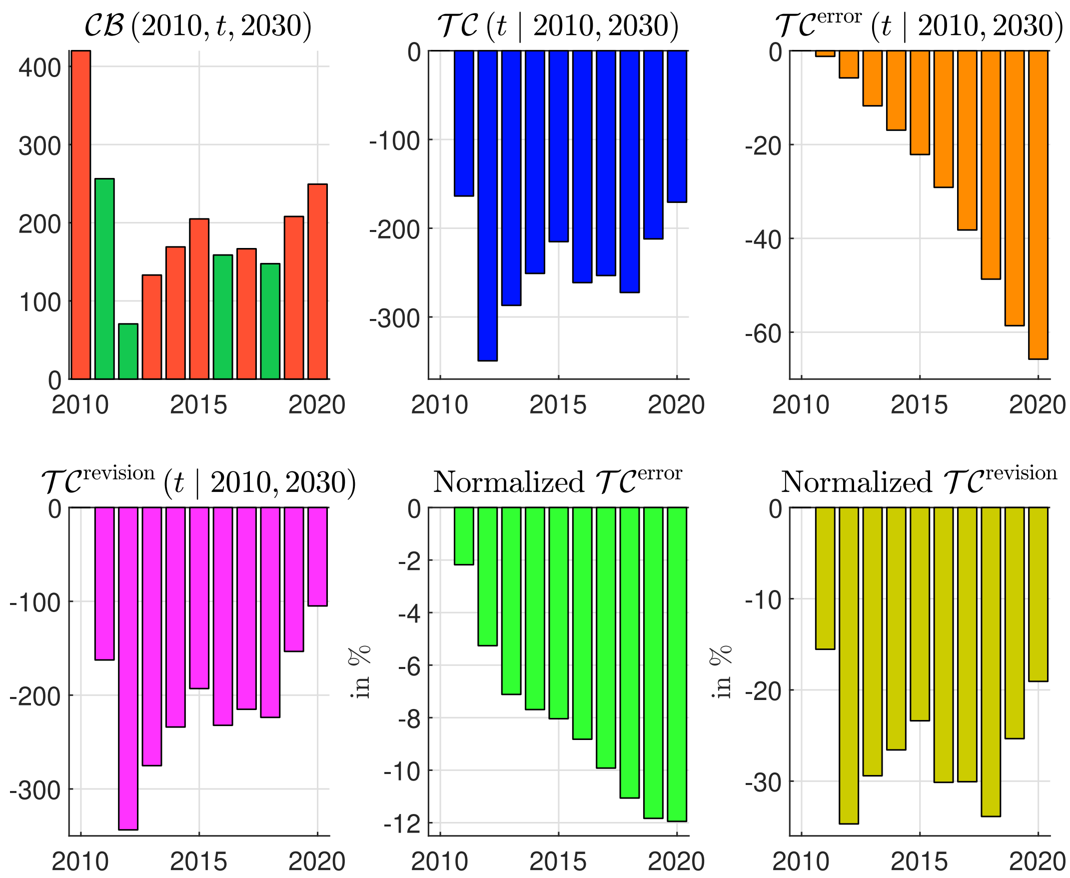
Figure 15: Impact of 2021 scenarios on the carbon budget (Example 6)



Source: Le Guenedal *et al.* (2022).

Time contribution

Figure 16: Dynamic analysis of the carbon budget $\mathcal{CB}_i(2010, t, 2030)$ (Example 6)



Source: Le Guenedal *et al.* (2022).

The NZE velocity

- The NZE velocity $\boldsymbol{v}_i(t_1, t_2)$ is defined as:

$$\boldsymbol{v}_i(t_1, t_2) := \frac{\Delta\hat{\beta}_{i,1}(t_1, t_2)}{t_2 - t_1}$$

- This measure is expressed in tCO_2e
- The h-step velocity is defined by $\boldsymbol{v}_i^{(h)}(t) = \boldsymbol{v}_i(t-h, t)$
- The one-step velocity measures the change of the slope by adding a new observation: $\boldsymbol{v}_i^{(1)}(t) = \hat{\beta}_1(t) - \hat{\beta}_{i,1}(t-1)$

The NZE velocity

Table 13: Computation of the h-step velocity (Example 5)

t	$\hat{\beta}_1(t)$	$\boldsymbol{v}_i^{(1)}(t)$	$\boldsymbol{v}_i^{(2)}(t)$	$\boldsymbol{v}_i^{(5)}(t)$
2010	−0.903			
2011	−1.551	−0.648		
2012	−2.270	−0.719	−0.684	
2013	−2.204	0.067	−0.326	
2014	−2.076	0.127	0.097	
2015	−1.932	0.144	0.136	−0.206
2016	−2.006	−0.073	0.035	−0.091
2017	−2.016	−0.010	−0.042	0.051
2018	−2.069	−0.053	−0.032	0.027
2019	−1.949	0.120	0.034	0.026
2020	−1.783	0.166	0.143	0.030

Source: Le Guenedal *et al.* (2022).

The zero-velocity scenario

We have:

$$\boldsymbol{v}_i^{(h)}(t+1) \leq 0 \Leftrightarrow \boldsymbol{\mathcal{CE}}_i(t+1) \leq \boldsymbol{\mathcal{ZV}}_i^{(h)}(t+1)$$

$\Rightarrow \boldsymbol{\mathcal{ZV}}_i^{(h)}(t+1)$ is the value of carbon emissions to obtain a zero velocity. In the case $h=1$, we obtain:

$$\boldsymbol{\mathcal{ZV}}_i^{(1)}(t+1) = \frac{18(n+1)\cdot\widetilde{\boldsymbol{\mathcal{CE}}}_i(t) - 12(n+2)\cdot\overline{\boldsymbol{\mathcal{CE}}}_i(t)}{6(n-1)}$$

The zero-velocity scenario

Table 14: Computation of the zero-velocity scenario $\mathcal{ZV}_i^{(h)}(2021)$ (Example 5)

h	$\mathcal{ZV}_i^{(h)}(2021)$	$\mathcal{R}_i(2020, 2021)$
1	33.82	15.25%
2	27.20	31.85%
3	22.39	43.90%
4	24.51	38.59%
5	24.92	37.57%

Source: Le Guenedal *et al.* (2022).

We recall that $\mathcal{CE}_i(2020) = 39.91$ $MtCO_2e$

The NZE burn-out scenario

- The burn-out scenario refers to a sudden and violent reduction of carbon emissions in order to satisfy the NZE trajectory
- The NZE burn-out scenario is then the value of the carbon emissions next year such that the gap is equal to zero, meaning that the NZE scenario will be achieved on average
- The burn-out scenario is denoted by $\mathcal{BO}_i\left(t+1, \mathcal{CE}_i^{\mathrm{nze}}\left(t^\star\right)\right)$ where t is the last reporting date, $\mathcal{CE}_i^{\mathrm{nze}}\left(t^\star\right)$ is the NZE scenario and $t^\star$ is the NZE date

The NZE burn-out scenario

- Let $\mathcal{R}_i^{\mathcal{T}arget}(t+1, t^\star)$ be the reduction rate between the date $t+1$ and the NZE date $t^\star$ when we consider the carbon targets of the issuer
- We have:

$$\mathcal{BO}_i^{\mathcal{T}arget}\left(t+1, \mathcal{CE}_i^{\mathrm{nze}}(t^\star)\right) = \frac{\mathcal{CE}_i^{\mathrm{nze}}(t^\star)}{1 - \mathcal{R}_i^{\mathcal{T}arget}(t+1, t^\star)}$$

- If we consider the linear trend model, we have:

$$\mathcal{BO}_i^{\mathcal{T}rend}\left(t+1, \mathcal{CE}_i^{\mathrm{nze}}(t^\star)\right) =$$

$$\left\{\mathcal{CE}_i(t+1) : \hat{\beta}_{i,0}(t+1) + \hat{\beta}_{i,1}(t+1)\cdot t^\star = \mathcal{CE}_i^{\mathrm{nze}}(t^\star)\right\}$$

The NZE burn-out scenario

Table 15: Computation of the burn-out scenario $\mathcal{BO}_i\left(2021, \mathcal{CE}_i^{\mathrm{nze}}(2030)\right)$ (Example 5)

$\mathcal{CE}_i^{\mathrm{nze}}(2030)$	Target		Trend	
	$\mathcal{BO}_i(2021)$	$\mathcal{R}_i(2020, 2021)$	$\mathcal{BO}_i(2021)$	$\mathcal{R}_i(2020, 2021)$
5.00	5.76	85.58%	6.45	83.84%
10.00	11.51	71.16%	17.17	56.99%
15.00	17.27	56.73%	27.88	30.14%
20.00	23.02	42.31%	38.59	3.30%
25.00	28.78	27.89%	49.31	−23.55%
−30%	32.16	19.42%	55.60	−39.32%

Source: Le Guenedal *et al.* (2022).

The $\mathcal{PAC}$ framework

The $\mathcal{PAC}$ framework

- **P**articipation
- **A**mbition
- **C**redibility

The $\mathcal{PAC}$ framework

Three questions:

- Is the trend of the issuer in line with the net zero emissions scenario? $\Rightarrow$ **P**articipation
- Is the commitment of the issuer to fight climate change ambitious? $\Rightarrow$ **A**mbition
- Is the target setting of this issuer relevant and robust? $\Rightarrow$ **C**redibility

The $\mathcal{PAC}$ framework

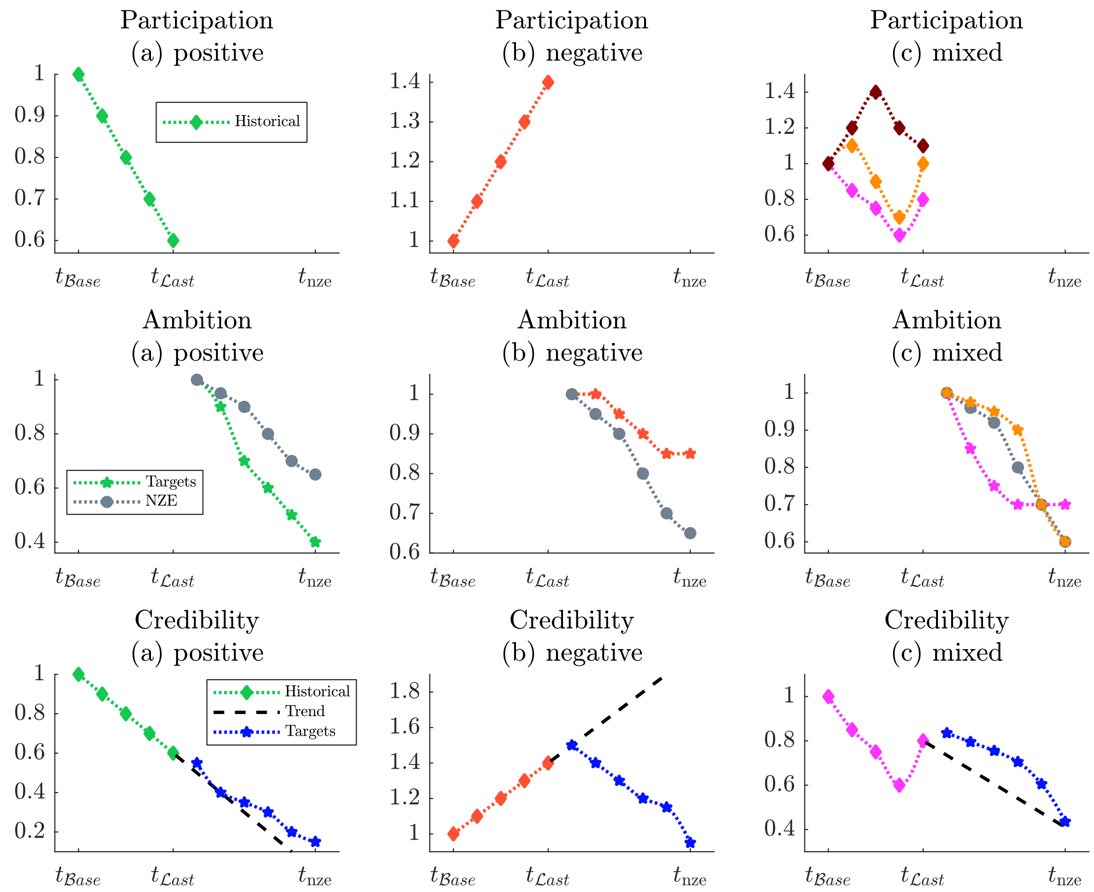
The three pillars depends on the carbon trajectories $\mathcal{CE}_i(t)$, $\mathcal{CE}_i^{\mathcal{T}rend}(t)$, $\mathcal{CE}_i^{\mathcal{T}arget}(t)$ and $\mathcal{CE}_i^{\mathrm{nze}}(t)$ where:

1. $\mathcal{CE}_i(t)$ is the time series of historical carbon emissions
2. $\mathcal{CE}_i^{\mathcal{T}rend}(t)$ and $\mathcal{CE}_i^{\mathcal{T}arget}(t)$ are the estimated carbon emissions deduced from the trend model and the target
3. $\mathcal{CE}_i^{\mathrm{nze}}(t)$ is the market-based NZE scenario

$t_{\mathcal{B}ase}$ is the base date, $t_{\mathcal{L}ast}$ is the last reporting date and t_{nze} is the target date of the NZE scenario

The $\mathcal{PAC}$ framework

Figure 17: Illustration of the participation, ambition and credibility pillars



Source: Le Guenedal *et al.* (2022).

The $\mathcal{PAC}$ framework

Table 16: The three pillars of an effective NZE strategy

Pillar	Metric	Condition
Participation	Gap	$\mathcal{G}ap_i^{\mathcal{T}rend}(t_{\mathcal{L}ast}) \leq 0$
	Reduction	$\mathcal{R}_i(t_{\mathcal{B}ase}, t_{\mathcal{L}ast}) < 0$
	Time contribution	$\mathcal{TC}_i(t_{\mathcal{L}ast}+1 \mid t_{\mathcal{L}ast}, t_{\mathrm{nze}}) < 0$
	Trend	$\hat{\beta}_{i,1} < 0$ and $\mathbf{R}_i^2 > 50\%$
	Trend	$\mathcal{CE}_i^{\mathcal{T}rend}(t)$ for $t > t_{\mathcal{L}ast}$
	Velocity	$v_i^{(1)}(t_{\mathcal{L}ast}) \leq 0$
Ambition	Budget	$\mathcal{CB}_i^{\mathcal{T}arget}(t_{\mathcal{L}ast}, t_{\mathrm{nze}}) \leq \mathcal{CB}_{\mathcal{S}ector}^{\mathcal{T}arget}(t_{\mathcal{L}ast}, t_{\mathrm{nze}})$
	Budget	$\mathcal{CB}_i^{\mathcal{T}arget}(t_{\mathcal{L}ast}, t_{\mathrm{nze}}) \leq \mathcal{CB}_i^{\mathcal{T}rend}(t_{\mathcal{L}ast}, t_{\mathrm{nze}})$
	Duration	$\tau_i^{\mathcal{T}arget} \leq t_{\mathrm{nze}}$
	Gap	$\mathcal{G}ap_i^{\mathcal{T}arget}(t_{\mathrm{nze}}) \leq 0$
Credibility	Budget	$\mathcal{CB}_i^{\mathcal{T}arget}(t_{\mathcal{L}ast}, t_{\mathrm{nze}}) > \mathcal{CB}_i^{\mathcal{T}rend}(t_{\mathcal{L}ast}, t_{\mathrm{nze}})$
	Burn-out Scenario	$\mathcal{BO}_i(t_{\mathcal{L}ast}+1, \mathcal{CE}_i^{\mathrm{nze}}(t^{\mathrm{nze}})) \geq \varphi_{\mathcal{BO}} \cdot \mathcal{CE}_i(t_{\mathcal{L}ast})$
	Duration	$\tau_i^{\mathcal{T}rend} \leq t_{\mathrm{nze}}$
	Gap	$\mathcal{G}ap_i^{\mathcal{T}rend}(t_{\mathrm{nze}}) \leq 0$
	Gap	$\mathcal{G}ap_i^{\mathcal{T}rend}(t_{\mathrm{nze}}) \leq \mathcal{G}ap_i^{\mathcal{T}arget}(t_{\mathrm{nze}})$
	Slope	$\mathcal{S}lope_i(t_{\mathrm{nze}}) \geq \mathcal{S}lope_{\mathcal{S}ector}(t_{\mathrm{nze}})$
	Slope	$m_i^{\mathcal{S}lope} \ll 1$
	Trend	$\mathbf{R}_i^2 > 50\%$
	Zero-velocity	$\mathcal{ZV}_i^{(1)}(t_{\mathcal{L}ast}+1) \geq \varphi_{\mathcal{ZV}} \cdot \mathcal{CE}_i(t_{\mathcal{L}ast})$

The $\mathcal{PAC}$ framework

If we compare the carbon budget $\mathcal{CB}_i^{\mathcal{T}arget}\left(t_{\mathcal{L}ast}, t_{\mathrm{nze}}\right)$ using the targets and the carbon budget $\mathcal{CB}_i^{\mathcal{T}rend}\left(t_{\mathcal{L}ast}, t_{\mathrm{nze}}\right)$ using the trend model, we can face two extreme situations:

1. The company is ambitious but not credible if $\mathcal{CB}_i^{\mathcal{T}arget}\left(t_{\mathcal{L}ast}, t_{\mathrm{nze}}\right) \ll \mathcal{CB}_i^{\mathcal{T}rend}\left(t_{\mathcal{L}ast}, t_{\mathrm{nze}}\right)$
2. The company is credible but not ambitious if $\mathcal{CB}_i^{\mathcal{T}arget}\left(t_{\mathcal{L}ast}, t_{\mathrm{nze}}\right) \gg \mathcal{CB}_i^{\mathcal{T}rend}\left(t_{\mathcal{L}ast}, t_{\mathrm{nze}}\right)$

$\Rightarrow$ the pillars can be (negatively) correlated

The $\mathcal{PAC}$ scoring system

In order to analyse the $\mathcal{PAC}$ pillars, we can use a scoring system:

$$\begin{aligned} q_i &= \Phi(z_i) \\ z_i &= \frac{s_i - \mu(s_i)}{\sigma(s_i)} \end{aligned}$$

Examples

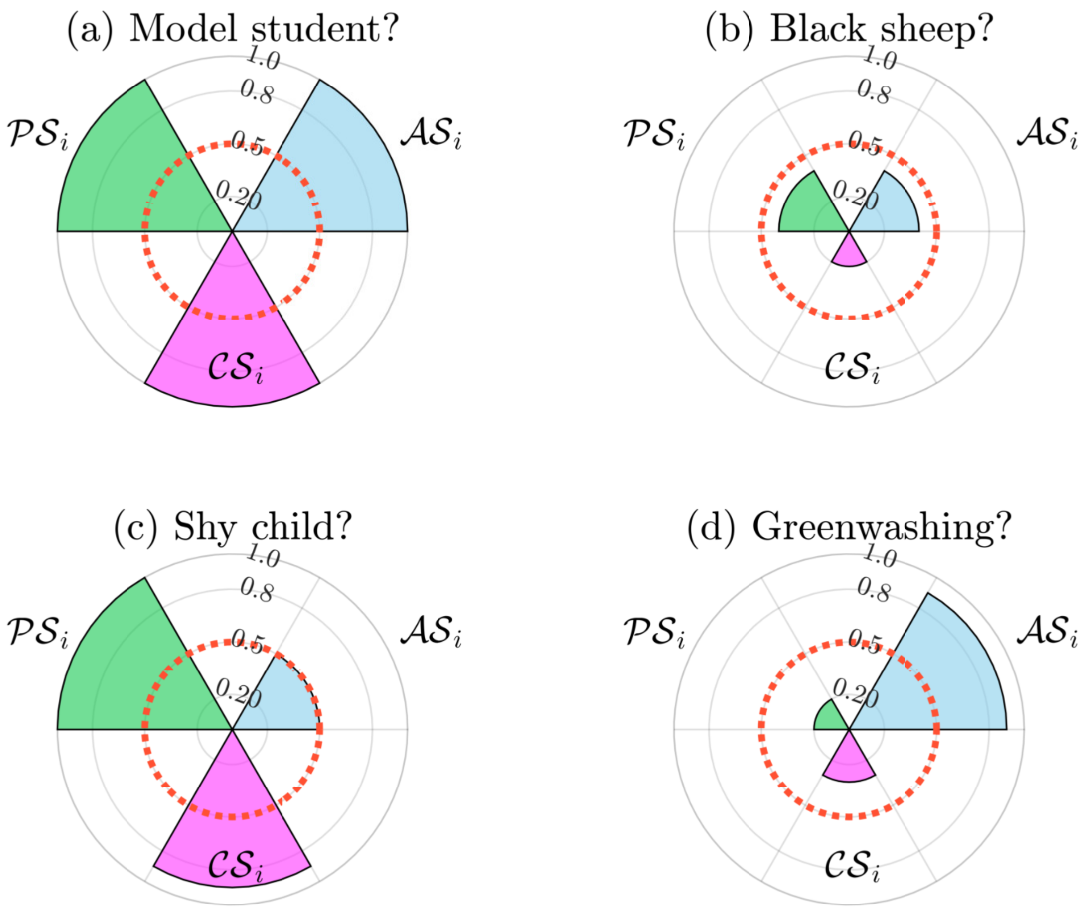
Participation $\quad s_i = -\dfrac{\hat{\beta}_{i,1}}{\mathcal{CE}_i(t_{\mathcal{L}ast})}$

Ambition $\quad s_i = \dfrac{\mathcal{CB}_i^{\mathcal{T}rend}(t_{\mathcal{L}ast}, t_{\mathrm{nze}}) - \mathcal{CB}_i^{\mathcal{T}arget}(t_{\mathcal{L}ast}, t_{\mathrm{nze}})}{\mathcal{CE}_i(t_{\mathcal{L}ast})}$

Credibility $\quad s_i = \dfrac{\mathcal{BO}_i(t_{\mathcal{L}ast}+1, \mathcal{CE}_i^{\mathrm{nze}}(t^{\mathrm{nze}}))}{\mathcal{CE}_i(t_{\mathcal{L}ast})}$

The $\mathcal{PAC}$ scoring system

Figure 18: The $\mathcal{PAC}$ scoring system



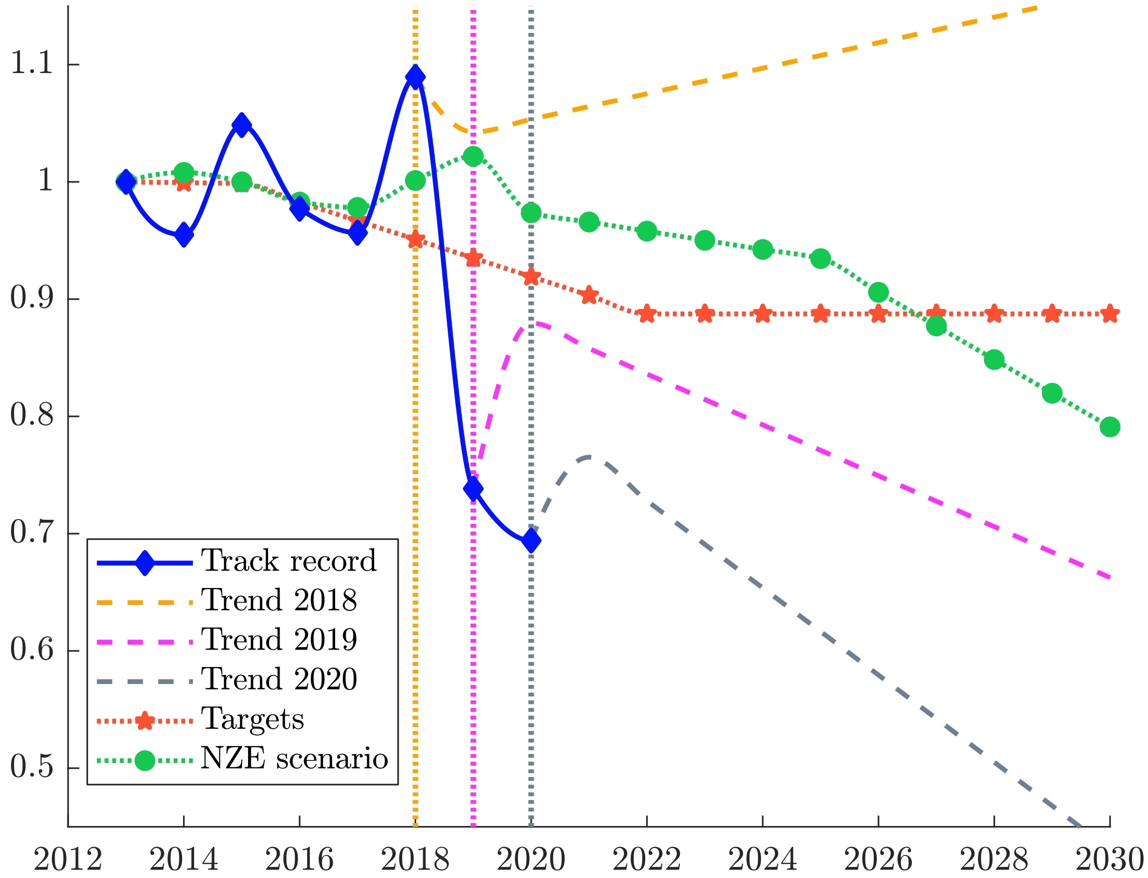
Source: Le Guenedal *et al.* (2022).

A tale of three companies

- Company A is a US based multinational technology conglomerate
  - It has communicated in September 2021 on their ambition and committed to net zero GHG emissions by 2040
- Company B which is one of the major airlines of the US
  - It announced a carbon neutrality ambition in September 2021
  - Its policy seems to require the purchase of carbon offsets
- Company C is an European multinational company which supplies industrial resources and services to various industries
  - It has a clear ambition and has embraced the NZE context
  - It positions its business on the climate change opportunity

A tale of three companies

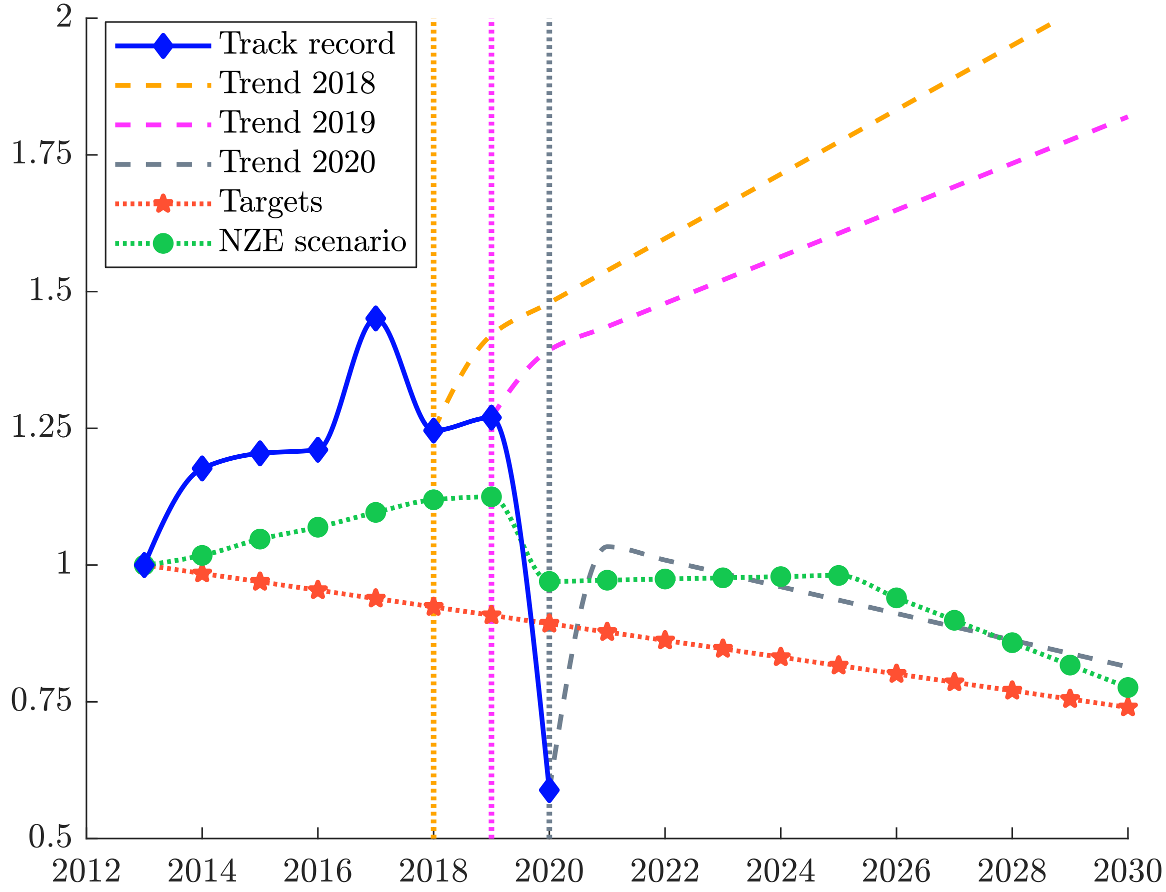
Figure 19: Carbon emissions, trends and targets and NZE scenario (Company A)



Source: CDP database (2020) & Le Guenedal *et al.* (2022).

A tale of three companies

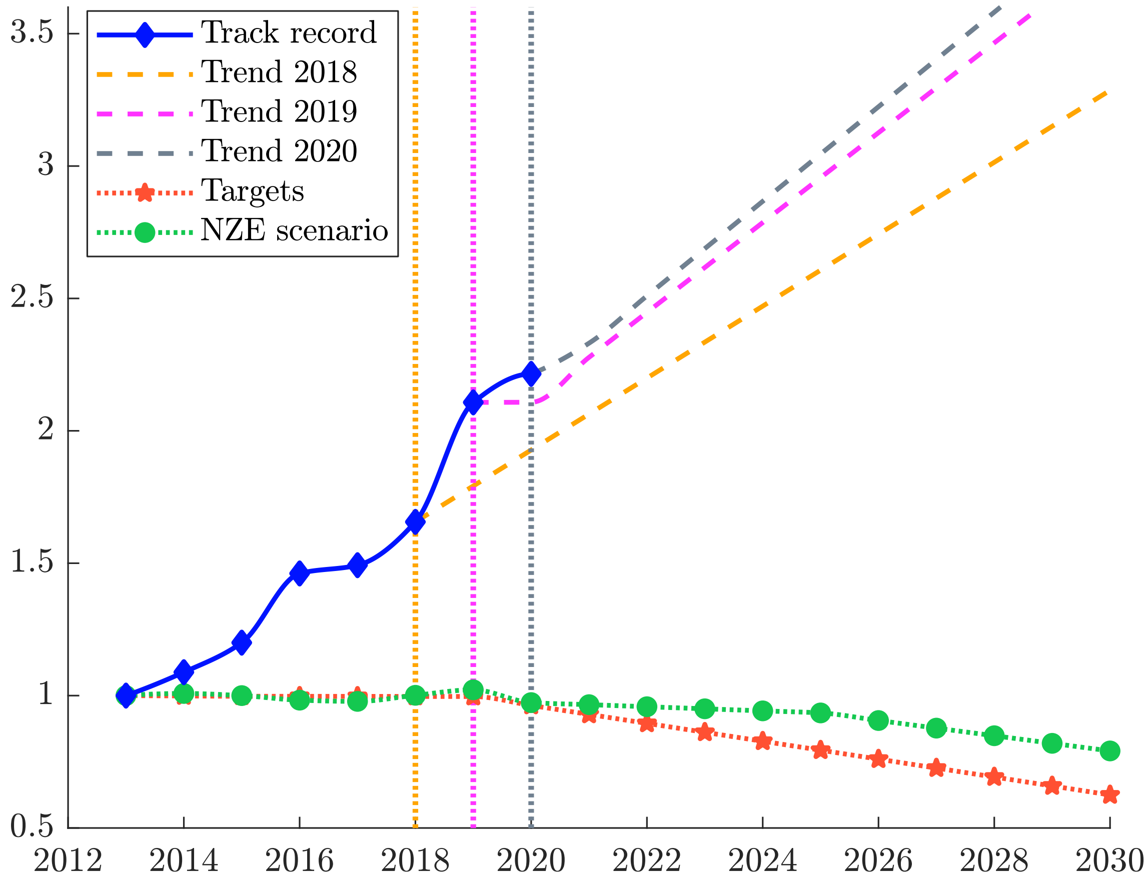
Figure 20: Carbon emissions, trends and targets and NZE scenario (Company B)



Source: CDP database (2020) & Le Guenedal *et al.* (2022).

A tale of three companies

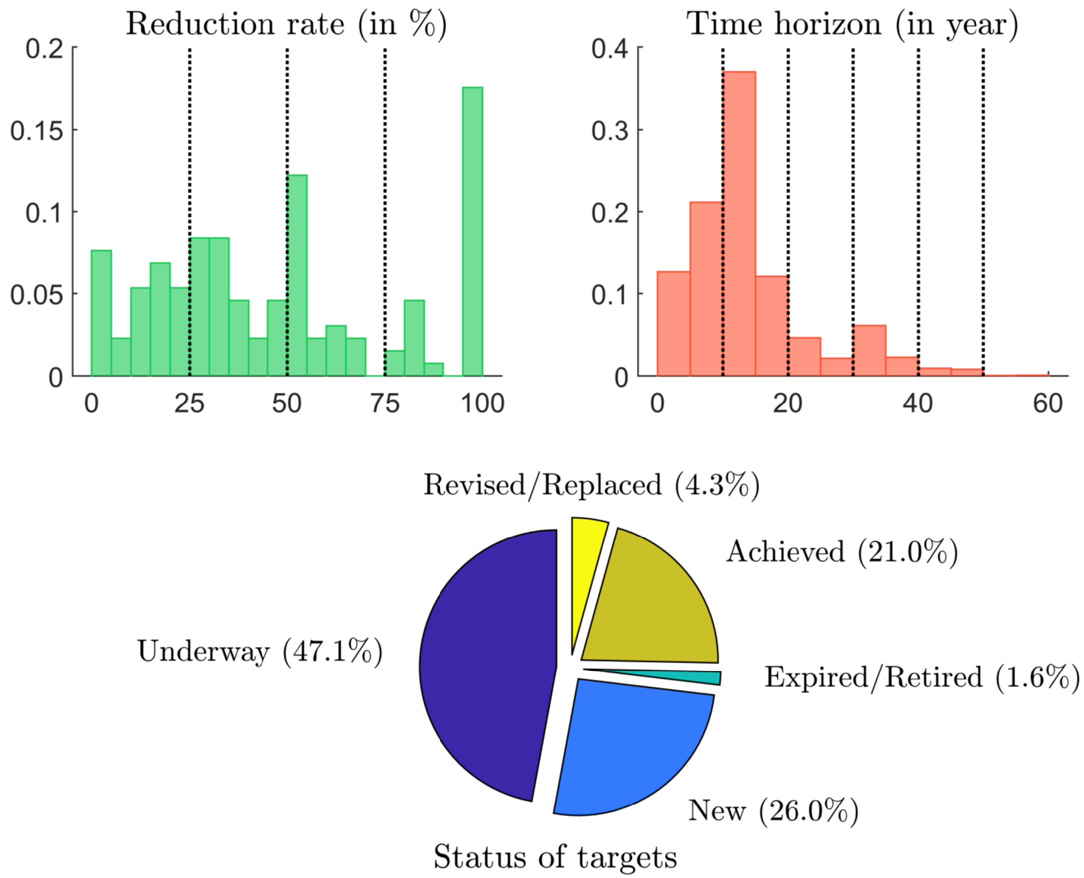
Figure 21: Carbon emissions, trends and targets and NZE scenario (Company C)



Source: CDP database (2020) & Le Guenedal *et al.* (2022).

The CDP database

Figure 22: Status, time horizon and scale of reduction targets



Source: CDP database (2020) & Le Guenedal *et al.* (2022).

The CDP database

Table 17: Coverage of CDP data for the MSCI index universes

IEA sector	All Issuers			EMU			North America			EM Asia		
	P	NP	NR	P	NP	NR	P	NP	NR	P	NP	NR
Electricity	227	57	381	27		3	51	6	21	18	12	85
Industry	1 136	262	1 237	85	7	11	202	29	51	120	40	390
Other	904	264	1 318	71	15	14	196	35	99	80	50	335
Transport	88	21	81	2			18	1	6	4	5	14
Total	2 355	604	3 017	185	22	28	467	71	177	222	107	824
# issuers		5 976			235			715			1 153	
Frequency (in %)	39.4	10.1	50.5	78.7	9.4	11.9	65.3	9.9	24.8	19.3	9.3	71.5

P = public, NP = non-public, NR = non-responder.

Source: CDP database (2021), MSCI indices & Le Guenedal *et al.* (2022).

The study universe

We consider issuers that have:

1. at least one reduction target between 2013 and 2030
2. and a full track record of carbon emissions between 2013 and 2020
3. an ISIN code that match with the IEA and GICS sector classification.

$\Rightarrow$ Finally, we obtain a database of 751 issuers

The study universe

Table 18: Number of issuers by sector

GICS sector	IEA sector				Total
	Electricity	Industry	Other	Transport	
Communication Services			41		41
Consumer Discretionary		52	29		81
Consumer Staples		57	16		73
Energy	23		7	4	34
Financials			135		135
Health Care	4	29	7		40
Industrials	3	74	42	16	135
Information Technology		46	24		70
Materials		63			63
Real Estate		21	2		23
Utilities	56				56
Total	86	342	303	20	751

Source: CDP database (2020) & Le Guenedal *et al.* (2022).

The study universe

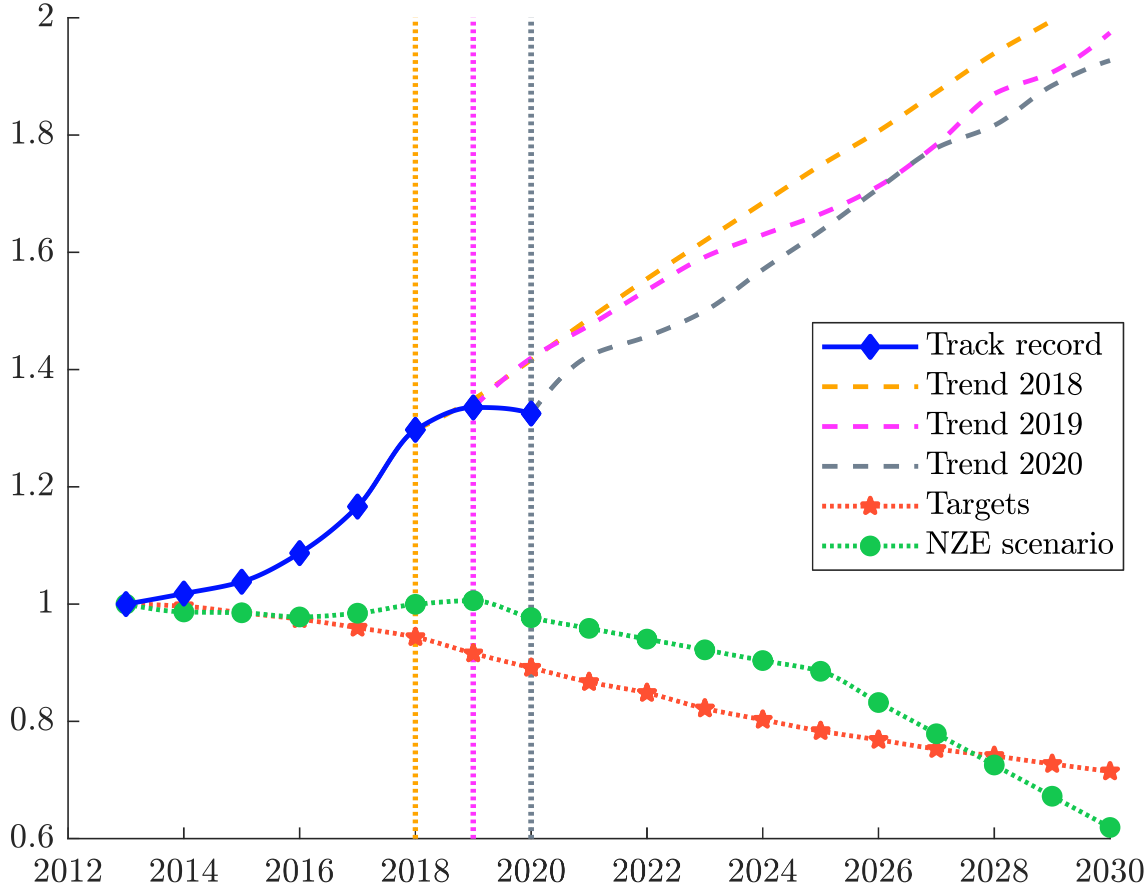
Table 19: Number of issuers by region

Region	IEA sector				Total
	Electricity	Industry	Other	Transport	
DM	66	276	245	19	606
EMU	31	88	71	4	194
Europe-ex-EMU	7	67	60	4	138
North America	26	93	106	9	234
Other DM	2	28	8	2	40
EM	20	66	58	1	145
Total	86	342	303	20	751

Source: CDP database (2020) & Le Guenedal *et al.* (2022).

Global analysis

Figure 23: Carbon emissions, trends and targets and NZE scenario (median analysis)



Source: CDP database (2020) & Le Guenedal *et al.* (2022).

Global analysis

Table 20: Statistics of the normalized slope and velocity (expressed in %)

Slope		$\frac{\hat{\beta}_{i,1}(t_{\mathcal{L}ast})}{\mathcal{CE}_i(2013)}$ $Q_{25\%}$	$Q_{50\%}$	$Q_{75\%}$	$\frac{\hat{\beta}_{i,1}(t_{\mathcal{L}ast})}{\mathcal{CE}_i(t_{\mathcal{L}ast})}$ $Q_{25\%}$	$Q_{50\%}$	$Q_{75\%}$	$\#\left\{\hat{\beta}_{i,1} < 0\right\}$
$t_{\mathcal{L}ast}$	2018	−2.44	6.06	41.29	−2.85	4.46	12.93	32.36
	2019	−2.13	6.38	44.23	−2.31	4.18	11.42	29.56
	2020	−2.97	6.16	52.01	−3.82	3.66	10.60	32.62
Velocity		$\frac{\boldsymbol{v}_i^{(1)}(t_{\mathcal{L}ast})}{\mathcal{CE}_i(2013)}$ $Q_{25\%}$	$Q_{50\%}$	$Q_{75\%}$	$\frac{\boldsymbol{v}_i^{(1)}(t_{\mathcal{L}ast})}{\mathcal{CE}_i(t_{\mathcal{L}ast})}$ $Q_{25\%}$	$Q_{50\%}$	$Q_{75\%}$	$\#\left\{\boldsymbol{v}_i^{(1)}(t_{\mathcal{L}ast}) < 0\right\}$
$t_{\mathcal{L}ast}$	2019	−4.38	−0.09	2.62	−2.15	−0.37	1.99	51.27
	2020	−6.99	−1.53	1.15	−3.68	−0.99	1.11	65.11

Source: CDP database (2020) & Le Guenedal *et al.* (2022).

Global analysis

Table 21: Statistics of the budget difference

$\Delta\mathcal{CB}_i\,(2020, 2030)$	$Q_{25\%}$	$Q_{50\%}$	$Q_{75\%}$	$\#\{<0\}$
$\mathcal{CB}_i^{\mathcal{T}rend}\,(2020, 2030) - \mathcal{CB}_i^{\mathrm{nze}}\,(2020, 2030)$	-3.00	5.78	13.45	32.9%
$\mathcal{CB}_i^{\mathcal{T}arget}\,(2020, 2030) - \mathcal{CB}_i^{\mathrm{nze}}\,(2020, 2030)$	-1.54	-0.18	0.54	59.9%
$\mathcal{CB}_i^{\mathcal{T}arget}\,(2020, 2030) - \mathcal{CB}_i^{\mathcal{T}rend}\,(2020, 2030)$	-14.48	-7.19	2.64	68.9%

Source: CDP database (2020) & Le Guenedal *et al.* (2022).

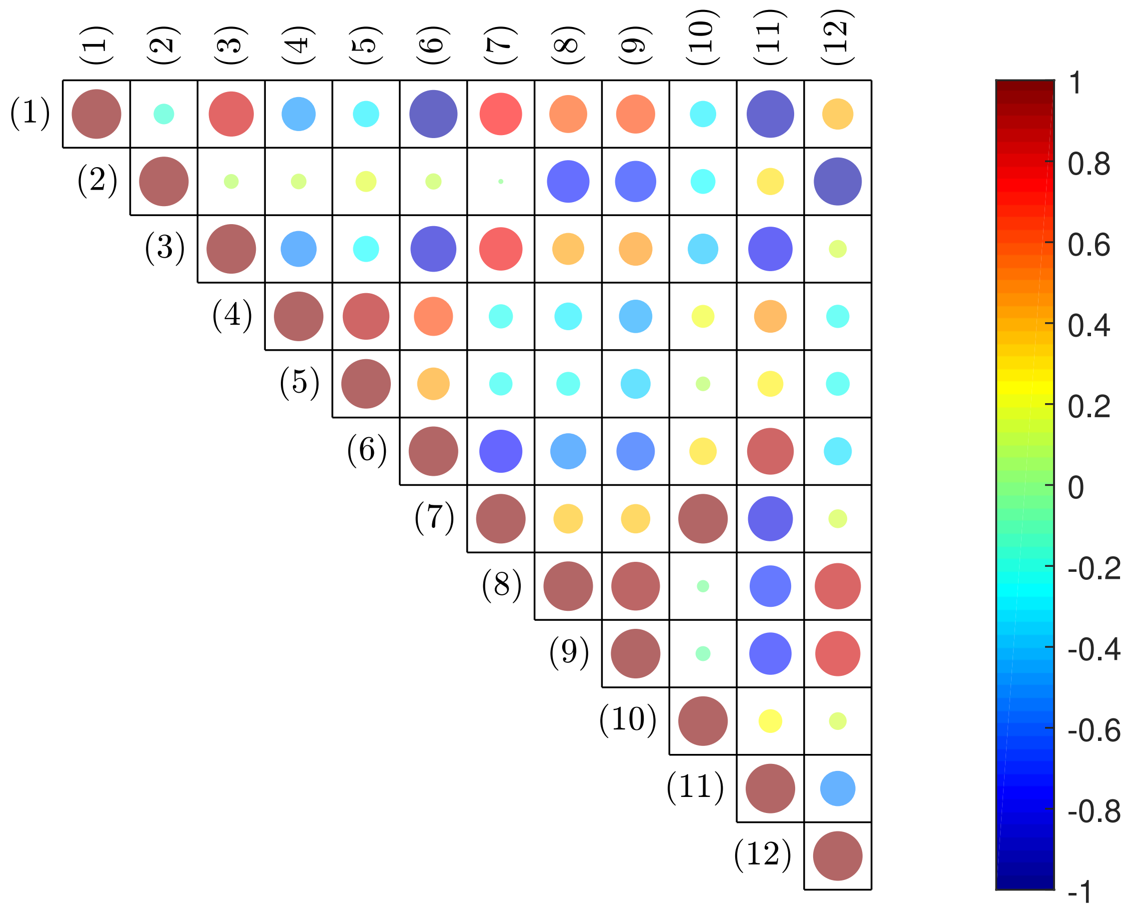
Global analysis

We consider the following NZE metrics:

1. the slope $\hat{\beta}_{i,1}$
2. the velocity $\boldsymbol{v}_i^{(1)}(2020)$
3. the current gap of the trend model $\mathcal{G}ap_i^{\mathcal{T}rend}(2020)$
4. the 2030 gap of the carbon targets $\mathcal{G}ap_i^{\mathcal{T}arget}(2030)$
5. the net budget of the carbon targets $\mathcal{CB}_i^{\mathcal{T}arget}(2020, 2030) - \mathcal{CB}_i^{\mathrm{nze}}(2020, 2030)$
6. the budget difference $\mathcal{CB}_i^{\mathcal{T}arget}(2020, 2030) - \mathcal{CB}_i^{\mathcal{T}rend}(2020, 2030)$
7. the trend duration $\boldsymbol{\tau}_i^{\mathcal{T}rend}$
8. the 2030 gap of the trend model $\mathcal{G}ap_i^{\mathcal{T}rend}(2030)$
9. the gap difference $\mathcal{G}ap_i^{\mathcal{T}rend}(2030) - \mathcal{G}ap_i^{\mathcal{T}arget}(2030)$
10. the (non-normalized) slope multiplier $m_i^{\mathcal{S}lope}$
11. the burn-out scenario $\mathcal{BO}_i(2021, \mathcal{CE}_i^{\mathrm{nze}}(2030))$
12. the zero-velocity scenario $\mathcal{ZV}_i^{(1)}(2021)$

Global analysis

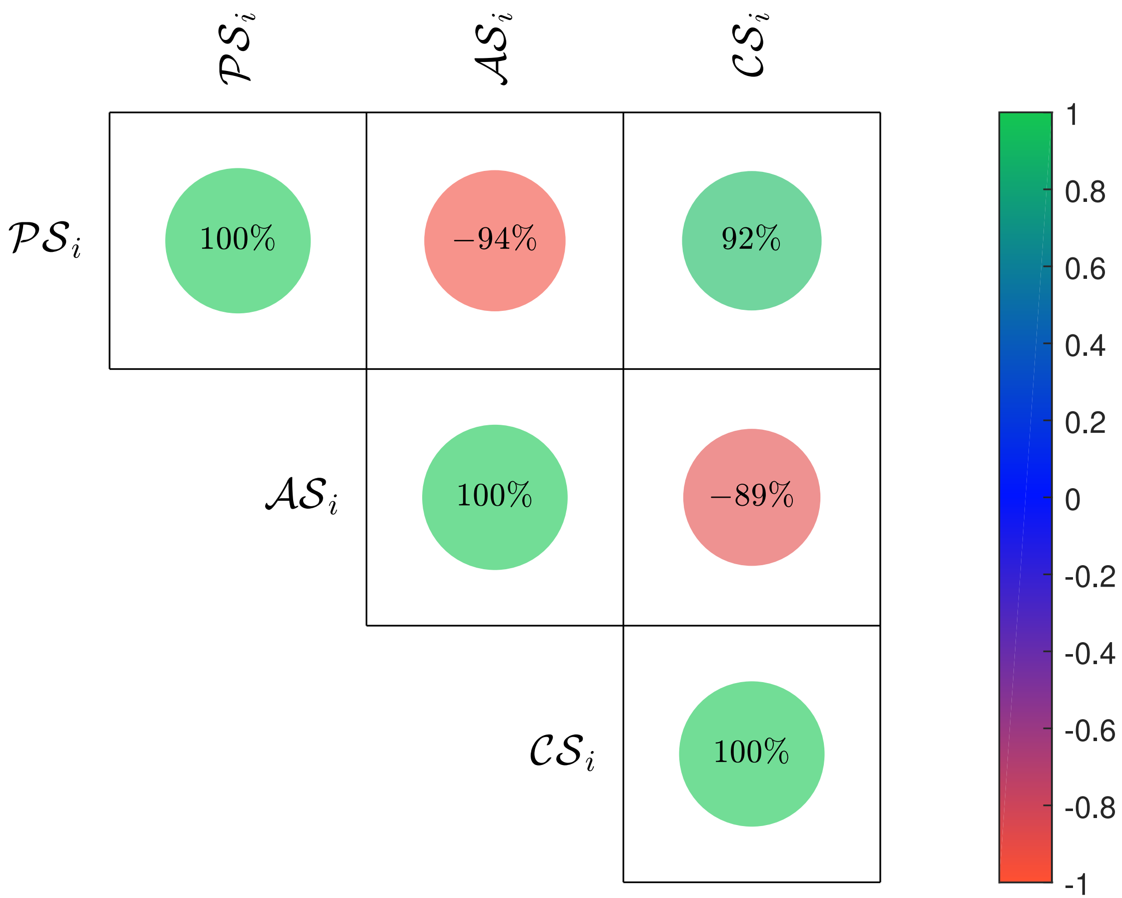
Figure 24: Rank correlation matrix of the $\mathcal{PAC}$ metrics



Source: CDP database (2020) & Le Guenedal *et al.* (2022).

Global analysis

Figure 25: Rank correlation matrix of the $\mathcal{PAC}$ scoring system



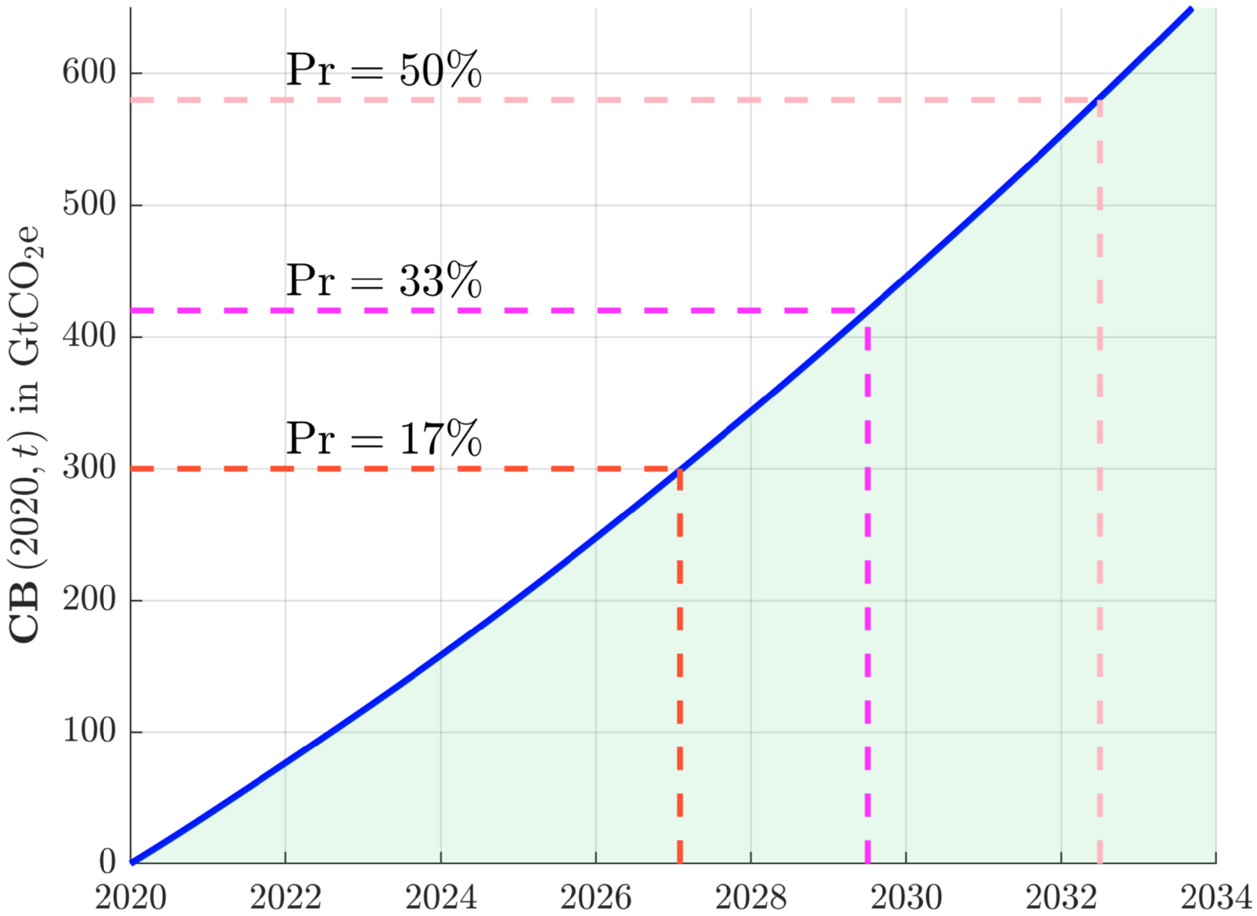
Source: CDP database (2020) & Le Guenedal *et al.* (2022).

Global analysis

"Using global mean surface air temperature, as in AR5, gives an estimate of the remaining carbon budget of 580 *$GtCO_2e$ for a* 50% *probability of limiting warming to* $1.5^{\circ}\mathrm{C}$*, and* 420 *$GtCO_2e$ for a* 66% *probability (medium confidence)" (IPCC, 2018).*

Global analysis

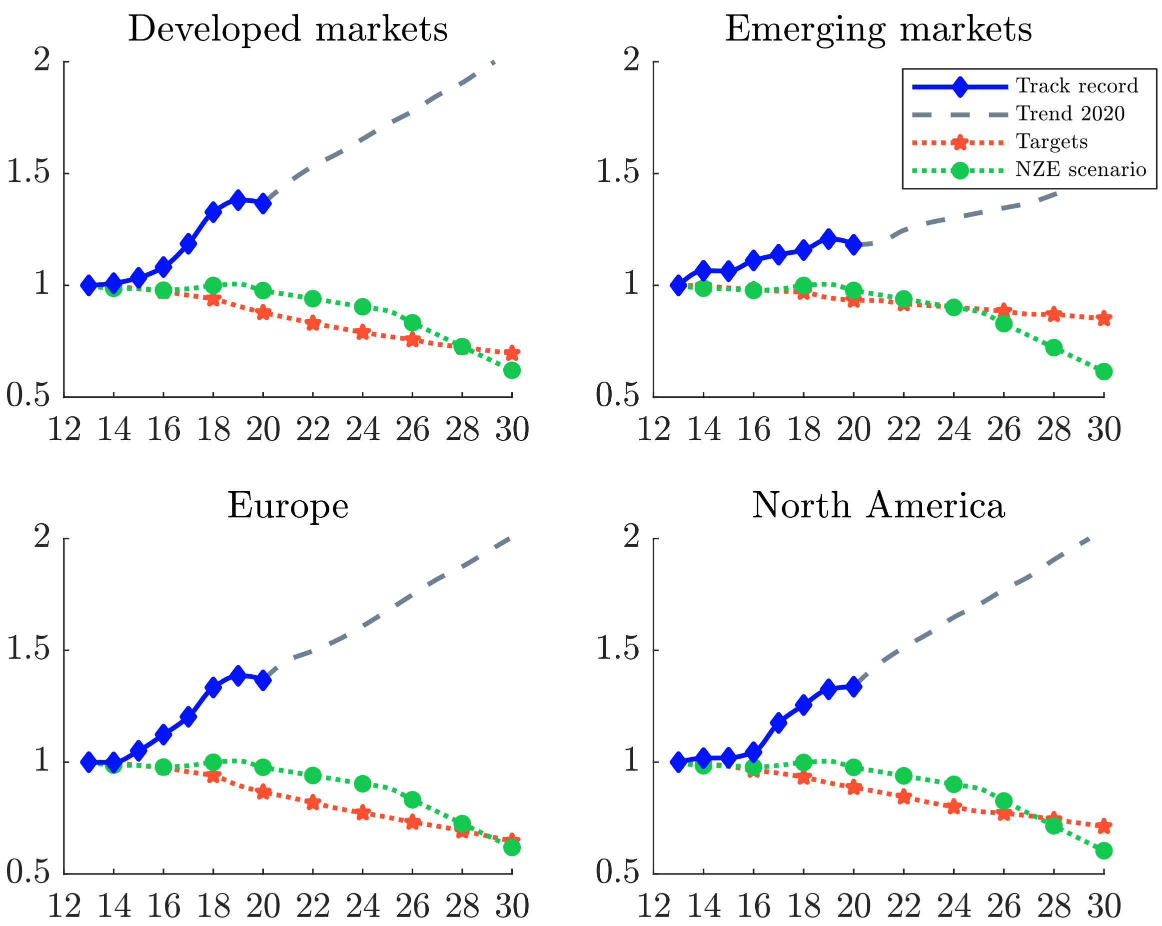
Figure 26: Probability to reach 1.5°C



Source: Le Guenedal *et al.* (2022).

Regional analysis

Figure 27: Carbon emissions, trends and targets and NZE scenario (median analysis)



Regional analysis

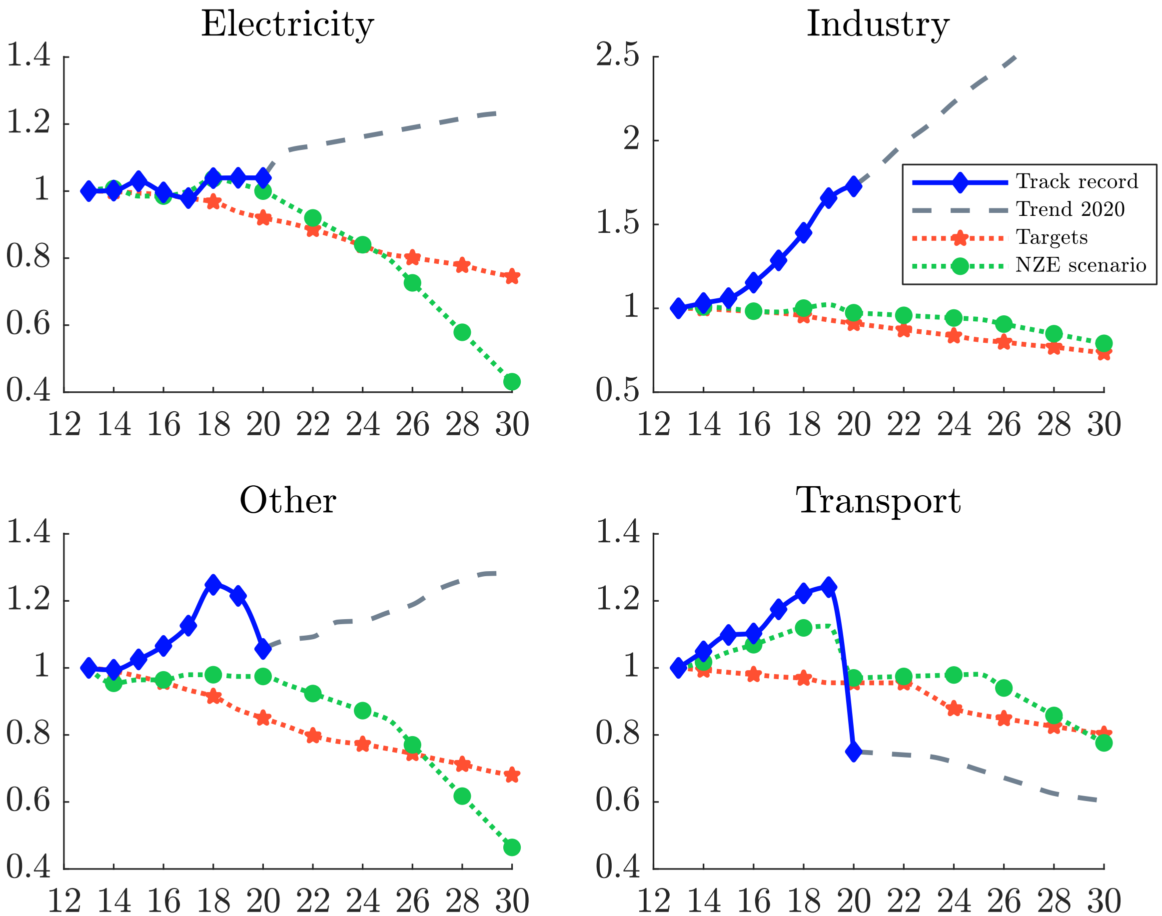
Table 22: Frequencies of targets lower or greater than the trend in 2030

	Lower	Greater
DM	79.21%	20.79%
EM	71.03%	28.97%
Europe	79.17%	20.83%
North America	76.92%	23.08%
EMU	79.90%	20.10%
Asia	67.61%	32.39%
Global	77.63%	22.37%

Source: IEA (2021), CDP database (2020) & Le Guenedal *et al.* (2022).

Sectoral analysis

Figure 28: Carbon emissions, trends and targets and NZE scenario (median analysis)



Application to the MSCI World index

Table 23: Scope 1 + 2 + 3 carbon emissions of the MSCI World index in tCO_2e ($W = \$1$ mn, $h = 1$ year)

Year	Missing	$\mathcal{CE}(x; W)$			$\mathcal{CI}(x)$		
		(1)	(2)	(3)	(1)	(2)	(3)
2013	3.63%	389.6	401.0	451.7	346.3	346.3	346.1
2014	3.72%	372.7	383.0	426.5	343.0	341.3	341.2
2015	4.51%	371.4	381.3	417.7	325.9	324.5	324.4
2016	3.85%	325.3	337.9	364.6	340.5	341.4	341.4
2017	2.79%	272.6	277.6	295.1	355.9	352.9	352.9
2018	2.31%	330.4	337.4	359.2	351.4	348.7	348.6
2019	3.67%	267.1	268.4	282.5	315.6	313.8	313.6
2020	4.30%	206.7	210.9	225.2	275.1	272.9	272.6
2021	7.09%	138.1	154.6	181.7	259.9	262.1	262.4

Source: MSCI (2021), Trucost reporting year (2021) & Le Guenedal *et al.* (2022).

Application to the MSCI World index

Table 24: Scope $1+2+3$ carbon emissions of the MSCI World index in $GtCO_2e$ ($h = 1$ year)

Year	$\sum_{i=1}^{n} \mathcal{MC}_i$ (in \$ tn)	$\sum_{i=1}^{n} \mathcal{CE}_i$ (1)	(2)	(3)
2013	31.9	12.8	12.8	14.4
2014	33.1	12.8	12.7	14.1
2015	32.3	12.4	12.3	13.5
2016	33.7	11.3	11.4	12.3
2017	40.4	11.4	11.2	11.9
2018	35.8	12.1	12.1	12.8
2019	44.7	12.3	12.0	12.6
2020	51.4	11.2	10.8	11.6
2021	62.4	9.5	9.7	11.3

Source: MSCI (2021), Trucost reporting year (2021) & Le Guenedal *et al.* (2022).

Application to the MSCI World index

"Using global mean surface air temperature, as in AR5, gives an estimate of the remaining carbon budget of 580 *GtCO*$_2$*e for a* 50% *probability of limiting warming to* $1.5^\circ\mathrm{C}$*, and* 420 *GtCO*$_2$*e for a* 66% *probability (medium confidence)" (IPCC, 2018).*

Application to the MSCI World index

Arithmetic

What is the carbon footprint of the investment industry if:

1. Each investor decreases its carbon footprint by $x\%$;
2. Each investor increases its wealth by $y\%$;

Answer

The carbon emissions change is equal to:

$$
\begin{aligned}
z &= (1 - x)(1 + y) - 1 \\
&= y - x - xy
\end{aligned}
$$

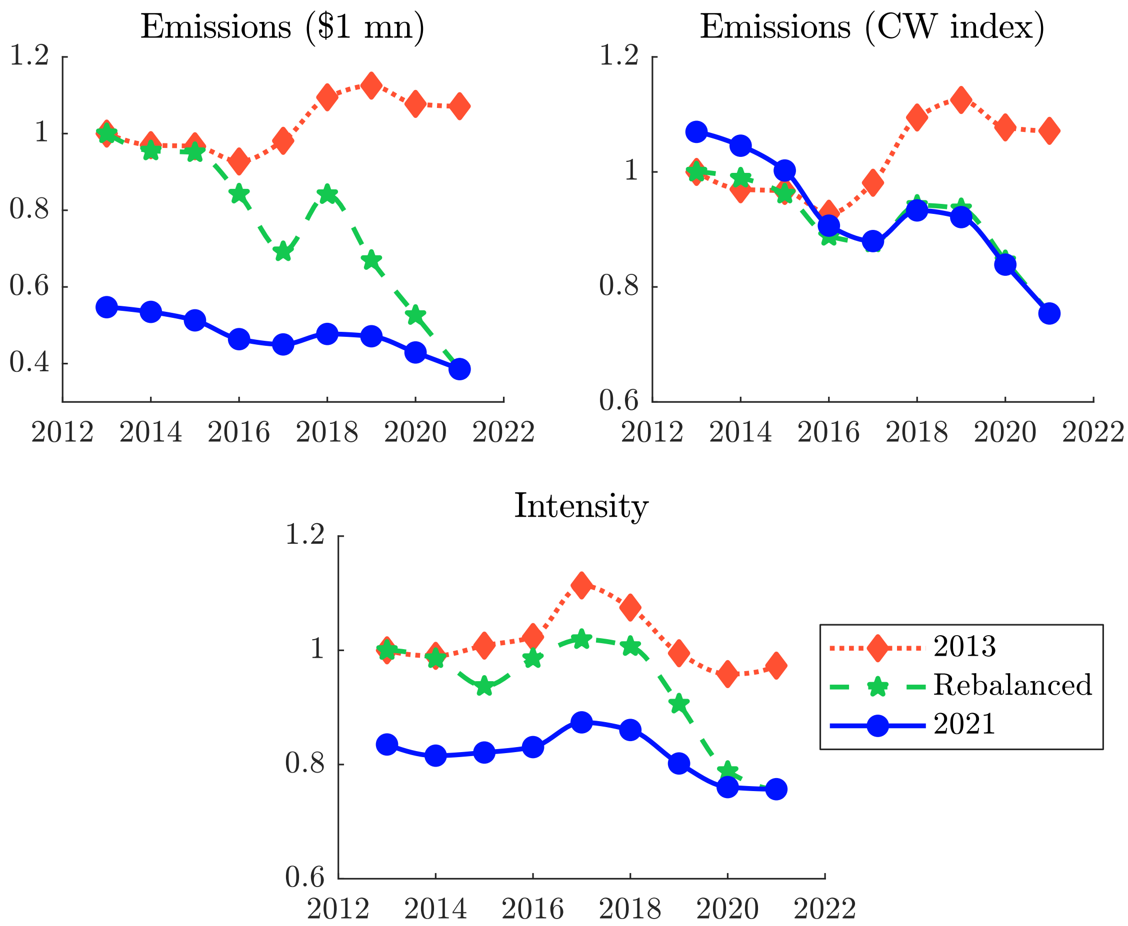
Application to the MSCI World index

Table 25: Carbon emissions change (in %)

		y in %						
		0.0	25.0	50.0	75.0	100.0	200.0	300.0
	0.0	0.0	25.0	50.0	75.0	100.0	200.0	300.0
	10.0	-10.0	12.5	35.0	57.5	80.0	170.0	260.0
	20.0	-20.0	0.0	20.0	40.0	60.0	140.0	220.0
	30.0	-30.0	-12.5	5.0	22.5	40.0	110.0	180.0
	40.0	-40.0	-25.0	-10.0	5.0	20.0	80.0	140.0
x	50.0	-50.0	-37.5	-25.0	-12.5	0.0	50.0	100.0
	60.0	-60.0	-50.0	-40.0	-30.0	-20.0	20.0	60.0
	70.0	-70.0	-62.5	-55.0	-47.5	-40.0	-10.0	20.0
	80.0	-80.0	-75.0	-70.0	-65.0	-60.0	-40.0	-20.0
	90.0	-90.0	-87.5	-85.0	-82.5	-80.0	-70.0	-60.0
	100.0	-100.0	-100.0	-100.0	-100.0	-100.0	-100.0	-100.0

Application to the MSCI World index

Figure 29: Scope $1+2+3$ carbon emissions and intensity



Source: MSCI (2021), Trucost reporting year (2021) & Le Guenedal *et al.* (2022).

Carbon trend of a portfolio

We can show that:

$$\mathcal{CE}\left(t, x; 1\right) = \sum_{i=1}^{n} w_i \cdot \mathcal{CE}_i\left(t\right)$$

where:

$$w_i = \frac{x_i \cdot \mathcal{FP}_i}{\mathcal{MC}_i}$$

We deduce that:

$$\mathcal{CE}\left(t, x; 1\right) = \underbrace{\left(\sum_{i=1}^{n} w_i \beta_{i,0}\right)}_{\beta_0(x)} + \underbrace{\left(\sum_{i=1}^{n} w_i \beta_{i,1}\right)}_{\beta_1(x)} t + \underbrace{\left(\sum_{i=1}^{n} w_i u_i\left(t\right)\right)}_{\varepsilon(t)}$$

Application to the MSCI World index

Puzzle

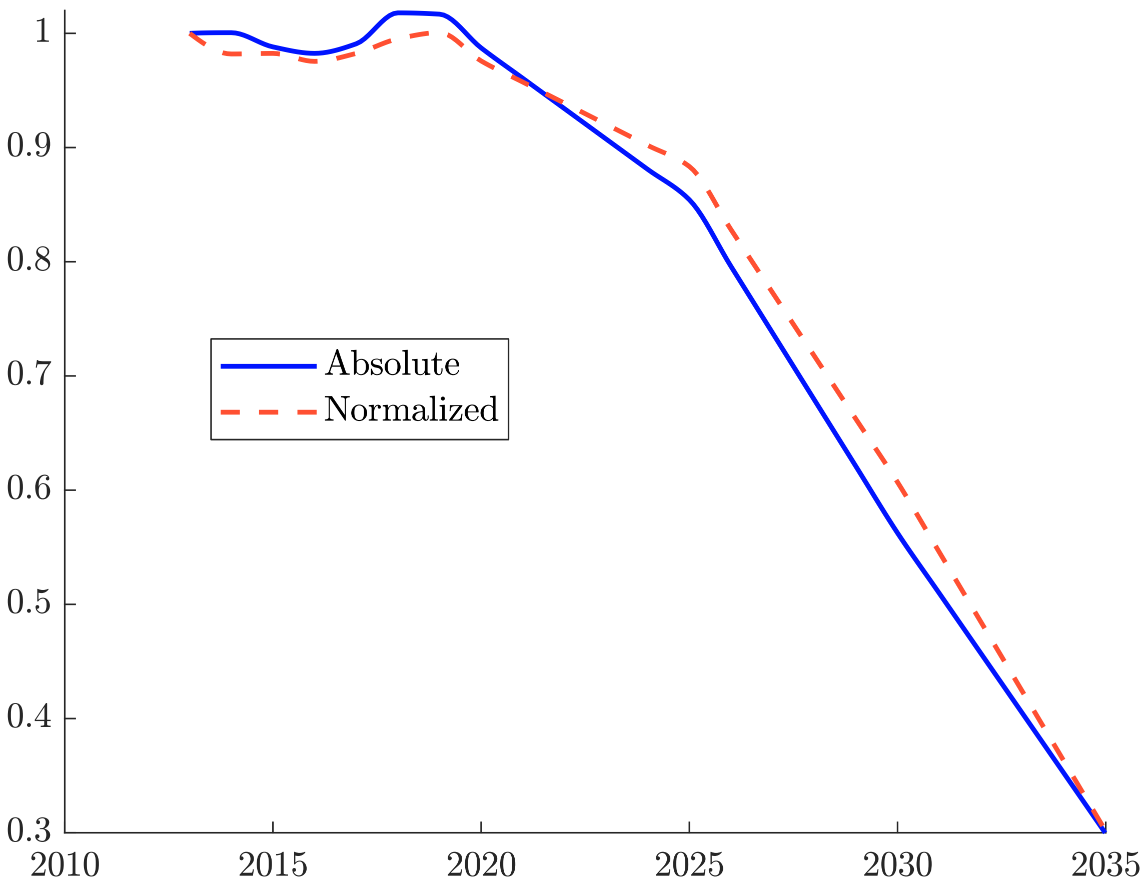
- $\hat{\beta}_1 = -28.80$ tCO_2e/\$ mn
- $\hat{\beta}_1\,(2019) = -4.69$ tCO_2e/\$ mn
- $\hat{\beta}_1\,(2019) = -4.07$ tCO_2e/\$ mn
- $\hat{\beta}_1\,(2019) = -3.24$ tCO_2e/\$ mn

WHY?

- The rebalancing of the index composition explains 80% of the reduction
- The remaining 20% is explained by the reduction of the issuers

Application to the MSCI World index

Figure 30: NZE scenario of the MSCI World index (2021)



Source: IEA (2021), MSCI (2021), Trucost reporting year (2021) & Le Guenedal *et al.* (2022).

NZE alliances

- **NZAOA** Net Zero Asset Owner Alliance
  - `https://www.unepfi.org/net-zero-alliance`
  - 66 signatories with $10 trillion in assets under management
- **NZAMI** Net Zero Asset Managers initiative
  - `https://www.netzeroassetmanagers.org`
  - 236 signatories with $57.5 trillion in assets under management
- **NZBA** Net Zero Banking Alliance
  - `https://www.unepfi.org/net-zero-banking`
  - 100 signatories representing 40 countries and 43% of global banking assets
- **NZIA** Net Zero Insurance Alliance
  - `https://www.unepfi.org/net-zero-insurance`
  - Eight founding members: AXA, Allianz, Aviva, Generali, Munich Re, SCOR, Swiss Re and Zurich Insurance Group
- **GFANZ** Glasgow Financial Alliance for Net Zero
  - `https://www.gfanzero.com`
  - 450 financial firms across 45 countries responsible for assets of over $130 trillion

How to define an NZE policy

With all these alliances, we may think that defining an NZE policy is simple

It is not simple, it is a nightmare!

Too much side effects

How to define an NZE policy

Key elements

- Engagement
  - Shareholder activism (active ownership, exit, media, controversies)
  - Voting policy & resolutions
  - Stewardship
- Capital allocation
  - Financing green solutions
    - Power/electricity sector
    - Renewable energies (wind, solar, etc.)
    - Cleantech & CCS (carbon capture and storage)
    - Green/blue hydrogen
  - Portfolio allocation
    - Strategic asset allocation
    - Portfolio construction
    - Portfolio alignment ($\neq$ portfolio decarbonization)

How to define an NZE policy

Current timing and priorities

Portfolio allocation $\succ$ (Engagement, Green financing)

Right timing and priorities

(Engagement, Green financing) $\succ$ Portfolio allocation

Remark

The three biggest US asset managers are the largest shareholders in 90% of S&P 500 companies

How to define an NZE policy

The magic formula is:

$$\textbf{Cost of Capital} = \textbf{Cost of Equity} + \textbf{Cost of Debt}$$

$\Rightarrow$ The power of finance and capital allocation:

1. Banks
2. Asset owners
3. Asset managers

How to define an NZE policy

- Traditional view of capital allocation:

  Innovations first, then finance the industrialization

- Alternative view of capital allocation:

  Money first, then innovations

Cost of capital = price equilibrium between supply and demand

- Is Supply the Problem?
- Is Demand the Problem?

How to boost supply?

- By creating the demand (new fiduciary role of asset managers)
- By the regulation

$\Rightarrow$ This is always a question about cost of capital

How to define an NZE policy

The example of low-carbon hydrogen solutions:

- Advancing Hydrogen Fund (CEFC)
- CPR Invest – Hydrogen Fund
- GLOBAL X Hydrogen ETF (HYDR)
- Green Hydrogen Fund (EIB)
- Green Hydrogen Fund (Hy24)
- Hydrogen Economy ETF (Legal & General IM)

How to define an NZE policy

Absolute carbon emissions vs. carbon intensity

Any normalization is an issue: $\mathcal{CI} = \dfrac{\mathcal{CE}}{Y}$

Are we on the right track if:

- the carbon intensity of issuers decreases by 7% p.a. and their revenues increase by 3% p.a.?
- the carbon intensity of countries decreases by 10% p.a. and their gdp increase by 3% p.a.?
- the carbon intensity of the aviation sector decreases by 15% p.a. (in terms of revenue passenger kilometers) and the number of passenger is multiplied by 3 in 2050?
- the carbon intensity of issuers decreases by 12% p.a. and the number of issuers is multiplied by 2 in 2050?

How to define an NZE policy

Absolute carbon emissions vs. carbon intensity

Static analysis

- Baseline date

$$\mathcal{CI}(t_0) = \frac{\mathcal{CE}(t_0)}{Y(t_0)}$$

- Current date

$$\mathcal{CI}(t) = \frac{\mathcal{CE}(t)}{Y(t)}$$

- We deduce that:

$$\mathcal{CI}(t) = \left(\frac{1 + \upsilon_{\mathcal{CE}}(t)}{1 + \upsilon_{Y}(t)}\right)\frac{\mathcal{CE}(t_0)}{Y(t_0)} = \left(1 + \upsilon_{\mathcal{CI}}(t)\right)\mathcal{CI}(t_0)$$

where:

$$\upsilon_{\mathcal{CI}}(t) = \frac{\upsilon_{\mathcal{CE}}(t) - \upsilon_{Y}(t)}{1 + \upsilon_{Y}(t)}$$

How to define an NZE policy

Absolute carbon emissions vs. carbon intensity

Table 26: Values* of $\upsilon_{\mathcal{CI}}(t)$ (in %)

		$\upsilon_{\mathcal{CE}}(t)$						
		−90.0	−75.0	−50.0	−25.0	0.0	25.0	50.0
	−50.0	−80.0	−50.0	0.0	50.0	100.0	150.0	200.0
	−25.0	−86.7	−66.7	−33.3	0.0	33.3	66.7	100.0
	0.0	−90.0	−75.0	−50.0	−25.0	0.0	25.0	50.0
$\upsilon_Y(t)$	25.0	−92.0	−80.0	−60.0	−40.0	−20.0	0.0	20.0
	50.0	−93.3	−83.3	−66.7	−50.0	−33.3	−16.7	0.0
	75.0	−94.3	−85.7	−71.4	−57.1	−42.9	−28.6	−14.3
	90.0	−94.7	−86.8	−73.7	−60.5	−47.4	−34.2	−21.1

$^{(*)}$If the issuer does not reduce its carbon emissions and increases its revenues (or the normalization variable) by 25%, its carbon intensity is reduced by 20%

How to define an NZE policy

Absolute carbon emissions vs. carbon intensity

Dynamic analysis

- The carbon budget constraint is $\int_{t_0}^{t} \mathcal{CE}(s)\,\mathrm{d}s \leq \mathcal{CB}^+$. We can show that this constraint is equivalent to:

$$m^{\mathrm{nze}} \cdot (t - t_0) \leq \frac{\mathcal{CB}^+}{\mathcal{CE}(t_0)}$$

  where* $m^{\mathrm{nze}} = 1 + \bar{\upsilon}_{\mathcal{CI}} + \bar{\upsilon}_Y + \bar{\upsilon}_{\mathcal{CI},Y}$

- Interpretation
  - $t - t_0$ is the time period before net zero target date (e.g., 30 years)
  - The ratio $\dfrac{\mathcal{CB}^+}{\mathcal{CE}(t_0)}$ indicates the number of remaining years before reaching the carbon budget if nothing is done (e.g., 20 ans)
  - m^{nze} is the carbon emissions average multiplier (e.g., $m^{\mathrm{nze}} = 0.50$)

(*) Generally, we have $\upsilon_{\mathcal{CI}}(t) < 0$ and $\upsilon_Y(t) > 0$ (implying that $\upsilon_{\mathcal{CI}}(t)\,\upsilon_Y(t) < 0$)

How to define an NZE policy

Absolute carbon emissions vs. carbon intensity

Proof.

We have:

$$\begin{aligned}
(*) &= \int_{t_0}^{t} \mathcal{CE}(s)\,\mathrm{d}s \leq \mathcal{CB}^{+} \\
&\Leftrightarrow \int_{t_0}^{t} \left(1 + \upsilon_{\mathcal{CE}}(s)\right) \mathcal{CE}(t_0)\,\mathrm{d}s \leq \mathcal{CB}^{+} \\
&\Leftrightarrow \int_{t_0}^{t} \left(1 + \upsilon_{\mathcal{CI}}(s)\right)\left(1 + \upsilon_{Y}(s)\right)\mathrm{d}s \leq \frac{\mathcal{CB}^{+}}{\mathcal{CE}(t_0)} \\
&\Leftrightarrow \int_{t_0}^{t} \left(1 + \upsilon_{\mathcal{CI}}(s) + \upsilon_{Y}(s) + \upsilon_{\mathcal{CI}}(s)\,\upsilon_{Y}(s)\right)\mathrm{d}s \leq \frac{\mathcal{CB}^{+}}{\mathcal{CE}(t_0)}
\end{aligned}$$

Using the mean value theorem, we have $\int_{t_0}^{t} \upsilon(s)\,\mathrm{d}s = \bar{\upsilon}\cdot(t - t_0)$. We deduce that:

$$(*) \Leftrightarrow \left(1 + \bar{\upsilon}_{\mathcal{CI}} + \bar{\upsilon}_{Y} + \bar{\upsilon}_{\mathcal{CI},Y}\right)\cdot(t - t_0) \leq \frac{\mathcal{CB}^{+}}{\mathcal{CE}(t_0)}$$

How to define an NZE policy

Absolute carbon emissions vs. carbon intensity

Example: 50% probability to reach net zero by 2050

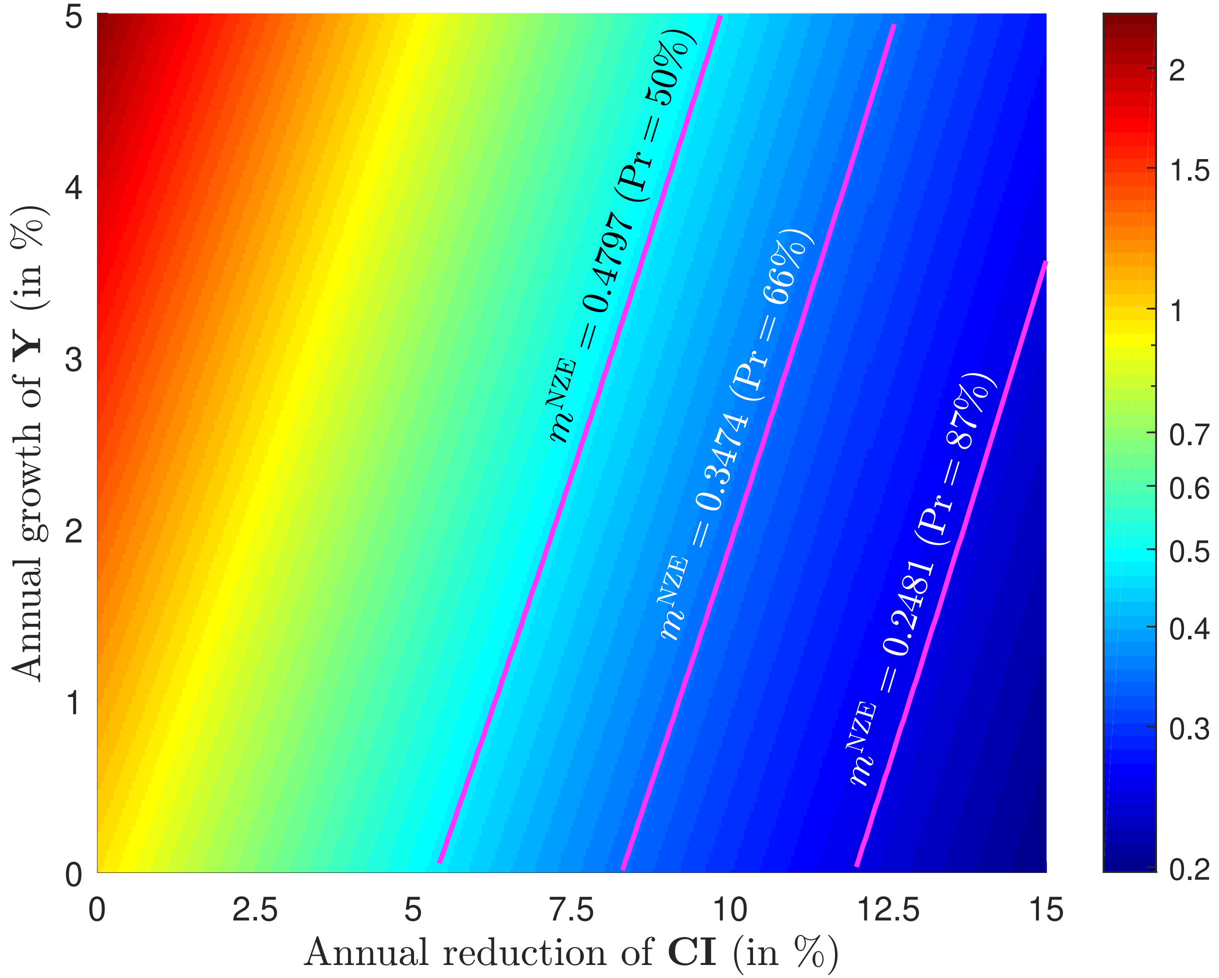
- $t_0 = 2019$
- $\mathcal{CE}(2019) = 36$ $\mathrm{GtCO_2e}$
- $t = 2050$
- $\mathcal{CB}^+ = 580$ $\mathrm{GtCO_2e}$
- $t - t_0 = 31$ years
- $\tau = \dfrac{\mathcal{CB}^+}{\mathcal{CE}(t_0)} = 14.87$ years
- We deduce that:

$$m^{\mathrm{nze}} \leq \frac{14.87}{31} = 0.4797$$

How to define an NZE policy

Absolute carbon emissions vs. carbon intensity

Figure 31: Value of the carbon emissions average multiplier



Paris-aligned benchmarks

The EU Technical Expert Group on sustainable finance (TEG) has created two climate benchmark labels:

1. Climate transition benchmark (CTB)
2. Paris-aligned benchmark (PAB)

Paris-aligned benchmarks

Principles

- A year-on-year self-decarbonization of 7% on average per annum, based on scope 1, 2 and 3 emissions
- A minimum carbon intensity reduction $\mathcal{R}^-$ compared to the investable universe
- A minimum exposure to sectors highly exposed to climate change
- Issuer exclusions (controversial weapons and societal norms violators)
- Minimum green share revenue

CTB

$$\mathcal{R}^- = 30\%$$

PAB

$$\mathcal{R}^- = 50\%$$

Decarbonization pathway

- t_0 is the base date of the climate benchmark
- The minimum reduction $\mathcal{R}(t_0, t)$ of the carbon intensity between the current date t and the base date t_0 is equal to:

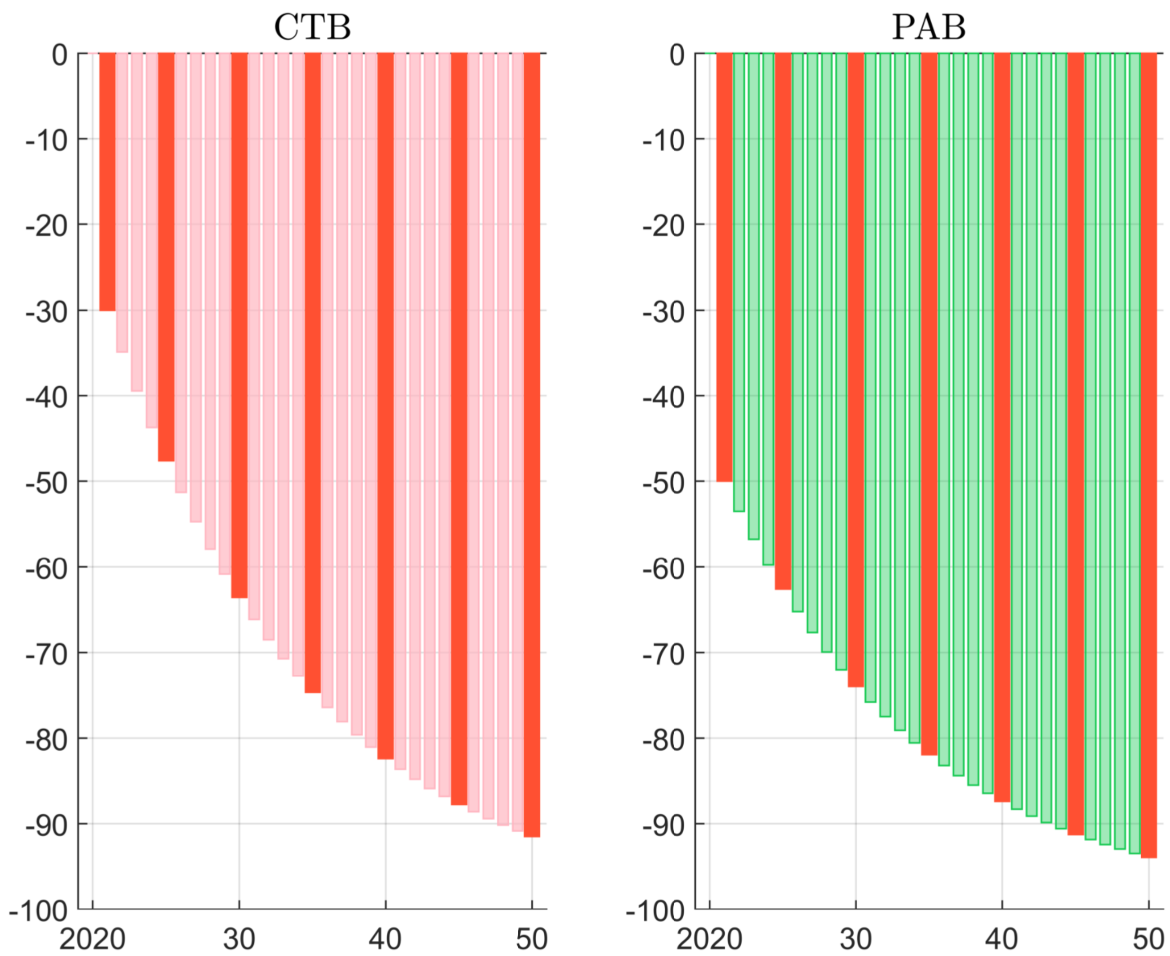
$$\mathcal{R}(t_0, t) = 1 - (1 - 7\%)^{t - t_0} \cdot \left(1 - \mathcal{R}^-\right)$$

- At date t, the CTB and PAB labels impose the following inequality constraint for the portfolio $x(t)$:

$$\mathcal{CI}(x(t)) \leq (1 - \mathcal{R}(t_0, t)) \cdot \mathcal{CI}(b(t_0))$$

Decarbonization pathway

Figure 32: Decarbonization pathway of CTB and PAB labels (base year = 2021)



Climate impact sector

Two types of sectors:

1. High climate impact sectors (HCIS or $\mathcal{CIS}_{\mathcal{H}igh}$)
2. Low climate impact sectors (LCIS or $\mathcal{CIS}_{\mathcal{L}ow}$)

- The HCIS category is made up of sectors that are key to the low-carbon transition
- At each rebalancing date t, we must verify that:

$$\mathcal{CIS}_{\mathcal{H}igh}\left(x\left(t\right)\right) \geq \varphi_{\mathcal{CIS}} \cdot \mathcal{CIS}_{\mathcal{H}igh}\left(b\left(t\right)\right)$$

where $\varphi_{\mathcal{CIS}} = 1$ and $\mathcal{CIS}_{\mathcal{H}igh}\left(x\right) = \sum_{i \in \mathcal{CIS}_{\mathcal{H}igh}} x_i$ is the HCIS weight of Portfolio x

NACE classification of high climate impact sectors

- A. Agriculture, Forestry, and Fishing
- B. Mining and Quarrying
- C. Manufacturing
- D. Electricity, Gas, Steam, and Air Conditioning Supply
- E. Water Supply; Sewerage, Waste Management, and Remediation Activities
- F. Construction
- G. Wholesale and Retail Trade; Repair of Motor Vehicles and Motorcycles
- H. Transportation and Storage
- L. Real Estate Activities

Broad HCIS measure

Mapping between the NACE classes and several sector classification structures (TEG, 2019):

- BICS (Bloomberg)
- GICS (MSCI and S&P)
  - 129 sub-industries out of a total of 185 are classified as high climate impact sectors
  - Only two sectors are classified in low climate impact sectors: Communication Services and Financials
  - Half of the Health Care and Information Technology sub-industries are viewed as high climate impact sectors
- ICB (FTSE)
- TRBC (Refinitiv)

Narrow HCIS measure

Table 27: The narrow measure of high climate impact sectors

NACE Code	NACE Sector	GICS Code	GICS Sector
A	Agriculture, Forestry & Fishing	302020	Food Products
B	Mining & Quarrying	10 151040	Energy Metals & Mining
C	Manufacturing	20	Industrials
D	Electricity, Gas, Steam & Air Conditioning Supply	55	Utilities
E	Water Supply Sewerage, Waste Management & Remediation Activities		
F	Construction	151020	Construction Materials
G	Wholesale & retail trade Repair of Motor Vehicles & Motorcycles	301010	Food & Staples Retailing
H	Transportation & Storage	2030	Transportation
L	Real Estate Activities	60	Real Estate

Source: Le Guenedal and Roncalli (2022).

High climate impact sectors

Table 28: Weights and carbon intensity of high climate impact sectors

Sector	S&P 500		Narrow HCIS		Broad HCIS	
	b_s	$\mathcal{CI}_s$	b_s	$\mathcal{CI}_s$	b_s	$\mathcal{CI}_s$
Communication Services	10.89%	80				
Consumer Discretionary	13.57%	190			10.22%	185
Consumer Staples	6.10%	355	2.73%	348	6.10%	355
Energy	2.81%	790	2.81%	790	2.81%	790
Financials	11.13%	67				
Health Care	12.74%	126			8.56%	152
Industrials	7.97%	330	7.97%	330	6.32%	368
Information Technology	27.50%	99			13.30%	139
Materials	2.45%	966	0.44%	850	2.45%	966
Real Estate	2.55%	198	2.55%	198	2.55%	198
Utilities	2.30%	2 669	2.30%	2 669	2.30%	2 669
Total	100.00%	245	18.79%	681	54.59%	380

Source: Le Guenedal and Roncalli (2022).

Optimization problem

We have:

$$
\begin{aligned}
x^{\star}(t) &= \arg\min_{x(t)} \frac{1}{2}\sigma^2\left(x(t) \mid b(t)\right) + \lambda \tau\left(x(t) \mid x^{\star}(t-1)\right) \\
\text{s.t.} & \left\{
\begin{array}{l}
\mathbf{1}_n^\top x(t) = 1 \\
x(t) \geq \mathbf{0}_n \\
\mathcal{CI}\left(x(t)\right) \leq \left(1 - \mathcal{R}(t_0, t)\right) \cdot \mathcal{CI}\left(b(t_0)\right) \\
\mathcal{CIS}_{\mathcal{H}igh}\left(x(t)\right) \geq \varphi_{\mathcal{CIS}} \cdot \mathcal{CIS}_{\mathcal{H}igh}\left(b(t)\right) \\
\left|\sum_{i \in \mathcal{S}ector_j} x_i(t) - \sum_{i \in \mathcal{S}ector_j} b_i(t)\right| \leq \delta_j
\end{array}
\right.
\end{aligned}
$$

where $\lambda \geq 0$, $\sigma\left(x(t) \mid b(t)\right)$ is the tracking error risk:

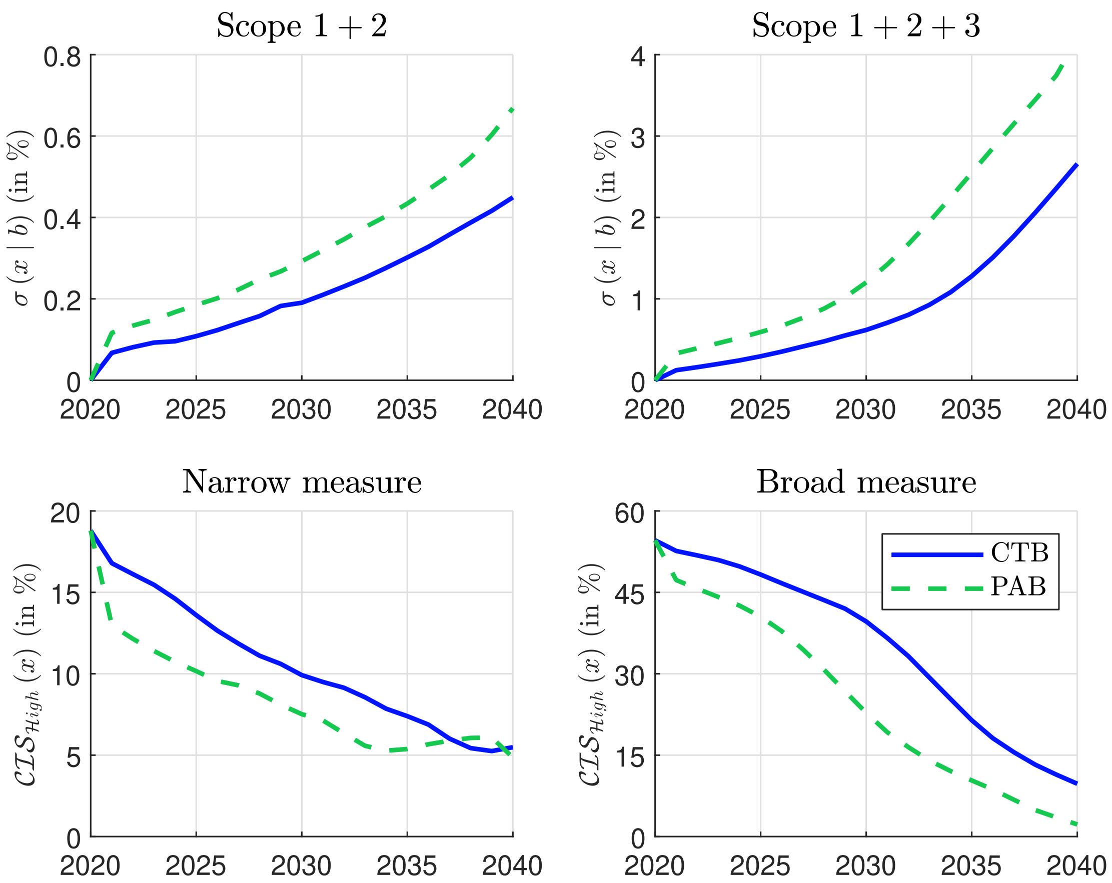
$$
\sigma\left(x(t) \mid b(t)\right) = \sqrt{\left(x(t) - b(t)\right)^\top \Sigma(t) \left(x(t) - b(t)\right)}
$$

and $\tau\left(x(t) \mid x^{\star}(t-1)\right)$ is the one-way turnover of the portfolio between $t-1$ and t:

$$
\tau\left(x(t) \mid x^{\star}(t-1)\right) = \frac{1}{2}\left\|x(t) - x^{\star}(t-1)\right\|_1
$$

Optimization solution

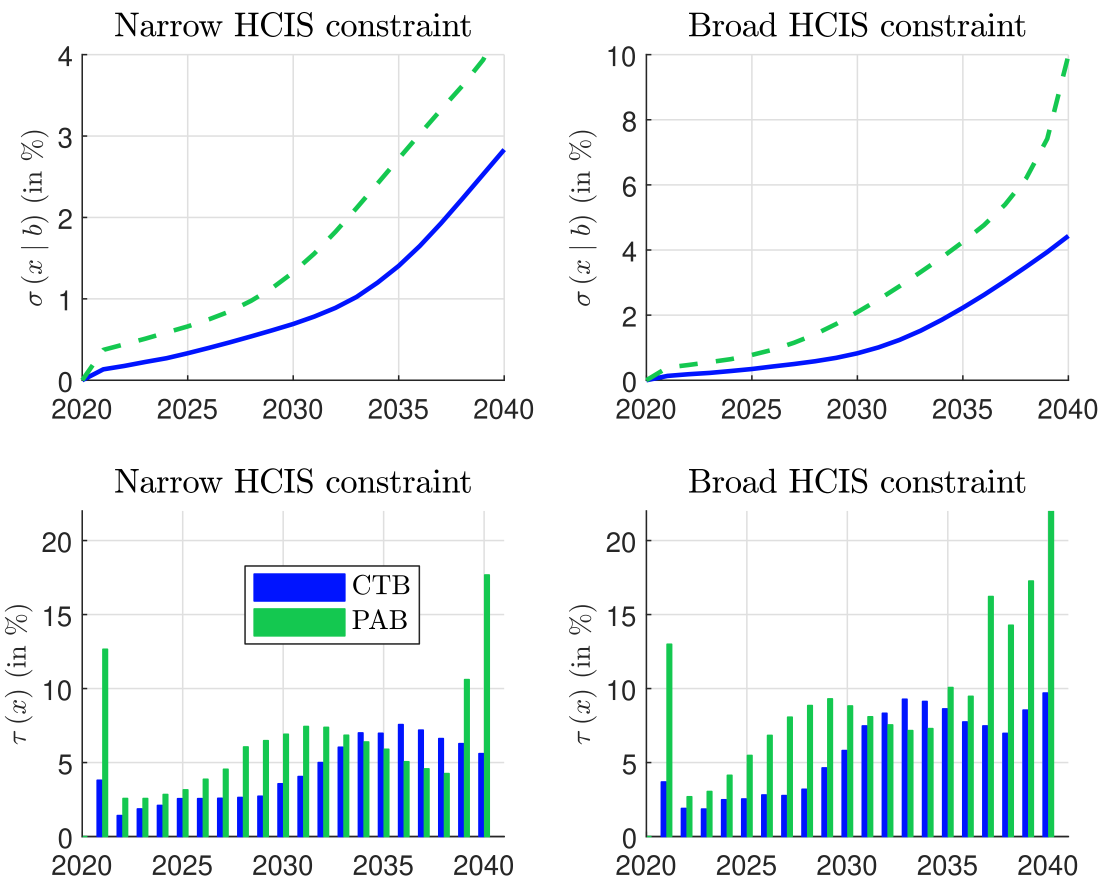
Figure 33: The impact of scope 3 on CTB and PAB labels



Source: Le Guenedal and Roncalli (2022).

Optimization solution

Figure 34: The impact of the HCIS constraint on CTB and PAB labels



Source: Le Guenedal and Roncalli (2022).

Optimization solution

Table 29: Tracking error risk of CTB and PAB labels

Year	CTB			PAB		
	Scope 3	+ Narrow	+ Broad	Scope 3	+ Narrow	+ Broad
2021	0.12%	0.13%	0.13%	0.33%	0.37%	0.39%
2022	0.16%	0.18%	0.19%	0.39%	0.44%	0.47%
2023	0.20%	0.23%	0.23%	0.46%	0.51%	0.56%
2024	0.24%	0.27%	0.28%	0.52%	0.59%	0.65%
2025	0.29%	0.33%	0.35%	0.59%	0.66%	0.78%
2030	0.62%	0.69%	0.83%	1.20%	1.33%	2.09%
2035	1.28%	1.40%	2.23%	2.55%	2.72%	4.25%
2040	2.66%	2.83%	4.43%	4.19%	4.43%	9.97%

Source: Le Guenedal and Roncalli (2022).

Optimization solution

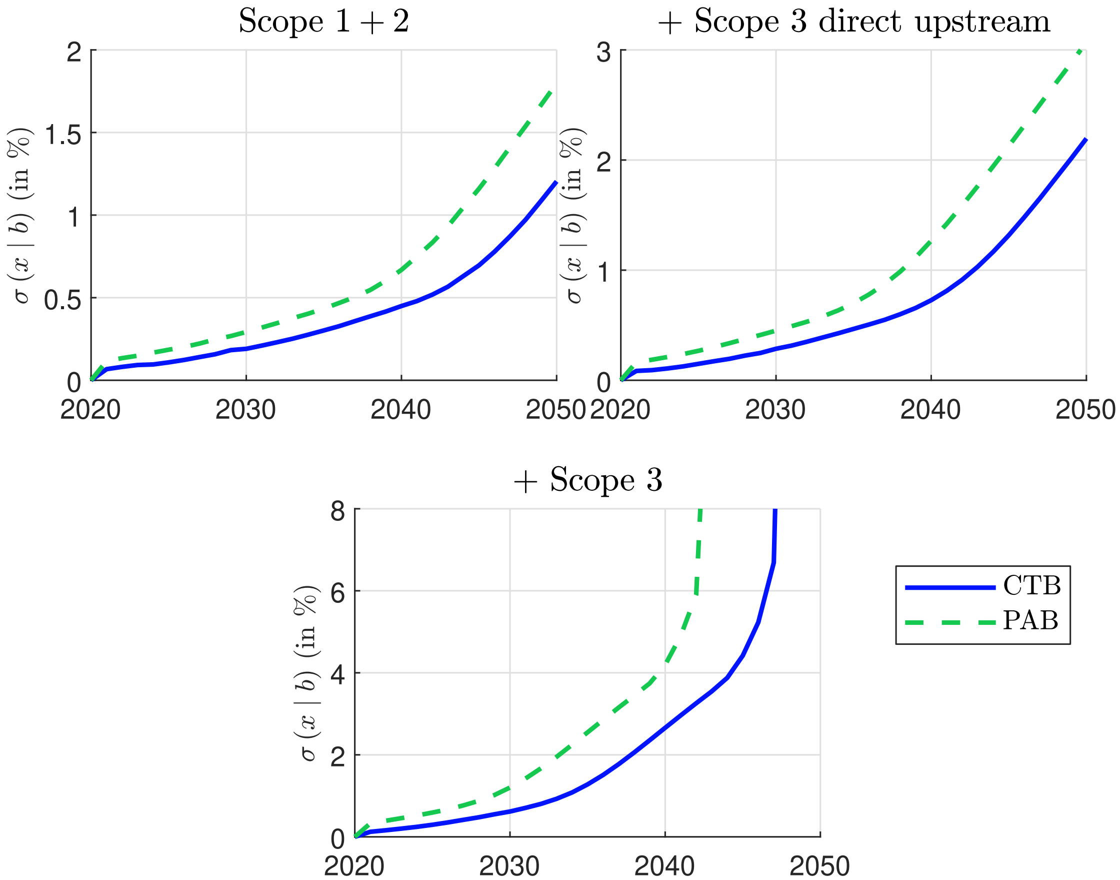
Table 30: Effective number of bets

Year	CTB			PAB		
	Scope 3	+ Narrow	+ Broad	Scope 3	+ Narrow	+ Broad
2020	70.56	70.56	70.56	70.56	70.56	70.56
2021	69.95	70.29	70.15	68.37	69.30	68.78
2022	69.77	70.24	70.53	68.06	68.93	68.30
2023	69.48	70.22	69.88	67.59	68.43	67.95
2024	69.07	69.73	69.68	67.02	68.12	67.11
2025	68.66	69.52	69.08	66.58	67.46	66.75
2030	66.26	67.24	66.42	66.64	68.82	66.85
2035	67.36	69.61	66.15	76.35	76.42	44.72
2040	76.26	75.67	41.45	49.97	42.61	5.48

Source: Le Guenedal and Roncalli (2022).

The scope 3 issue (which scope 3?)

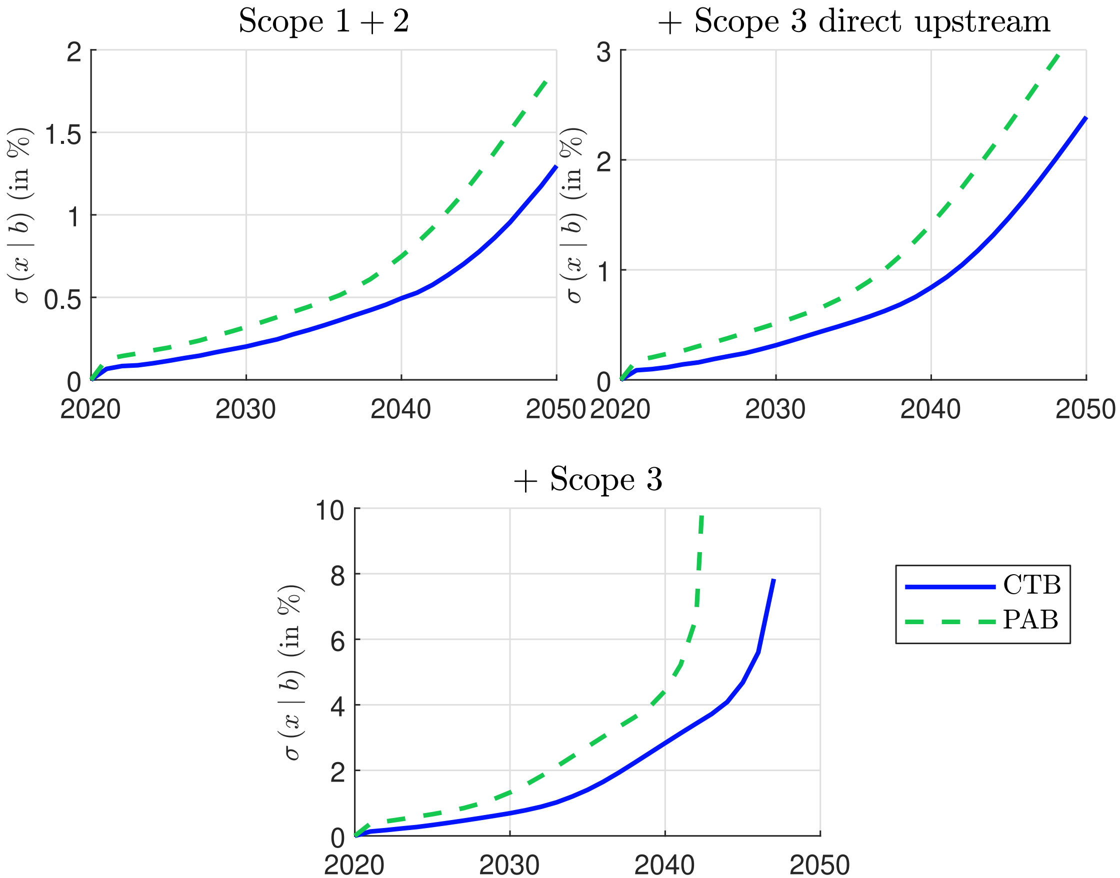
Figure 35: Tracking error of CTB and PAB labels when implementing the decarbonization pathway



Source: Le Guenedal and Roncalli (2022).

The scope 3 issue (which scope 3?)

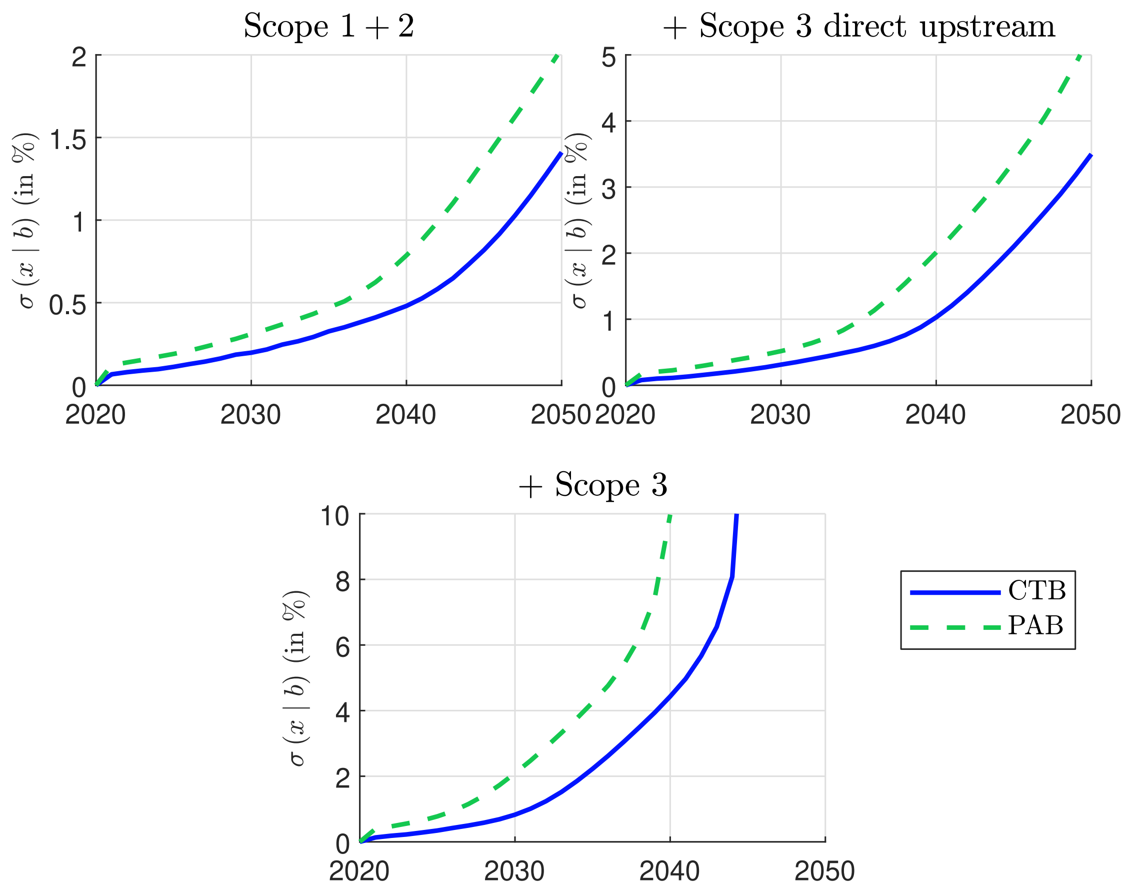
Figure 36: Tracking error of CTB and PAB labels when implementing the decarbonization pathway and the narrow HCIS constraint



Source: Le Guenedal and Roncalli (2022).

The scope 3 issue (which scope 3?)

Figure 37: Tracking error of CTB and PAB labels when implementing the decarbonization pathway and the broad HCIS constraint



Source: Le Guenedal and Roncalli (2022).

Understanding allocation effects

See Barahhou and Roncalli (2022) $\Rightarrow$ additional slides

Top-down approach $\Rightarrow$ bottom-up approach

Preamble

- NZE portfolio alignment cannot be reduced to portfolio decarbonization with a carbon reduction pathway
- NZE portfolio alignment is more difficult than portfolio decarbonization for three reasons:
  1. Reduction rates $\mathcal{R}(t_0, t)$ are very high $\Rightarrow$ Diversification will be highly reduced!
  2. How avoiding to pass the hot potato on to the other investors? $\Rightarrow$ It is easy to decarbonize, but it is difficult to participate to the NZE effort!
  3. Uncertainty about the future trajectories and no turning back $\Rightarrow$ Current mistakes are cumulative

How to manage a portfolio in a highly constrained world in terms of investment universe?

Some risks

Portfolio management risks

- Economy decarbonization $\ll$ Finance decarbonization
- Diversification can be dramatically reduced between/within sectors
- Liquidity issues

Financial risks

- Performance
- Crowding
- How to remain an active manager?

Economic risks

- Who will finance the transition?
- Liability risk(s)

NZE portfolio optimization

The constraints

- We have to introduce the issuer/sector trajectories
- For instance, the carbon intensity constraint of the PAB problem:

$$\mathcal{CI}\left(x\left(t\right)\right) \leq \left(1 - \mathcal{R}\left(t_0, t\right)\right) \cdot \mathcal{CI}\left(b\left(t_0\right)\right)$$

becomes:

$$\widehat{\mathcal{CI}}\left(x\left(t\right)\right) \leq \left(1 - \mathcal{R}\left(t_0, t\right)\right) \cdot \mathcal{CI}\left(b\left(t_0\right)\right)$$

where:

$$\widehat{\mathcal{CI}}\left(x\left(t\right)\right) = \sum_{i=1}^{n} x_i\left(t\right) \cdot \widehat{\mathcal{CI}}_i\left(t\right)$$

- Which estimate measures?
  - Trend trajectory?
  - Target trajectory?
  - NZE trajectory?

NZE portfolio optimization

The constraints

- What is the drawback to use constraints on $\widehat{\mathcal{CI}}\left(x\left(t\right)\right)$ or $\widehat{\mathcal{CE}}\left(x\left(t\right)\right)$?
- The solution does not depend on the intermediate values of $\widehat{\mathcal{CI}}\left(x\left(t\right)\right)$ or $\widehat{\mathcal{CE}}\left(x\left(t\right)\right)$ between t_0 and $t-1$
- A better approach is to consider the carbon budget $\widehat{\mathcal{CB}}\left(t_0, t\right)$?

NZE portfolio optimization

The objective function

We consider this simple objective function:

$$
\begin{aligned}
x^{\text{nze}}(t) &= \arg\min_x \frac{1}{2}(x-b)^\top \Sigma (x-b) \\
&\text{s.t.} \quad \begin{cases} \mathbf{1}_n^\top x = 1 \\ x \geq \mathbf{0}_n \\ \widehat{\mathcal{CI}}(x) \leq (1-\mathcal{R}(t_0,t)) \cdot \mathcal{CI}(b(t_0)) \end{cases}
\end{aligned}
$$

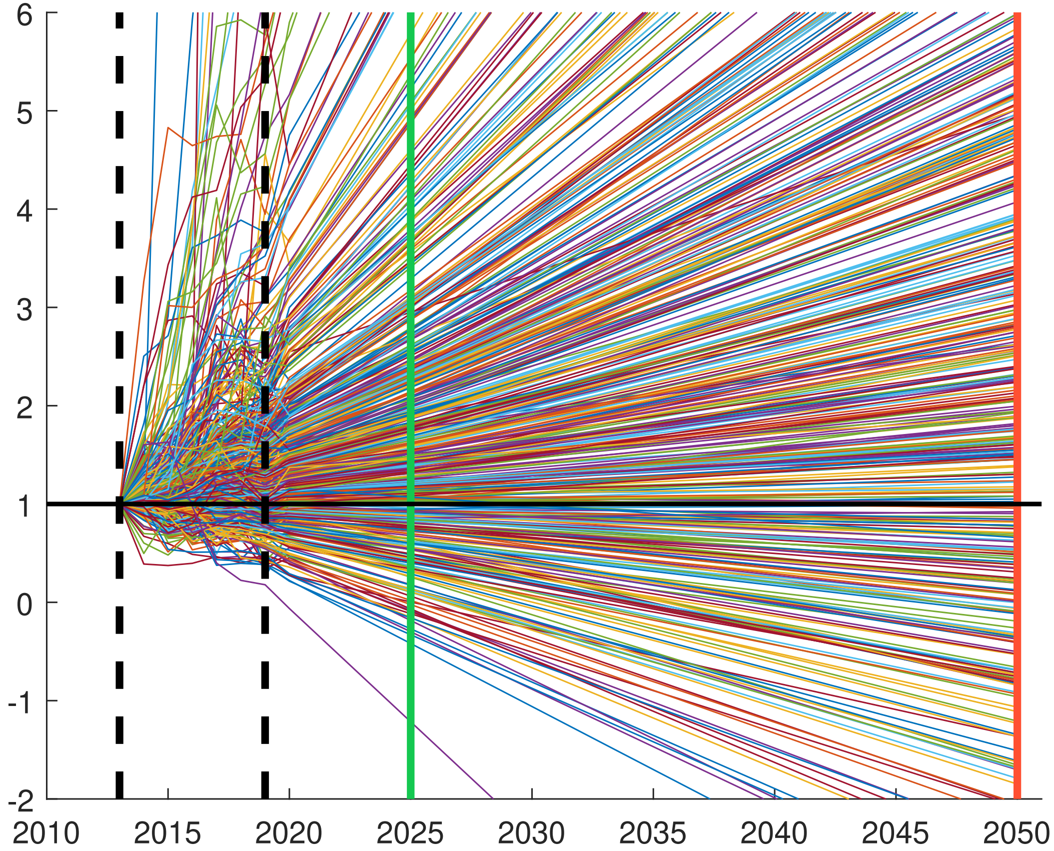
where $\widehat{\mathcal{CI}}(x)$ uses the projected trends:

$$
\widehat{\mathcal{CI}}(x) = \sum_{i=1}^{n} x_i \cdot \mathcal{CI}_i^{Trend}(t)
$$

NZE portfolio optimization

Results with the S&P 500 index

Figure 38: Carbon emissions trends of the S&P 500 constituents



Source: Le Guenedal and Roncalli (2022).

NZE portfolio optimization

Results with the S&P 500 index

We have:

Statistic	$\hat{\beta}_{i,1} \leq 0$	$\hat{\beta}_{i,1} > 0$	$m_i(2050) \geq 2$	$m_i(2050) \geq 5$
Frequency	26.9%	73.1%	59.41%	30.69%

where:

$$m_i(t) = \frac{\mathcal{CI}_i^{Trend}(t)}{\mathcal{CI}_i(2019)}$$

NZE portfolio optimization

Results with the S&P 500 index

We consider:

- The solution $x^{NZE}(t)$
- The solution $x^{\mathrm{DCN}}(t)$ obtained by considering the current carbon intensities $\mathcal{CI}_i(t_0)$ instead of the estimated values $\mathcal{CI}_i^{Trend}(t)$

We compute the active share between the two portfolios:

$$\mathcal{AS}\left(x^{\mathrm{NZE}}(t), x^{\mathrm{DCN}}(t)\right) = \frac{1}{2}\left\|x^{\mathrm{NZE}}(t) - x^{\mathrm{DCN}}(t)\right\|_1$$

Table 31: Active share between NZE and DCN portfolios

Year	$\mathcal{R}(t_0, t)$ 10%	20%	30%	40%	50%	60%	70%	80%
2025	1.0%	1.3%	2.0%	3.2%	4.4%	7.8%	18.4%	48.9%
2030	1.1%	1.4%	2.7%	4.8%	9.2%	15.3%	28.5%	58.3%
2035	1.1%	1.8%	3.3%	5.9%	11.0%	17.3%	30.6%	60.0%
2040	1.1%	2.0%	3.6%	6.3%	11.5%	18.0%	31.3%	60.6%
2045	1.2%	2.1%	3.8%	6.5%	11.8%	18.3%	31.6%	60.8%
2050	1.2%	2.1%	3.8%	6.7%	11.9%	18.5%	31.7%	60.9%

The no-feasible NZE solution

- The Financials/Industrials solution is not an NZE solution!
- Too much constraints & objectives $\Rightarrow$ No solution!
- The gap between portfolio decarbonization and economy decarbonization must be reduced sooner or later $\Rightarrow$ The asset management industry is at risk!