Course 2024–2025 in Sustainable Finance
Lecture 12. Climate Risk Measures

Thierry Roncalli*

*Amundi Asset Management[1]

*University of Paris-Saclay

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[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.

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Definition

How to define the carbon footprint?

Wackernagel and Rees (1996) published the seminal book on the ecological footprint:

> *"the carbon footprint stands for a certain amount of gaseous emissions that are relevant to climate change and associated with human production or consumption activities"*

Wiedmann and Minx (2008) proposed this definition:

> *"The carbon footprint is a measure of the exclusive total amount of carbon dioxide emissions that is directly and indirectly caused by an activity or is accumulated over the life stages of a product"*

Carbon footprint

- The carbon footprint is measured in carbon dioxide equivalent ($\mathrm{CO_2e}$) ⇒ a common unit
- We have:

$$\text{equivalent mass of } \mathrm{CO}_2 = \text{mass of the gas} \times \text{gwp of the gas}$$

- Examples (IPCC, AR5, 2013):
  - 1 kg of methane corresponds to 28 kg of CO_2
  - 1 kg of nitrous oxide corresponds to 265 kg of CO_2
- The carbon footprint is equal to:

$$m = \sum_{i=1}^{n} m_i \cdot \mathrm{gwp}_i$$

- The units are: $\mathrm{kgCO_2e}$, $\mathrm{tCO_2e}$, $\mathrm{ktCO_2e}$, $\mathrm{MtCO_2e}$ and $\mathrm{GtCO_2e}$

Carbon footprint

Example #1

We consider a company A that emits 3 017 tonnes of CO_2, 10 tonnes of CH_4 and 1.8 tonnes of N_2O. For the company B, the GHG emissions are respectively equal to 2 302 tonnes of CO_2, 32 tonnes of CH_4 and 3.0 tonnes of N_2O.

The mass of CO_2 equivalent for companies A and B is equal to:

$$m_A = 3017 \times 1 + 10 \times 28 + 1.8 \times 265 = 3\,774 \ \mathrm{tCO_2e}$$

and:

$$m_B = 2302 \times 1 + 32 \times 28 + 3.0 \times 265 = 3\,993 \ \mathrm{tCO_2e}$$

Estimation of the global warming potential

- According to IPCC (2007), GWP is defined as "*the cumulative radiative forcing, both direct and indirect effects, over a specified time horizon resulting from the emission of a unit mass of gas related to some reference gas*".
- Each gas differs in their capacity to absorb the energy (radiative efficiency) and how long it stays in the atmosphere (lifetime)
- The impact of a gas on global warming depends on the combination of radiative efficiency and lifetime

Estimation of the global warming potential

The mathematics of GWP

- The mathematical definition of the global warming potential is:

$$\mathrm{gwp}_i(t) = \frac{\mathrm{Agwp}_i(t)}{\mathrm{Agwp}_0(t)} = \frac{\int_0^t RF_i(s)\,\mathrm{d}s}{\int_0^t RF_0(s)\,\mathrm{d}s} = \frac{\int_0^t A_i(s)\,\mathbf{S}_i(s)\,\mathrm{d}s}{\int_0^t A_0(s)\,\mathbf{S}_0(s)\,\mathrm{d}s}$$

  where $A_i(t)$ is the radiative efficiency value of gas i, $\mathbf{S}_i(t)$ is the decay function and $i = 0$ is the reference gas (e.g, CO_2)

- We assume that:

$$\mathbf{S}_i(t) = \sum_{j=1}^{m} a_{i,j} e^{-\lambda_{i,j} t}$$

  where $\sum_{j=1}^{m} a_{i,j} = 1$

- We obtain:

$$\mathrm{gwp}_i(t) = \frac{A_i \sum_{j=1}^{m} a_{i,j} \lambda_{i,j}^{-1} \left(1 - e^{-\lambda_{i,j} t}\right)}{A_0 \sum_{j=1}^{m} a_{0,j} \lambda_{0,j}^{-1} \left(1 - e^{-\lambda_{0,j} t}\right)}$$

Estimation of the global warming potential

- Carbon dioxide
  - $A_{\mathrm{CO}_2} = 1.76 \times 10^{-18}$
  - The impulse response function is:

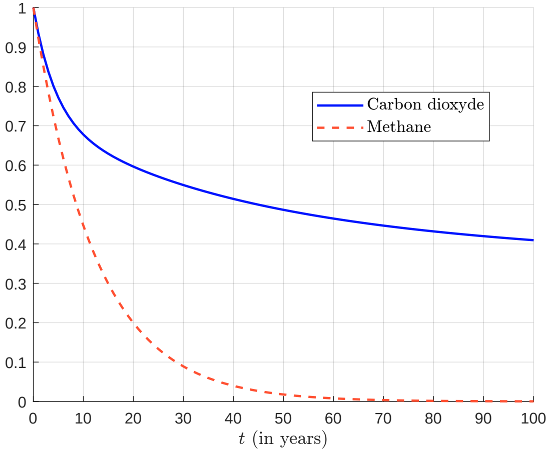
$$\begin{aligned} \mathbf{S}_{\mathrm{CO}_2}(t) &= 0.2173 + \\ & 0.2240 \cdot \exp\left(-\frac{t}{394.4}\right) + \\ & 0.2824 \cdot \exp\left(-\frac{t}{36.54}\right) + \\ & 0.2763 \cdot \exp\left(-\frac{t}{4.304}\right) \end{aligned}$$

- Methane
  - $A_{\mathrm{CH}_4} = 2.11 \times 10^{-16}$
  - The impulse response function is:

$$\mathbf{S}_{\mathrm{CH}_4}(t) = \exp\left(-\frac{t}{12.4}\right)$$

Estimation of the global warming potential

Figure 1: Fraction of gas remaining in the atmosphere



Source: Kleinberg(2020) & Author's calculations.

Estimation of the global warming potential

Remark

- The decay function is a survival function
- The density function is equal to $f_i(t) = -\partial_t \mathbf{S}_i(t)$
- Let τ_i be random time that the gas remains in the atmosphere
- In the case of the exponential distribution $\mathcal{E}(\lambda)$, we have

$$\begin{array}{rcl} \mathbf{S}_i(t) & = & e^{-\lambda t} \\ f_i(t) & = & \lambda e^{-\lambda t} \\ \mathbb{E}[\tau_i] & = & \dfrac{1}{\lambda} \end{array}$$

⇒ The survival function of the CH_4 gas is exponential with a mean time equal to 12.4 years ($\lambda = 1/12.4$)

Estimation of the global warming potential

- In the general case, the probability density function is equal to:

$$f_i(t) = -\partial_t \mathbf{S}_i(t) = \sum\nolimits_{j=1}^{m} a_{i,j} \lambda_{i,j} e^{-\lambda_{i,j} t}$$

- The mean time $\mathcal{T}_i$ is given by:

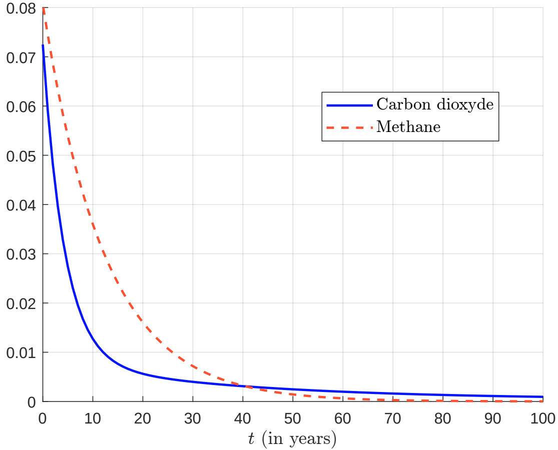
$$\begin{aligned} \mathcal{T}_i := \mathbb{E}[\tau_i] &= \int_0^\infty s f_i(s) \,\mathrm{d}s \\ &= \sum\nolimits_{j=1}^{m} a_{i,j} \int_0^\infty \lambda_{i,j} s e^{-\lambda_{i,j} s} \,\mathrm{d}s \\ &= \sum\nolimits_{j=1}^{m} \frac{a_{i,j}}{\lambda_{i,j}} \end{aligned}$$

Remark

We have $\mathcal{T}_{\mathrm{CH}_4} = 12.4$ years, but $\mathcal{T}_{\mathrm{CO}_2} = \infty$

Estimation of the global warming potential

Figure 2: Probability density function of the random time



Source: Kleinberg (2020) & Author's calculations.

Estimation of the global warming potential

Remark

- $f_i(t)$ is an exponential mixture distribution where m is the number of mixture components
- $\mathcal{E}(\lambda_{i,j})$ is the probability distribution associated with the j^{th} component
- $a_{i,j}$ is the mixture weight of the j^{th} component

We have:

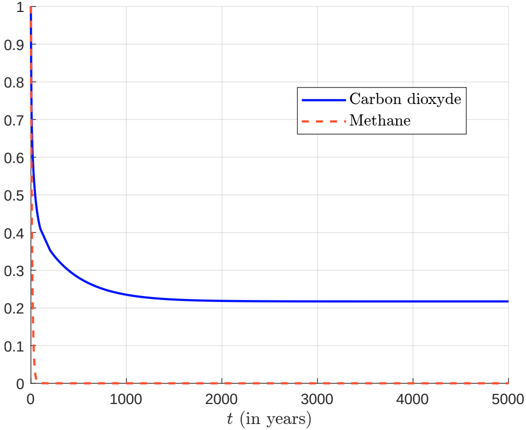
$$\mathcal{T}_i = \mathbb{E}[\tau_i] = \sum\nolimits_{j=1}^{m} a_{i,j}\mathbb{E}[\tau_{i,j}] = \sum\nolimits_{j=1}^{m} a_{i,j}\mathcal{T}_{i,j}$$

For the CO_2 gas, the exponential mixture distribution is defined by the following parameters:

j	1	2	3	4
$a_{i,j}$	0.2173	0.2240	0.2824	0.2763
$\lambda_{i,j}$ ($\times 10^3$)	0.00	2.535	27.367	232.342
$\mathcal{T}_{i,j}$ (in years)	∞	394.4	36.54	4.304

Estimation of the global warming potential

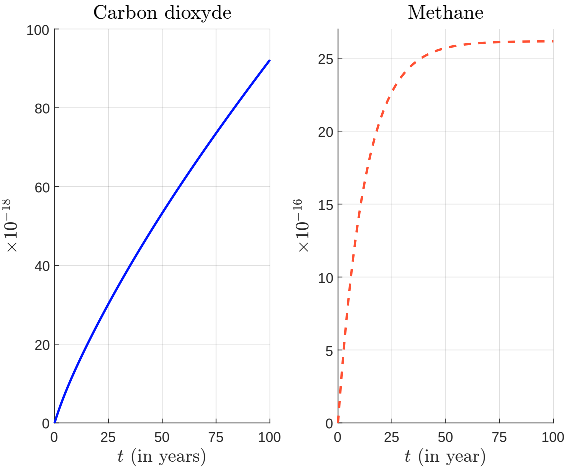
Figure 3: Survival function



We have $\mathbf{S}_{\mathrm{CO}_2}(\infty) = 21.73\%$!

Estimation of the global warming potential

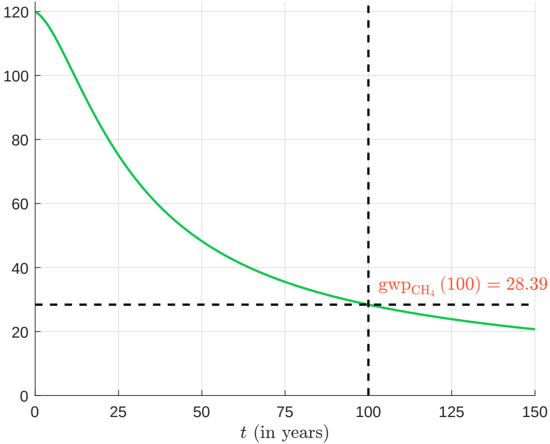
Figure 4: Absolute global warming potential



Source: Kleinberg (2020) & Author's calculations.

Estimation of the global warming potential

Figure 5: Global warming potential for methane



Source: Kleinberg (2020) & Author's calculations.

Estimation of the global warming potential

We have:

- $\mathrm{Agwp}_{\mathrm{CO}_2}(\infty) = \infty$
- $\mathrm{Agwp}_{\mathrm{CH}_4}(\infty) = A_{\mathrm{CH}_4} \times \mathcal{T}_{\mathrm{CH}_4} \propto 2.11 \times 12.4 = 26.164$
- The instantaneous global warming potential of the methane is equal to:

$$\mathrm{gwp}_{\mathrm{CH}_4}(0) = \frac{A_{\mathrm{CH}_4}}{A_{\mathrm{CO}_2}} = \frac{2.11 \times 10^{-16}}{1.76 \times 10^{-18}} \approx 119.9$$

- After 100 years, we obtain:

$$\boxed{\mathrm{gwp}_{\mathrm{CH}_4}(100) = 28.3853}$$

This is the IPCC value!

- Because of the persistant regime of the carbon dioxyde, we have $\mathrm{gwp}_{\mathrm{CH}_4}(\infty) = 0$
- We have:

$$\mathrm{gwp}_{\mathrm{CH}_4}(t) \leq 1 \Leftrightarrow t \geq 6\,382 \text{ years}$$

Estimation of the global warming potential

Table 1: GWP values for 100-year time horizon

Name	Formula	AR2	AR4	AR5	AR6
Carbon dioxide	CO_2	1	1	1	1
Methane	CH_4	21	25	28	27.9
Nitrous oxide	N_2O	310	298	265	273
Sulphur hexafluoride	SF_6	23 900	22 800	23 500	25 200
Hydrofluorocarbons (HFC)	CHF_3	11 700	14 800	12 400	14 600
	CH_2F_2	650	675	677	771
	Etc.				
Perfluorocarbons (PFC)	CF_4	6 500	7 390	6 630	7 380
	C_2F_6	9 200	12 200	11 100	12 400
	Etc.				

Consolidation accounting at the company level

Two approaches:

1. Equity share approach
2. Control approach
    1. Financial control
    2. Operational control

Consolidation accounting at the company level

Table 2: Percent of reported GHG emissions under each consolidation method

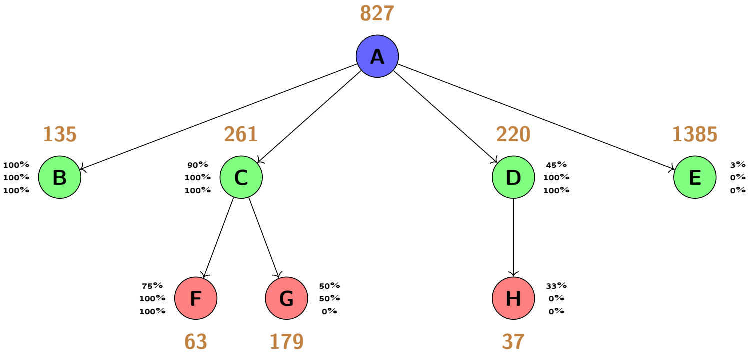
Accounting categories	GHG accouting based on		
	equity share	financial control	operational control
Wholly owned asset	100%	100%	100%
Group companies/subsidiaries	OWNR	100%	100%
Associated/affiliated companies	OWNR	0%	0%/100%
Joint ventures/partnerships	OWNR	OWNR	0%/100%
Fixed asset investments	0%	0%	0%
Franchises	0%	0%	0%
	OWNR	100%	100%

Source: GHG Protocol (2004, Table 1, page 19).

OWNR = Ownership ratio

Consolidation accounting at the company level

Figure 6: Defining the organizational boundary of company *A*



For each company, the brown number corresponds to the carbon emissions in $\mathrm{tCO_2e}$. The three figures at the right or left of the node corresponds respectively to the equity share, the financial control and the operational control

Consolidation accounting at the company level

- Equity share approach:

$$\begin{aligned}\mathcal{CE}_A &= 827 + 100\% \times 135 + 90\% \times 261 + 45\% \times 220 + 0\% \times 1\,385 + \\ &\quad 90\% \times 75\% \times 63 + 90\% \times 50\% \times 179 + 45\% \times 33\% \times 37 \\ &= 1\,424.4\,\mathrm{tCO_2e}\end{aligned}$$

- Financial control approach:

$$\begin{aligned}\mathcal{CE}_A &= 827 + 100\% \times 135 + 100\% \times 261 + 100\% \times 220 + 0\% \times 1\,385 + \\ &\quad 100\% \times 100\% \times 63 + 100\% \times 50\% \times 179 + 100\% \times 0\% \times 37 \\ &= 1\,595.50\,\mathrm{tCO_2e}\end{aligned}$$

- Operational control approach:

$$\begin{aligned}\mathcal{CE}_A &= 827 + 100\% \times 135 + 100\% \times 261 + 100\% \times 220 + 0\% \times 1385 + \\ &\quad 100\% \times 100\% \times 63 + 100\% \times 0\% \times 179 + 100\% \times 0\% \times 37 \\ &= 1\,506.00\,\mathrm{tCO_2e}\end{aligned}$$

Scope 1, 2 and 3 of carbon emissions

GHG Protocol (`www.ghgprotocol.org/corporate-standard`)

- Scope 1 denotes direct GHG emissions occurring from sources that are owned and controlled by the issuer.
- Scope 2 corresponds to the indirect GHG emissions from the consumption of purchased electricity, heat or steam.
- Scope 3 are other indirect emissions (not included in scope 2) of the entire value chain. They can be divided into two main categories[a]:
  - Upstream scope 3 emissions are defined as indirect carbon emissions related to purchased goods and services.
  - Downstream scope 3 emissions are defined as indirect carbon emissions related to sold goods and services.

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[a] The upstream value chain includes all activities related to the suppliers whereas the downstream value chain refers to post-manufacturing activities.

Scope 1, 2 and 3 of carbon emissions

Table 3: Examples of CDP reporting ($\mathcal{CE}$ in $\mathrm{tCO_2e}$, year 2020)

Scope	Category	Sub-category	Amazon	Danone	ENEL	Pfizer	Netflix	Walmart
1			9 623 138	668 354	45 255 000	654 460	30 883	7 236 499
2	Location-based (2a)		9 019 786	864 710	4 990 685	551 577	28 585	11 031 800
	Market-based (2b)		5 265 089	479 210	7 855 954	542 521	141	9 190 337
3	Upstream	Purchased goods and services	16 683 423	19 920 918		2 526 537	765 208	130 200 000
		Capital goods	13 202 065			191 894	116 366	645 328
		Fuel and energy related activities	1 248 847	283 764	1 061 268	203 093	12 287	3 327 874
		Upstream transportation and distribution	8 563 695	321 558	112 358	723 558	64 693	342 577
		Waste generated in operations	16 628	152 789	3 161	14 940		869 927
		Business travel	313 043			35 128	41 439	37 439
		Employee commuting	306 033			48 414	19 116	3 500 000
		Upstream leased assets	1 223 903			30 522	131	
	Downstream	Downstream transportation and distribution	2 785 676	1 627 090		7 295		5 099
		Processing of sold products						
		Use of sold products	1 426 543	1 885 548	46 524 860		952	32 211 000
		End-of-life treatment of sold products	0	782 649				130
		Downstream leased assets					349	130 000
		Franchises						
		Investments				36 839		
Total	Scope 1 + 2a		18 642 924	1 533 064	50 245 685	1 206 037	59 468	18 268 299
	Scope 1 + 2b		14 888 227	1 147 564	53 110 954	1 196 981	31 024	16 426 836
	Scope 3 upstream		41 557 637	20 679 029	1 176 787	3 774 086	1 019 240	138 923 145
	Scope 3 downstream		4 212 219	4 295 287	46 524 860	44 134	1 301	32 346 229
	Scope 3		45 769 856	24 974 316	47 701 647	3 818 220	1 020 541	171 269 374
	Scope 1 + 2a + 3		64 412 780	26 507 380	97 947 332	5 024 257	1 080 009	189 537 673
	Scope 1 + 2b + 3		60 658 083	26 121 880	100 812 601	5 015 201	1 051 565	187 696 210

Source: CDP database as of 01/07/2022 & Author's computation.

Scope 1, 2 and 3 of carbon emissions

CDP questionnaire for corporates

- `www.cdp.net/en/guidance/guidance-for-companies`
- HTML, Word and PDF formats
- 129 pages and 16 sections: $\mathcal{SC}_1$ (§C6.1), $\mathcal{SC}_2$ (§C6.3) and $\mathcal{SC}_3$ emissions (§C6.5) — emissions intensities (§C6.10)

CDP Climate Change 2023 Questionnaire

Computation of scope 1 emissions

- We allocate the activities to the three scopes
- Then, we apply an **emission factor** to each activity and each gas:

$$E_{g,h} = A_h \cdot \boldsymbol{\mathcal{EF}}_{g,h}$$

where A_h is the h^{th} **activity rate** (also called activity data) and $\boldsymbol{\mathcal{EF}}_{g,h}$ is the emission factor for the h^{th} activity and the g^{th} gas

  - A_h can be measured in volume, weight, distance, duration, surface, etc.
  - $E_{g,h}$ is expressed in tonne
  - $\boldsymbol{\mathcal{EF}}_{g,h}$ is measured in tonne per activity unit

- For each gas, we calculate the total emissions:

$$E_g = \sum_{h=1}^{n_A} E_{g,h} = \sum_{h=1}^{n_A} A_h \cdot \boldsymbol{\mathcal{EF}}_{g,h}$$

- Finally, we estimate the carbon emissions by applying the right GWP:

$$\boldsymbol{\mathcal{CE}} = \sum_{g=1}^{n_G} \mathrm{gwp}_g \cdot E_g$$

Tier methods

The choice of data inputs is codified by IPCC (2019):

- Tier 1 methods use global default emission factors;
- Tier 2 methods use country-level or region-specific emission factors;
- Tier 3 methods use directly monitored or site-specific emission factors.

⇒ IPCC Emission Factor Database, National Inventory Reports (NIRs), country emission factor databases, etc.

France

- The database of emission factors is managed by **ADEME** (Agence de l'Environnement et de la Maîtrise de l'Energie)
- It contains about 5 300 validated emission factors
- `https://bilans-ges.ademe.fr`

Reporting of scope 1 emissions

GHG inventory document of Enel (2021)

- Scope 1 emissions expressed in $\mathrm{ktCO_2e}$:

	CO_2	CH_4	N_2O	NF_3	SF_6	HFCs	Total
Electricity power generation	50 643.54	385.25	98.14	0.014	31.15	10.22	51 168.32
Electricity distribution	208.33	0.24	0.45		111.62		320.64
Real estate	79.87	0.22	1.24				81.30
Total	50 931.72	385.71	99.83	0.014	142.77	10.22	51 750.26

- The scope 1 emissions of Enel is equal to 51.75 $\mathrm{MtCO_2e}$

Scope 1 emissions

Table 4: Examples of emission factors (EFDB, IPCC)

Category	Description	Gas	Region	Value	Unit
Iron and steel production	Integrated facility	CO_2	Canada	1.6	t/tonne
	Electrode consumption from steel produced in electric arc furnaces	CO_2	Global	5.0	kg/tonne
	Steel processing (rolling mills)	N_2O	Global	40	g/tonne
Manufacture of solid fuels	Metallurgical coke production	CO_2	Global	0.56	t/tonne
		CH_4	Global	0.1	g/tonne
Fuel combustion activities	Crude oil	CO_2	Global	20	tCarbon/TeraJoule
	Natural gas	CO_2	Global	15.3	tCarbon/TeraJoule
	Ethane	CO_2	Global	16.8	tCarbon/TeraJoule
Integrated circuit or semiconductor	Semiconductor manufacturing (silicon)	CF_4	Global	0.9	kg/m^2
Cement production	Cement production	CO_2	Global	0.4985	t/tonne
Horses	Enteric fermentation	CH_4	Global	18	kg/head/year
	Manure management (annual average temperature is less than 15oC)	CH_4	Developed countries	1.4	kg/head/year
	Manure management (annual average temperature is between 15oC and 25oc)	CH_4	Developed countries	2.1	kg/head/year
Buffalo	Enteric fermentation	CH_4	Global	55	kg/head/year
Poultry	Manure management (annual average temperature is less than 15oC)	CH_4	Developed countries	0.078	kg/head/year
	Manure management (annual average temperature is between 15oC and 25oc)	CH_4	Developed countries	0.117	kg/head/year
	Manure management (annual average temperature is greater than 25oC)	CH_4	Developed countries	0.157	kg/head/year
	Manure management (annual average temperature is greater than 25oC)	CH_4	Developing countries	0.023	kg/head/year

Source: EFDB, `www.ipcc-nggip.iges.or.jp/EFDB`.

Scope 2 emissions

Definition

Scope 2 is "*an indirect emission category that includes GHG emissions from the purchased or acquired electricity, steam, heat, or cooling consumed*" (GHG Protocol, 2015):

- Electricity
  People use electricity for operating machines, lighting, heating, cooling, electric vehicle charging, computers, electronics, public transportation systems, etc.
- Steam
  Industries use steam for mechanical work, heating, propulsion, driven turbines in electric power plants, etc.
- Heat
  Buildings use heat to control inside temperature and heat water, while the industrial sector uses heat for washing, cooking, sterilizing, drying, etc. Heat may be produced from electricity, solar heat processes or thermal combustion.
- Cooling
  It is produced from electricity or though the processes of forced air, conduction, convection, etc.

Scope 2 emissions

Figure 7: Energy production and consumption from owned/operated generation

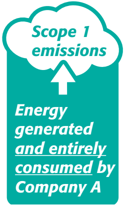
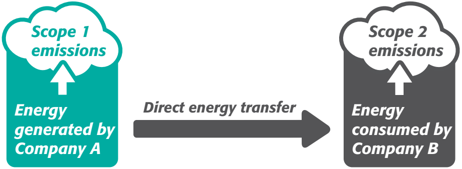


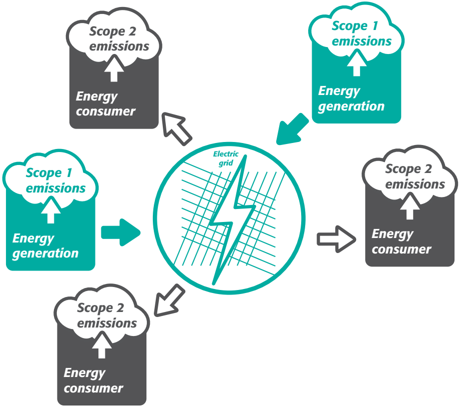
Figure 8: Direct line energy transfer



Source: GHG Protocol (2015, Figures 5.1 and 5.2, pages 35-36).

Scope 2 emissions

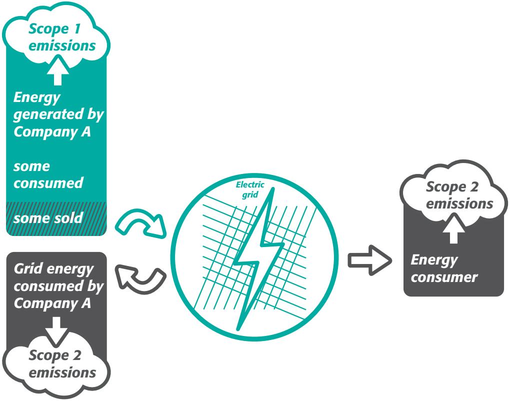
Figure 9: Electricity production on a grid



Source: GHG Protocol (2015, Figure 5.4, page 38).

Scope 2 emissions

Figure 10: Facility consuming both energy generated on-site and purchased from the grid



Source: GHG Protocol (2015, Figure 5.3, page 37).

Computation of scope 2 emissions

Scope 2 emissions are calculated using activity data and emission factors expressed in MWh and $\mathrm{tCO_2e}$/MWh:

$$\mathcal{CE} = \sum_s A_s \cdot \mathcal{EF}_s$$

where:

- A_s is the amount of purchased electricity for the energy generation source s
- $\mathcal{EF}_s$ is the emission factor of the source s

Computation of scope 2 emissions

Example #2

We consider a company, whose electricity consumption is equal to 2 000 MWh per year. The electricity comes from two sources: 60% from a direct line with an electricity supplier (source S_1) and 40% from the country grid (source S_2). The emission factors are respectively equal to 200 and 350 $\mathrm{gCO_2e}$/kWh.

Computation of scope 2 emissions

- The electricity consumption from source S_1 is equal to $60\% \times 2\,000 = 1\,200$ MWh or $1\,200\,000$ kWh
- We deduce that the carbon emissions from this source is:

$$\mathcal{CE}\left(S_1\right) = \left(1.2 \times 10^6\right) \times 200 = 240 \times 10^6 \text{ gCO}_2\text{e} = 240 \text{ tCO}_2\text{e}$$

- For the second source, we obtain:

$$\mathcal{CE}\left(S_2\right) = \left(0.8 \times 10^6\right) \times 350 = 280 \times 10^6 \text{ gCO}_2\text{e} = 280 \text{ tCO}_2\text{e}$$

- We deduce that the Scope 2 carbon emissions of this company is equal to 520 tCO_2e

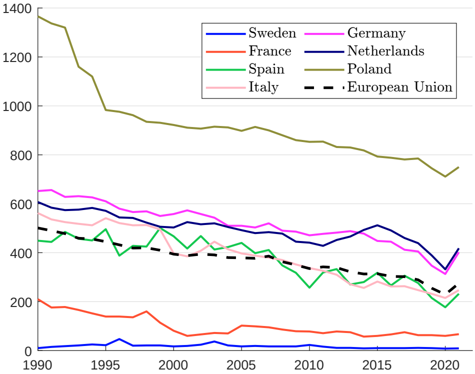
Scope 2 emissions accounting

Two main methods:

- **Location-based method**
  In this approach, the company uses the average emission factor of the region or the country. For instance, if the electricity consumption is located in France, the company can use the emission intensity of the French energy mix;
- **Market-based method**
  This approach reflects the GHG emissions from the electricity that the company has chosen in the market. This means that the scope 2 carbon emissions will depend on the scope 1 carbon intensity of the electricity supplier

Scope 2 emission factors

Figure 11: Emission factor in $\mathrm{gCO_2e}$/kWh of electricity generation (European Union, 1990 – 1992)



Source: European Environment Agency (2022), `www.eea.europa.eu/data-and-maps` & Author's calculations.

Scope 2 emission factors

Table 5: Emission factor in $\mathrm{gCO_2e}$/kWh of electricity generation in the world

Region	$\mathcal{EF}$	Country	$\mathcal{EF}$	Country	$\mathcal{EF}$	Country	$\mathcal{EF}$
Africa	484	Australia	531	Germany	354	Portugal	183
Asia	539	Canada	128	India	637	Russia	360
Europe	280	China	544	Iran	492	Spain	169
North America	352	Costa Rica	33	Italy	226	Switzerland	47
South America	204	Cuba	575	Japan	479	United Kingdom	270
World	442	France	58	Norway	26	United States	380

Source: `https://ourworldindata.org/grapher/carbon-intensity-electricity`

Computation of scope 2 emissions

Example #3

We consider a French bank, whose activities are mainly located in France and the Western Europe. Below, we report the energy consumption (in MWh) by country:

Belgium	125 807	France	1 132 261
Germany	71 890	Ireland	125 807
Italy	197 696	Luxembourg	33 069
Netherlands	18 152	Portugal	12 581
Spain	61 106	Switzerland	73 148
UK	124 010	World	37 742

Computation of scope 2 emissions

- If we consider a Tier 1 approach, we can estimate the scope 2 emissions of the bank by computing the total activity data and multiplying by the global emission factor
- Since we have twelve sources, we obtain:

$$A = \sum_{s=1}^{12} A_s = 125\,807 + 1\,132\,261 + \ldots + 37\,742 = 2\,013\,269 \text{ MWh}$$

and:

$$\begin{aligned} \mathcal{CE} &= A \cdot \mathcal{EF}_{World} \\ &= \left(2\,013{,}269 \times 10^3\right) \times 442 \\ &= 889\,864\,898\,000 \ \mathrm{gCO_2e} \\ &= 889.86 \ \mathrm{ktCO_2e} \end{aligned}$$

Computation of scope 2 emissions

- Another Tier 1 approach is to consider the emission factor of the European Union, because the rest of the world represents less than 2% of the electricity consumption. Using $\mathcal{EF}_{EU} = 275$, we obtain $\mathcal{CE} = 553.65 \text{ ktCO}_2\text{e}$

Computation of scope 2 emissions

- The third approach uses a Tier 2 method by considering the emission factor of each country
- We use the previous figures and the following emission factors: Belgium (143); Ireland (402); Luxembourg (68) and Netherlands (331)
- We deduce that:

$$\begin{aligned}\mathcal{CE} &= \sum_{s=1}^{12} A_s \cdot \mathcal{EF}_s \\ &= (125\,807 \times 143 + 1\,132\,261 \times 58 + \ldots \\ &\quad + 124\,010 \times 270 + 37\,742 \times 442) \times \frac{10^3}{10^9} \\ &= 278.85 \ \mathrm{ktCO_2e}\end{aligned}$$

⇒ **The estimated scope 2 emissions of this bank are sensitive to the approach**

Computation of scope 2 emissions

Example #4

We consider a Norwegian company, whose current electricity consumption is equal to 1 351 Mwh. 60% of the electricity comes from the Norwegian hydroelectricity and the GO system guarantees that this green electricity emits 1 $\mathrm{gCO_2e}$/kWh.

If we assume that the remaining 40% of the electricity consumption comes from the Norwegian grid[2], the market based scope 2 emissions of this company are equal to:

$$\begin{aligned} \mathcal{CE} &= \frac{10^6 \times 60\% \times 1 + 10^6 \times 40\% \times 26}{10^6} \\ &= 11 \ \mathrm{ktCO_2e} \end{aligned}$$

---

[2] The emission factor for Norway is 26 $\mathrm{gCO_2e}$/kWh.

Computation of scope 2 emissions

Table 6: Emission factor in $\mathrm{gCO_2e}$/KWh from electricity supply technologies (IPCC, 2014; UNECE, 2022)

Technology	Characteristic	IPCC		UNECE	
		Mean	Min–Max	Mean	Min–Max
Wind	Onshore	11	7–56	12	8–16
	Offshore	12	8–35	13	13–23
Nuclear		12	3–110	6	
Hydro power		24	1–2200	11	6–147
Solar power	CSP	27	9–63	32	14–122
	Rooftop (PV)	41	26–60	22	9–83
	Utility/Ground (PV)	48	18–180	20	8–82
Geothermal		38	6–79		
Biomass	Dedicated	230	130–420		
Gas	CCS	169	90-370	130	92–221
	Combined cycle	490	410–650	430	403–513
Fuel oil			510–1170		
Coal	CCS	161	70–290	350	190–470
	PC	820	740–650	1 000	912–1095

CSP: concentrated solar power; PV: photovoltaic power; CCS: carbon capture and storage; PC: pulverized coal.

Reporting of scope 2 emissions

GHG inventory document of Enel (2021)

- The scope 2 emissions expressed in $\mathrm{ktCO_2e}$ are:

	Electricity purchased from the grid	Losses on the distribution grid	Total
Location-based	1 336.67	2 966.52	4 303.18
Market-based	2 351.00	4 763.15	7 114.15

Location-based versus market-based scope 2 emissions

Table 7: Statistics of CDP scope 2 emissions (2020)

	$\mathcal{CE}_{\mathrm{loc}} = 0$	$\mathcal{CE}_{\mathrm{loc}} = \mathcal{CE}_{\mathrm{mkt}} = 0$	$\mathcal{CE}_{\mathrm{mkt}} = 0$
Frequency	0.89%	0.39%	8.78%
	$\mathcal{CE}_{\mathrm{loc}} > \mathcal{CE}_{\mathrm{mkt}}$	$\mathcal{CE}_{\mathrm{loc}} = \mathcal{CE}_{mkt}$	$\mathcal{CE}_{\mathrm{loc}} < \mathcal{CE}_{\mathrm{mkt}}$
Frequency	70.43%	9.48%	20.09%
Mean variation ratio	$+43.89\%$	0.00%	-22.04%

Source: CDP database as of 01/07/2022 & Author's computation.

Scope 3 categories

Upstream

1. Purchased goods and services
2. Capital goods
3. Fuel and energy related activities
4. Upstream transportation and distribution
5. Waste generated in operations
6. Business travel
7. Employee commuting
8. Upstream leased assets
9. **Other upstream**

Downstream

1. Downstream transportation and distribution
2. Processing of sold products
3. Use of sold products
4. End-of-life treatment of sold products
5. Downstream leased assets
6. Franchises
7. Investments
8. **Other downstream**

Scope 3 emissions

Scope 3 emissions are all the indirect emissions in the company's value chain, apart from indirect emissions which are reported in scope 2:

1. **Purchased goods and services (not included in categories 2-8)**
   Extraction, production, and transportation of goods and services purchased or acquired by the company
2. **Capital goods**
   Extraction, production, and transportation of capital goods purchased or acquired by the company
3. **Fuel- and energy-related activities (not included in scopes 1 or 2)**
   Extraction, production, and transportation of fuels and energy purchased or acquired by the company
4. **Upstream transportation and distribution**
   Transportation and distribution of products purchased by the company between the company's tier 1 suppliers and its own operations; Transportation and distribution services purchased by the company, including inbound logistics, outbound logistics (e.g., sold products), and transportation and distribution between the company's own facilities

Scope 3 emissions

5. **Waste generated in operations**
   Disposal and treatment of waste generated in the company's operations
6. **Business travel**
   Transportation of employees for business-related activities
7. **Employee commuting**
   Transportation of employees between their homes and their work sites
8. **Upstream leased assets**
   Operation of assets leased by the company (lessee)

Scope 3 emissions

9. **Downstream transportation and distribution**
   Transportation and distribution of products sold by the company between the company's operations and the end consumer (if not paid for by the company)
10. **Processing of sold products**
    Processing of intermediate products sold by downstream companies (e.g., manufacturers)
11. **Use of sold products**
    End use of goods and services sold by the company
12. **End-of-life treatment of sold products**
    Waste disposal and treatment of products sold by the company at the end of their life

Scope 3 emissions

13. **Downstream leased assets**
    Operation of assets owned by the company (lessor) and leased to other entities
14. **Franchises**
    Operation of franchises reported by franchisor
15. **Investments**
    Operation of investments (including equity and debt investments and project finance)

Scope 3 emissions

Table 8: Scope 3 emission factors for business travel and employee commuting (United States)

Vehicle type	CO_2 (kg/unit)	CH_4 (g/unit)	N_2O (g/unit)	Unit
Passenger car	0.332	0.0070	0.0070	vehicle-mile
Light-duty truck	0.454	0.0120	0.0090	vehicle-mile
Motorcycle	0.183	0.0700	0.0070	vehicle-mile
Intercity rail (northeast corridor)	0.058	0.0055	0.0007	passenger-mile
Intercity rail (other routes)	0.150	0.0117	0.0038	passenger-mile
Intercity rail (national average)	0.113	0.0092	0.0026	passenger-mile
Commuter rail	0.139	0.0112	0.0028	passenger-mile
Transit rail (subway, tram)	0.099	0.0084	0.0012	passenger-mile
Bus	0.056	0.0210	0.0009	passenger-mile
Air travel (short haul, < 300 miles)	0.207	0.0064	0.0066	passenger-mile
Air travel (medium haul, 300-2300 miles)	0.129	0.0006	0.0041	passenger-mile
Air travel (long haul, > 2300 miles)	0.163	0.0006	0.0052	passenger-mile

Source: US EPA (2020), Table 10, `www.epa.gov`, `ghg-emission-factors-hub.xlsx`.

These factors are intended for use in the distance-based method defined in the Scope 3 Calculation Guidance. If fuel data are available, then the fuel-based method should be used.

Scope 3 emissions

Table 9: Examples of monetary scope 3 emission factors

Category	S3E	ADEME	Category	S3E	ADEME
Agriculture	2 500	2 300	Air transport	1 970	1 190
Construction	810	360	Education	310	120
Financial intermediation	140	110	Health and Social Work	300	500
Hotels and restaurants	560	320	Rubber and plastics	1 270	800
Telecommunications	300	170	Textiles	1 100	600

Source: Scope 3 Evaluator (S3E), `https://quantis-suite.com/Scope-3-Evaluator` & ADEME, `https://bilans-ges.ademe.fr`.

Carbon emissions of investment portfolios

Two methods for measuring the carbon footprint of an investment portfolio:

1. Financed emissions approach
2. Ownership approach

Carbon emissions of investment portfolios

Financed emissions approach

- The investor calculates the carbon emissions that are financed across both equity and debt
- EVIC is used to estimate the value of the enterprise. It is "*the sum of the market capitalization of ordinary and preferred shares at fiscal year end and the book values of total debt and minorities interests*" (TEG, 2019)
- Let W be the wealth invested in the company, the financed emissions are equal to:

$$\mathcal{CE}\left(W\right) = \frac{W}{\mathrm{EVIC}} \cdot \mathcal{CE}$$

- In the case of a portfolio $(W_1, \ldots, W_n)$ where W_i is the wealth invested in company i, we have:

$$\mathcal{CE}\left(W\right) = \sum_{i=1}^{n} \mathcal{CE}_i\left(W_i\right) = \sum_{i=1}^{n} \frac{W_i}{\mathrm{EVIC}_i} \cdot \mathcal{CE}_i$$

- $\mathcal{CE}\left(W\right)$ is expressed in $\mathrm{tCO_2e}$

Carbon emissions of investment portfolios
Ownership approach

- We break down the carbon emissions between the stockholders of the company
- We have:

$$\mathcal{CE}(W) = \sum_{i=1}^{n} \frac{W_i}{\mathrm{MV}_i} \cdot \mathcal{CE}_i = \sum_{i=1}^{n} \varpi_i \cdot \mathcal{CE}_i$$

where:

  - MV_i is the market value of company i
  - ϖ_i is the ownership ratio of the investor

Carbon emissions of investment portfolios

Ownership approach

- Let $W = \sum_{i=1}^{n} W_i$ be the portfolio value
- The portfolio weight of asset i is given by:

$$w_i = \frac{W_i}{W}$$

- We deduce that:

$$\varpi_i = \frac{W_i}{\mathrm{MV}_i} = \frac{w_i \cdot W}{\mathrm{MV}_i}$$

- It follows that:

$$\mathcal{CE}(W) = \sum_{i=1}^{n} \frac{w_i \cdot W}{\mathrm{MV}_i} CE_i = W \left(\sum_{i=1}^{n} w_i \cdot \frac{\mathcal{CE}_i}{\mathrm{MV}_i} \right) = W \left(\sum_{i=1}^{n} w_i \cdot \mathcal{CI}_i^{\mathrm{MV}} \right)$$

where $\mathcal{CI}_i^{\mathrm{MV}}$ is the market value-based carbon intensity:

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

- $\mathcal{CE}(W)$ is generally computed with $W = \$1$ mn and is expressed in $\mathrm{tCO_2e}$ (per \$ mn invested)

Carbon emissions of investment portfolios

Ownership approach

Remark

The ownership approach is valid only for equity portfolios. To compute the market value (or the total market capitalization), we use the following approximation:

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

where MC and $\mathcal{FP}$ are the free float market capitalisation and percentage of the company.

Carbon emissions of investment portfolios

Example #5

We consider a \$100 mn investment portfolio with the following composition: \$63.1 mn in company A, \$16.9 mn in company B and \$20.0 mn in company C. The data are the following:

Issuer	Market capitalization (in \$ bn)		
	31/12/2021	31/12/2022	31/01/2023
A	12.886	10.356	10.625
B	7.005	6.735	6.823
C	3.271	3.287	3.474

Issuer	Debt (in \$ bn)	$\mathcal{FP}$ (in %)	$\boldsymbol{\mathcal{SC}}_{1-2}$ (in $\mathrm{ktCO_2e}$)
A	1.112	99.8	756.144
B	0.000	39.3	23.112
C	0.458	96.7	454.460

Carbon emissions of investment portfolios

- As of 31 January 2023, the EVIC value for company A is equal to:

$$\mathrm{EVIC}_A = \frac{10\,356}{0.998} + 1\,112 = \$11489 \text{ mn}$$

- We deduce that the financed emissions are equal to:

$$\mathcal{CE}_A\left(\$63.1 \text{ mn}\right) = \frac{63.1}{11\,489} \times 756.144 = 4.153 \ \mathrm{ktCO_2e}$$

Carbon emissions of investment portfolios

- If we assume that the investor has no bond in the portfolio, we can use the ownership approach:

$$\varpi_A = \frac{63.1}{(10\,625/0.998)} = 59.2695 \text{ bps}$$

- The carbon emissions of the investment in company A is then equal to:

$$\mathcal{CE}_A\,(\$63.1 \text{ mn}) = 59.2695 \times 10^{-4} \times 756.144 = 4.482 \text{ ktCO}_2\text{e}$$

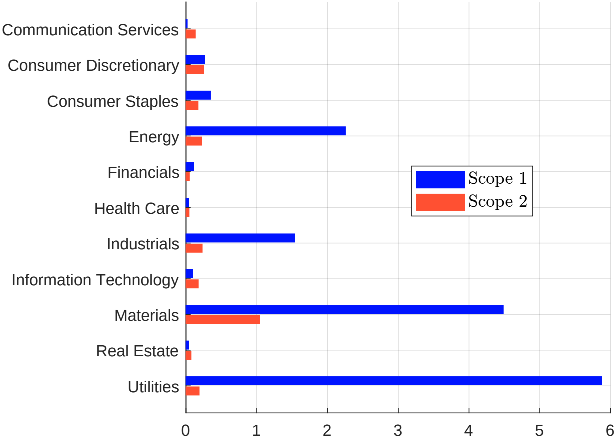
Carbon emissions of investment portfolios

Finally, we obtain the following results:

	Financed emissions	Carbon emissions
Company A	4.153	4.482
Company B	0.023	0.022
Company C	2.356	2.530
Portfolio	6.532	7.034

Statistics

Figure 12: 2019 carbon emissions per GICS sector in $\mathrm{GtCO_2e}$ (scopes 1 & 2)



Source: Trucost (2022) & Barahhou *et al.* (2022).

Statistics

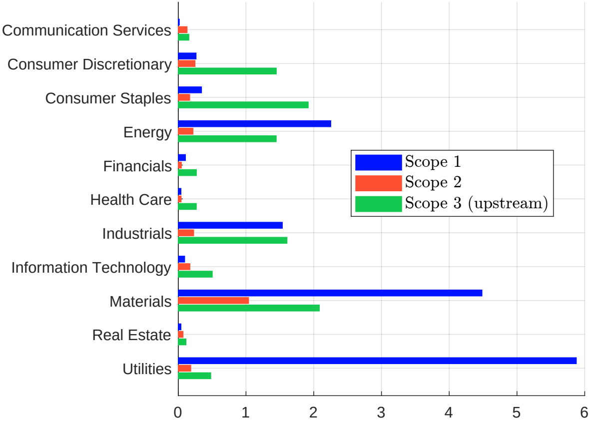
Table 10: Breakdown (in %) of carbon emissions in 2019

Sector	$\mathcal{SC}_1$	$\mathcal{SC}_2$	$\mathcal{SC}_{1-2}$	$\mathcal{SC}_3^{\mathrm{up}}$	$\mathcal{SC}_3^{\mathrm{down}}$	$\mathcal{SC}_3$	$\mathcal{SC}_{1-3}$
Communication Services	0.1	5.1	0.8	1.5	0.2	0.4	0.5
Consumer Discretionary	1.7	9.7	2.9	14.1	10.2	10.8	9.1
Consumer Staples	2.3	6.7	2.9	18.6	1.6	4.4	4.1
Energy	15.0	8.5	14.0	14.1	40.1	36.0	31.2
Financials	0.7	1.8	0.9	2.6	1.8	2.0	1.7
Health Care	0.3	1.7	0.5	2.6	0.2	0.6	0.6
Industrials	10.2	8.9	10.0	15.6	24.2	22.8	20.0
Information Technology	0.6	6.8	1.5	4.9	2.3	2.7	2.5
Materials	29.8	40.7	31.4	20.2	13.5	14.6	18.2
Real Estate	0.3	2.8	0.6	1.1	1.0	1.0	0.9
Utilities	39.0	7.3	34.4	4.7	4.8	4.8	11.2
Total (in $\mathrm{GtCO_2e}$)	15.1	2.6	17.6	10.3	53.7	64.0	81.6

Source: Trucost (2022) & Barahhou *et al.* (2022).

Statistics

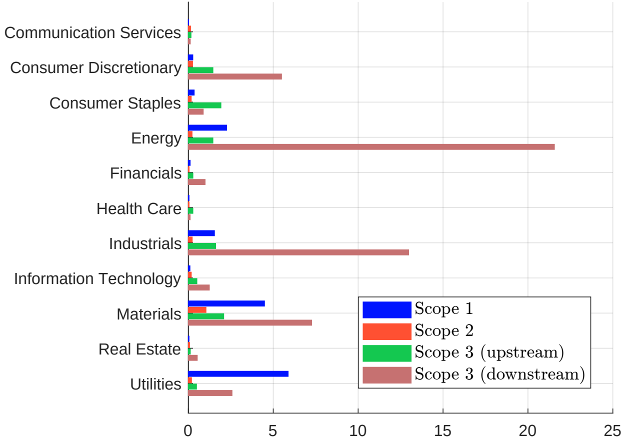
Figure 13: 2019 carbon emissions per GICS sector in $\mathrm{GtCO_2e}$ (scopes 1, 2 & 3 upstream)



Source: Trucost (2022) & Barahhou *et al.* (2022).

Statistics

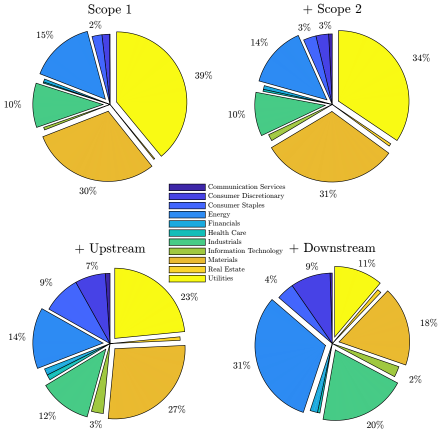
Figure 14: 2019 carbon emissions per GICS sector in $\mathrm{GtCO_2e}$ (scopes 1, 2 & 3)



Source: Trucost (2022) & Barahhou *et al.* (2022).

Statistics

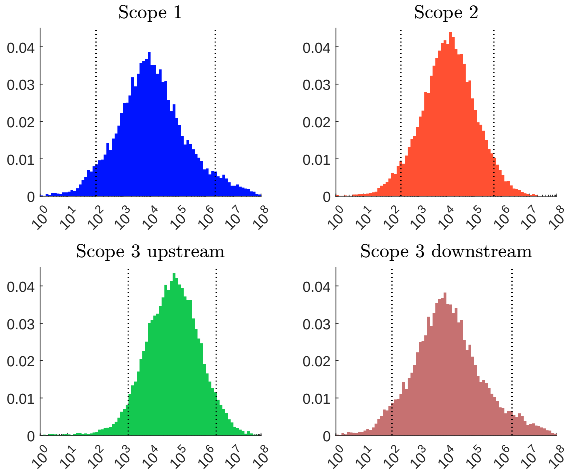
Figure 15: Sector contribution in %



Source: Trucost (2022) & Barahhou *et al.* (2022).

Statistics

Figure 16: Histogram of 2019 carbon emissions (logarithmic scale, $\mathrm{tCO_2e}$)



Source: Trucost (2022) & Barahhou *et al.* (2022).

Negative emissions, avoided emissions, and carbon offsetting

Definition

Negative emissions, also known as carbon dioxide removal or CDR, is the process of removing CO_2 from the atmosphere

There are two main categories of negative emissions:

1. Natural climate solutions
   Examples include forest restoration and afforestation, reducing soil disturbance, etc.
2. Negative emission technologies (NET)
   Examples are direct air capture with carbon storage (DACCS), bioenergy with carbon capture and storage (BECCS), enhanced weathering, ocean fertilization, etc.

Negative emissions, avoided emissions, and carbon offsetting

- **Afforestation** is the process of creating a new forest (planting trees in an area where there was no forest in the past), while reforestation is the process of planting trees in areas where there was forest before
- **Reducing soil disturbance** is the practice of minimizing disturbance to the soil surface and structure, such as using minimum tillage or planting certain crops that protect the soil
- **DACCS special filters** to capture CO_2 directly from the air, while the captured CO_2 is then stored underground or used in other applications

Negative emissions, avoided emissions, and carbon offsetting

- **BECCS** involves capturing and storing the CO_2 emissions from burning biomass, such as wood or grasses
- **Enhanced weathering** involves the application of finely ground minerals, such as olivine or basalt, to land surfaces. When these minerals react with atmospheric CO_2, they form harmless minerals and carbonates, trapping the carbon in a stable mineral form. The goal is to accelerate the natural process of weathering
- **Ocean fertilization** involves adding nutrients to the ocean, which can stimulate the growth of phytoplankton in the ocean, which then absorbs CO_2 through photosynthesis

Negative emissions, avoided emissions, and carbon offsetting

"[...] (1) Physical greenhouse gases are removed from the atmosphere. (2) The removed gases are stored out of the atmosphere in a manner intended to be permanent. (3) Upstream and downstream greenhouse gas emissions associated with the removal and storage process, such as biomass origin, energy use, gas fate, and co-product fate, are comprehensively estimated and included in the emission balance. (4) The total quantity of atmospheric greenhouse gases removed and permanently stored is greater than the total quantity of greenhouse gases emitted to the atmosphere." (Tanzer and Ramírez, 2019, page 1216).

Direct air capture

There are two general types of DAC processes:

1. DAC with liquid solvents (L-DAC)
2. DAC with solid sorbents (S-DAC)

Direct air capture

In an L-DAC process, there are four stages: absorption, regeneration, purification and separation:

$$\begin{array}{rcl} 2\,\mathrm{KOH}+\mathrm{CO}_2 & \longrightarrow & \mathrm{H}_2\mathrm{O}+\mathrm{K}_2\mathrm{CO}_3 \\ \mathrm{CaO}+\mathrm{H}_2\mathrm{O} & \longrightarrow & \mathrm{Ca}\left(\mathrm{OH}\right)_2 \\ \mathrm{K}_2\mathrm{CO}_3+\mathrm{Ca}\left(\mathrm{OH}\right)_2 & \longrightarrow & 2\,\mathrm{KOH}+\mathrm{CaCO}_3 \\ \mathrm{CaCO}_3 & \longrightarrow & \mathrm{CaO}+\mathrm{CO}_2 \end{array}$$

The goal is to use the liquid solvent KOH to react with atmospheric carbon dioxide CO_2 to produce pure CO_2 and calcium oxide CaO

In an S-DAC process, solid materials or sorbents, such as porous polymers or metal-organic frameworks, are used to adsorb CO_2

Direct air capture

- The costs associated with DAC technology include the initial investment to build the DAC system (*e.g.*, air contractor, causticizer, calciner, and slaker), the price of solvents and sorbents, the electricity needs to perform the chemical reactions, and the cost of storage
- The current price of removing a tonne of CO_2 is around \$1 000
- The carbon efficiency of the best DAC plans is less than 70%

Direct air capture

An example of DAC companies: Climeworks

Climeworks (`https://climeworks.com`) is a Swiss company founded in 2009 as a spin-off from ETH Zurich. It specializes in DAC technology and has established itself as a pioneer in this field with two other companies: Carbon Engineering (Canada) and Global Thermostat (USA). In September 2021, Climeworks inaugurates the world's first large-scale direct air capture and storage plant "*Orca*" in Iceland, with a capacity to capture 4 000 tonnes of CO_2 per year. The storage of CO_2 is carried out by the company Carbfix, which injects it deep underground, where it mineralizes and turns into stone. In June 2022, Climeworks announces a second, newest and largest direct air capture and storage facility, "*Mammoth*", also in Iceland. It will have a nominal CO_2 capture capacity of up to 36 000 tonnes per year when fully operational.

Avoided emissions

- Avoided emissions often incorrectly referred to as Scope 4 emissions
- This is the difference between the total, attributional, life-cycle GHG inventories of a company's product (the assessed product) and an alternative (or reference) product that provides an equivalent function:

$$\boldsymbol{\mathcal{AE}} = \boldsymbol{\mathcal{CE}}\,(\text{reference product}) - \boldsymbol{\mathcal{CE}}\,(\text{assessed product})$$

- Avoided emissions can be positive ($\boldsymbol{\mathcal{AE}} \geq 0$) or negative ($\boldsymbol{\mathcal{AE}} < 0$)

Avoided emissions

Electric car

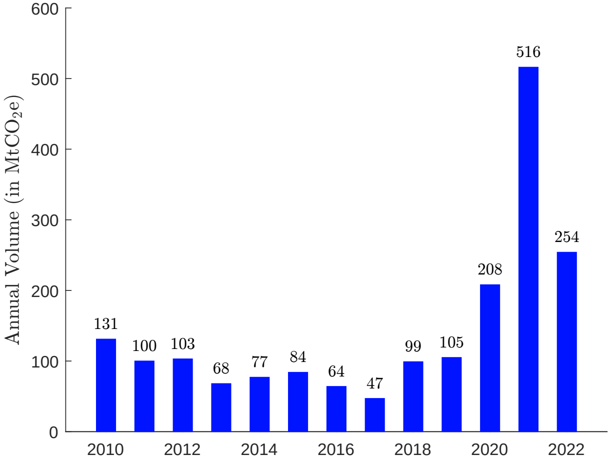
- An electric car emits CO_2, especially when we consider the life cycle of the batteries, but electric cars do not emit greenhouse gases from burning gasoline
- The reference product is the gasoline-powered car
- The assessed product is the electric car
- There are two issues in calculating avoided emissions:
  1. which car should we choose to represent the gasoline car or the reference product?
  2. what is the use of the electric car?
- The avoided emissions depend on many factors, such as the carbon intensity of the electricity, recycling assumptions, etc.

Carbon credits

- **Cap-and-trade systems**
  These systems place a limit on the total amount of GHG emissions that can be released from a given region or industry. Companies are allocated a certain number of carbon credits (emission allowances) and can buy or sell credits to meet their emissions targets. These government-regulated schemes make up the compliance carbon market.
- **Voluntary carbon markets**
  These markets are not regulated by the government, and companies can voluntarily buy carbon credits to offset their emissions. Voluntary carbon markets are often used to offset emissions from activities not covered by cap-and-trade systems. In this case, the avoided emissions from a carbon offset (*e.g.*, through the use of negative emission technologies) must be counted on the balance sheet of the buyer, not the seller, who is the developer of the project.

Carbon credits

Figure 17: Voluntary carbon market size by volume of traded carbon credits



Source: Ecosystem Marketplace (2023, Figure 2, page 8).

Efficiency of carbon dioxide removal

$$\eta(t) = \frac{\mathrm{CO}_2^{\mathsf{stored}}(t) - \mathrm{CO}_2^{\mathsf{leaked}}(t)}{\mathrm{CO}_2^{\mathsf{stored}}(t)}$$

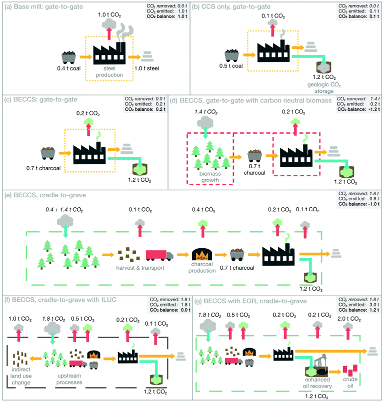
Table 11: Summary of key features for each CDR pathway

CDR	$\eta(100)$	$\eta(1000)$	Timing	Permanence
Afforestation	63 to 99%	31 to 95%	Decades	Very low
Reforestation	63 to 99%	31 to 95%	Decades	Very low
BECCS	52 to 87%	78 to 87%	Immediate to decades	High/very high
Biochar	20 to 39%	−3 to 5%	Immediate	Low/very low
DACCS	−5 to 90%	−5 to 90%	Immediate	Very high
Enhanced weathering	17 to 92%	51 to 92%	Immediate to decades	High/very high

Source: Chiquier *et al.* (2022, Table 1, page 4400).

Efficiency of carbon dioxide removal

Figure 18: Perceived CO_2 emissions of a simplified steel production system when viewed from different system boundaries



Source: Tanzer and Ramírez (2019, Figure 2, page 1214).

Carbon intensity

- Carbon emissions = absolute carbon footprint in an absolute value
- Carbon intensity = relative carbon footprint

⇒ **we normalize the carbon emissions by a size or activity unit**

Carbon intensity

We can measure the carbon footprint of:

- countries by $\mathrm{tCO_2e}$ per capita
- watching television by $\mathrm{CO_2e}$ emissions per viewer-hour
- washing machines by $\mathrm{kgCO_2e}$ per wash
- cars by $\mathrm{kgCO_2e}$ per kilometer driven
- companies by $\mathrm{ktCO_2e}$ per $1 mn revenue
- etc.

Physical intensity ratios

Product carbon footprint (PCF)

- The product carbon footprint measures the relative carbon emissions of a product throughout its life cycle
- Life cycle assessment (LCA), distinguishes two methods:
  1. **Cradle-to-gate** refers to the carbon footprint of a product from the moment it is produced (including the extraction of raw materials) to the moment it enters the store
  2. **Cradle-to-grave** covers the entire life cycle of a product, including the use-phase and recycling

Physical intensity ratios

Table 12: Examples of product carbon footprint (in $\mathrm{kgCO_2e}$ per unit)

Product	Category	Cradle-to-gate	Cradle-to-grave
Screen	21.5 inches	222	236
	23.8 inches	248	265
Computer	Laptop	156	169
	Desktop	169	189
	High performance	295	394
Smartphone	Classical	16	16
	5 inches	33	32
Oven	Built-in electric	187	319
	Professional (combi steamer)	734	12 676
Washing machine	Capacity 5kg	248	468
	Capacity 7kg	275	539
Shirt	Coton	10	13
	Viscose	9	12
Balloon	Football	3.4	5.1
	Basket-ball	3.6	5.9

Source: Lhotellier *et al* (2018, Annex 4, pages 212-215)

Physical intensity ratios

Corporate carbon footprint (CCF)

- Extension of the PCF to companies
- The CCF of a cement manufacturer is measured by the amount of GHG emissions per tonne of cement
- The CCF of airlines is measured by the amount of GHG emissions per RPK (revenue passenger kilometers, which is calculated by multiplying the number of paying passengers by the distance traveled)

Sector	Unit	Description
Transport sector (aviation)	CO_2e/RPK	Revenue passenger kilometers
Transport sector (shipping)	CO_2e/RTK	Revenue tonne kilometers
Industry (cement)	CO_2e/t cement	Tonne of cement
Industry (steel)	CO_2e/t steel	Tonne of steel
Electricity	CO_2e/MWh	Megawatt hour
Buildings	CO_2e/SQM	Square meter

Monetary intensity ratios

Problem

- How to aggregate carbon footprint?
- Portfolio managers use monetary intensity ratios, which are defined as:

$$\mathcal{CI} = \frac{\mathcal{CE}}{Y}$$

where $\mathcal{CE}$ is the company's carbon emissions and Y is a monetary variable measuring its activity

Monetary intensity ratios

For instance, we can use revenues, sales, etc. to normalize carbon emissions:

Revenue	Sales	EVIC	MV
$\mathcal{CI}^{\text{Revenue}} = \dfrac{\mathcal{CE}}{\text{Revenue}}$	$\mathcal{CI}^{\text{Sales}} = \dfrac{\mathcal{CE}}{\text{Sales}}$	$\mathcal{CI}^{\text{EVIC}} = \dfrac{\mathcal{CE}}{\text{EVIC}}$	$\mathcal{CI}^{\text{MV}} = \dfrac{\mathcal{CE}}{\text{MV}}$

Remark

The previous carbon emission metrics based on EVIC and market value can be viewed as carbon intensity metrics

Additivity property of $\mathcal{CI}$

- If we consider the EVIC-based approach, the carbon intensity of the portfolio is given by:

$$\begin{aligned}\mathcal{CI}^{\mathrm{EVIC}}(w) &= \frac{\mathcal{CE}^{\mathrm{EVIC}}(W)}{W} \\ &= \frac{1}{W}\sum_{i=1}^{n}\frac{W_i}{\mathrm{EVIC}_i}\cdot\mathcal{CE}_i \\ &= \sum_{i=1}^{n}\frac{W_i}{W}\cdot\frac{\mathcal{CE}_i}{\mathrm{EVIC}_i} \\ &= \sum_{i=1}^{n} w_i\cdot\mathcal{CI}_i^{\mathrm{EVIC}}\end{aligned}$$

  where $w = (w_1, \ldots, w_n)$ is the vector of portfolio weights
- In a similar way, we obtain:

$$\mathcal{CI}^{\mathrm{MV}}(w) = \sum_{i=1}^{n} w_i\cdot\mathcal{CI}_i^{\mathrm{MV}}$$

Non-additivity property of $\mathcal{CI}$

- We consider the revenue-based carbon intensity (also called the economic carbon intensity)
- The carbon intensity of the portfolio is:

$$\mathcal{CI}^{\mathrm{Revenue}}(w) = \frac{\mathcal{CE}(w)}{Y(w)}$$

where:

  - $\mathcal{CE}(w)$ measures the carbon emissions of the portfolio:

$$\mathcal{CE}(w) = \sum_{i=1}^{n} W_i \cdot \frac{\mathcal{CE}_i}{\mathrm{MV}_i} = W \sum_{i=1}^{n} \frac{w_i}{\mathrm{MV}_i} \cdot \mathcal{CE}_i$$

  - $Y(w)$ is the total revenue of the portfolio:

$$Y(w) = \sum_{i=1}^{n} W_i \cdot \frac{Y_i}{\mathrm{MV}_i} = W \sum_{i=1}^{n} \frac{w_i}{\mathrm{MV}_i} \cdot Y_i$$

Non-additivity property of $\mathcal{CI}$

- We deduce that:

$$\mathcal{CI}^{\mathrm{Revenue}}\left(w\right)=\frac{\sum_{i=1}^{n}\dfrac{w_i}{\mathrm{MV}_i}\cdot\mathcal{CE}_i}{\sum_{i=1}^{n}\dfrac{w_i}{\mathrm{MV}_i}\cdot Y_i}=\sum_{i=1}^{n}w_i\cdot\omega_i\cdot\mathcal{CI}_i^{\mathrm{Revenue}}$$

where ω_i is the ratio between the revenue per market value of company i and the weighted average revenue per market value of the portfolio:

$$\omega_i=\frac{\dfrac{Y_i}{\mathrm{MV}_i}}{\sum_{k=1}^{n}w_k\cdot\dfrac{Y_k}{\mathrm{MV}_k}}$$

- We conclude that:

$$\mathcal{CI}^{\mathrm{Revenue}}\left(w\right)\neq\sum_{i=1}^{n}w_i\cdot\mathcal{CI}_i^{\mathrm{Revenue}}$$

WACI

In order to avoid the previous problem, we generally use the weighted average carbon intensity (WACI) of the portfolio:

$$\mathcal{CI}^{\mathrm{Revenue}}(w) = \sum_{i=1}^{n} w_i \cdot \mathcal{CI}_i^{\mathrm{Revenue}}$$

This method is the standard approach in portfolio management

Additivity property of $\mathcal{CI}$

Carbon intensity is always additive when we consider a given issuer:

$$\begin{aligned}\mathcal{CI}_i\left(\mathcal{SC}_{1-3}\right) &= \frac{\mathcal{CE}_i\left(\mathcal{SC}_1\right)+\mathcal{CE}_i\left(\mathcal{SC}_2\right)+\mathcal{CE}_i\left(\mathcal{SC}_3\right)}{Y_i} \\ &= \mathcal{CI}_i\left(\mathcal{SC}_1\right)+\mathcal{CI}_i\left(\mathcal{SC}_2\right)+\mathcal{CI}_i\left(\mathcal{SC}_3\right)\end{aligned}$$

Illustration

Example #6

We assume that $\mathcal{CE}_1 = 5 \times 10^6 \ \mathrm{CO_2e}$, $Y_1 = \$0.2 \times 10^6$, $\mathrm{MV}_1 = \$10 \times 10^6$, $\mathcal{CE}_2 = 50 \times 10^6 \ \mathrm{CO_2e}$, $Y_2 = \$4 \times 10^6$ and $\mathrm{MV}_2 = \$10 \times 10^6$. We invest $W = \$10$ mn.

Illustration

- We deduce that:

$$\mathcal{CI}_1 = \frac{5 \times 10^6}{0.2 \times 10^6} = 25.0 \text{ tCO}_2\text{e/\$ mn}$$

and

$$\mathcal{CI}_2 = 12.5 \text{ tCO}_2\text{e/\$ mn}$$

- We have:

$$\left\{ \begin{array}{l} \mathcal{CE}\left(w\right) = W\left(w_1 \dfrac{\mathcal{CE}_1}{\mathrm{MV}_1} + w_2 \dfrac{\mathcal{CE}_2}{\mathrm{MV}_2}\right) \\ Y\left(w\right) = W\left(w_1 \dfrac{Y_1}{\mathrm{MV}_1} + w_2 \dfrac{Y_2}{\mathrm{MV}_2}\right) \\ \mathcal{CI}\left(w\right) = w_1 \mathcal{CI}_1 + w_2 \mathcal{CI}_2 \end{array} \right.$$

Illustration

- We obtain the following results:

w_1	w_2	$\mathcal{CE}(w)$ $(\times 10^6\ \mathrm{CO_2e})$	$Y(w)$ $(\times \$10^6)$	$\dfrac{\mathcal{CE}(w)}{Y(w)}$	$\mathcal{CI}(w)$
0%	100%	50.00	4.00	12.50	12.50
10%	90%	45.50	3.62	12.57	13.75
20%	80%	41.00	3.24	12.65	15.00
30%	70%	36.50	2.86	12.76	16.25
50%	50%	27.50	2.10	13.10	18.75
70%	30%	18.50	1.34	13.81	21.25
80%	20%	14.00	0.96	14.58	22.50
90%	10%	9.50	0.58	16.38	23.75
100%	0%	5.00	0.20	25.00	25.00

- We notice that the weighted average carbon intensity can be very different than the economic carbon intensity

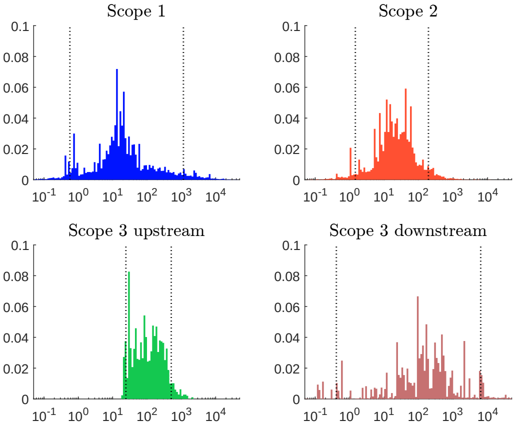
The case of sovereign issuers

Remark

For sovereign issuers, the economic carbon intensity is measured in mega-tonnes of $\mathrm{CO_2e}$ per million dollars of GDP while the physical carbon intensity unit is $\mathrm{tCO_2e}$ per capita

Statistics

Figure 19: Histogram of 2019 carbon intensities (logarithmic scale, $tCO_2e/\$$ mn)



Source: Trucost (2022) & Barahhou *et al.* (2022).

Statistics

Table 13: Examples of 2019 carbon emissions and intensities

Company	Carbon emissions (in $\mathrm{tCO_2e}$)				Revenue	Intensity (in $\mathrm{tCO_2e}/\$\ \mathrm{mn}$)			
	$\mathcal{SC}_1$	$\mathcal{SC}_2$	$\mathcal{SC}_3^{\mathrm{up}}$	$\mathcal{SC}_3^{\mathrm{down}}$	(in $ mn)	$\mathcal{SC}_1$	$\mathcal{SC}_2$	$\mathcal{SC}_3^{\mathrm{up}}$	$\mathcal{SC}_3^{\mathrm{down}}$
Airbus	576 705	386 674	12 284 183	23 661 432	78 899	7.3	4.9	155.7	299.9
Allianz	46 745	224 315	3 449 234	3 904 000	135 279	0.3	1.7	25.5	28.9
Alphabet	111 283	5 118 152	7 142 566		161 857	0.7	31.6	44.1	
Amazon	5 760 000	5 500 000	20 054 722	10 438 551	280 522	20.5	19.6	71.5	37.2
Apple	50 549	862 127	27 624 282	5 470 771	260 174	0.2	3.3	106.2	21.0
BNP Paribas	64 829	280 789	1 923 307	1 884	78 244	0.8	3.6	24.6	0.0
Boeing	611 001	871 000	9 878 431	22 959 719	76 559	8.0	11.4	129.0	299.9
BP	49 199 999	5 200 000	103 840 194	582 639 687	276 850	177.7	18.8	375.1	2 104.5
Caterpillar	905 000	926 000	15 197 607	401 993 744	53 800	16.8	17.2	282.5	7 472.0
Danone	722 122	944 877	28 969 780	4 464 773	28 308	25.5	33.4	1 023.4	157.7
Enel	69 981 891	5 365 386	8 726 973	53 774 821	86 610	808.0	61.9	100.8	620.9
Exxon	111 000 000	9 000 000	107 282 831	594 131 943	255 583	434.3	35.2	419.8	2 324.6
JPMorgan Chase	81 655	692 299	3 101 582	15 448 469	115 627	0.7	6.0	26.8	133.6
Juventus	6 665	15 739	35 842	77 114	709	9.4	22.2	50.6	108.8
LVMH	67 613	262 609	11 853 749	942 520	60 083	1.1	4.4	197.3	15.7
Microsoft	113 414	3 556 553	5 977 488	4 003 770	125 843	0.9	28.3	47.5	31.8
Nestle	3 291 303	3 206 495	61 262 078	33 900 606	93 153	35.3	34.4	657.6	363.9
Netflix	38 481	145 443	1 900 283	2 192 255	20 156	1.9	7.2	94.3	108.8
NVIDIA	2 767	65 048	2 756 353	1 184 981	11 716	0.2	5.6	235.3	101.1
PepsiCo	3 552 415	1 556 523	32 598 029	14 229 956	67 161	52.9	23.2	485.4	211.9
Pfizer	734 638	762 840	4 667 225	133 468	51 750	14.2	14.7	90.2	2.6
Roche	288 157	329 541	5 812 735	347 437	64 154	4.5	5.1	90.6	5.4
Samsung Electronics	5 067 000	10 998 000	33 554 245	60 978 947	197 733	25.6	55.6	169.7	308.4
TotalEnergies	40 909 135	3 596 127	49 817 293	456 993 576	200 316	204.2	18.0	248.7	2 280.0
Toyota	2 522 987	5 227 844	66 148 020	330 714 268	272 608	9.3	19.2	242.6	1 213.2
Volkswagen	4 494 066	5 973 894	65 335 372	354 913 446	282 817	15.9	21.1	231.0	1 254.9
Walmart	6 101 641	13 057 352	40 651 079	32 346 229	514 405	11.9	25.4	79.0	62.9

Source: Trucost (2022) & Barahhou *et al.* (2022).

Statistics

Table 14: Examples of 2019 carbon intensities

Company	Intensity (in $\mathrm{tCO_2e}/\$\ \mathrm{mn}$)			
	$\mathcal{SC}_1$	$\mathcal{SC}_2$	$\mathcal{SC}_3^{\mathrm{up}}$	$\mathcal{SC}_3^{\mathrm{down}}$
Amazon	20.5	19.6	71.5	37.2
Apple	**0.2**	**3.3**	**106.2**	21.0
BNP Paribas	0.8	3.6	24.6	0.0
BP	177.7	18.8	375.1	2 104.5
Caterpillar	16.8	17.2	282.5	7 472.0
Danone	25.5	33.4	**1 023.4**	**157.7**
Exxon	434.3	35.2	419.8	2 324.6
JPMorgan Chase	0.7	6.0	26.8	133.6
LVMH	1.1	4.4	197.3	15.7
Microsoft	0.9	28.3	47.5	31.8
Nestle	35.3	34.4	**657.6**	**363.9**
Pfizer	14.2	14.7	90.2	2.6
Samsung Electronics	**25.6**	**55.6**	169.7	308.4
Volkswagen	15.9	21.1	231.0	1 254.9
Walmart	11.9	25.4	79.0	62.9

Source: Trucost (2022) & Barahhou *et al.* (2022).

Statistics

Table 15: Carbon intensity in $\mathrm{tCO_2e}/\$\ \mathrm{mn}$ per GICS sector and sector contribution in % (MSCI World, June 2022)

Sector	b_i (in %)	Carbon intensity				Risk contribution			
		$\mathcal{SC}_1$	$\mathcal{SC}_{1-2}$	$\mathcal{SC}^{\mathrm{up}}_{1-3}$	$\mathcal{SC}_{1-3}$	$\mathcal{SC}_1$	$\mathcal{SC}_{1-2}$	$\mathcal{SC}^{\mathrm{up}}_{1-3}$	$\mathcal{SC}_{1-3}$
Communication Services	7.58	2	28	134	172	0.14	1.31	3.30	1.31
Consumer Discretionary	10.56	23	65	206	590	1.87	4.17	6.92	6.21
Consumer Staples	7.80	28	55	401	929	1.68	2.66	10.16	7.38
Energy	4.99	632	698	1 006	6 823	24.49	21.53	16.33	34.37
Financials	13.56	13	19	52	244	1.33	1.58	2.28	3.34
Health Care	14.15	10	22	120	146	1.12	1.92	5.54	2.12
Industrials	9.90	111	130	298	1 662	8.38	7.83	9.43	16.38
Information Technology	21.08	7	23	112	239	1.13	3.03	7.57	5.06
Materials	4.28	478	702	1 113	2 957	15.89	18.57	15.48	12.93
Real Estate	2.90	22	101	167	571	0.48	1.81	1.57	1.65
Utilities	3.21	1 744	1 794	2 053	2 840	43.47	35.59	21.41	9.24
MSCI World		130	163	310	992				
MSCI World EW		168	211	391	1 155				

Source: Trucost (2022) & Barahhou *et al.* (2022).

Statistics

- Let $b = (b_1, \ldots, b_n)$ be the weights of the assets that belong to a benchmark
- Its weighted average carbon intensity is given by:

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

  where $\mathcal{CI}_i$ is the carbon intensity of asset i
- If we focus on the carbon intensity for a given sector, we use the following formula:

$$\mathcal{CI}(\mathcal{S}ector_j) = \frac{\sum_{i \in \mathcal{S}ector_j} b_i \cdot \mathcal{CI}_i}{\sum_{i \in \mathcal{S}ector_j} b_i}$$

Carbon budget

Definition

- The carbon budget defines the amount of GHG emissions that a country, a company or an organization produces over the time period $[t_0, t]$
- From a mathematical point of view, it corresponds to the signed area of the region bounded by the function $\mathcal{CE}(t)$:

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

Carbon budget

Example #7

Below, we report the historical data of carbon emissions from 2010 to 2020. Moreover, the company has announced his carbon targets for the years until 2050

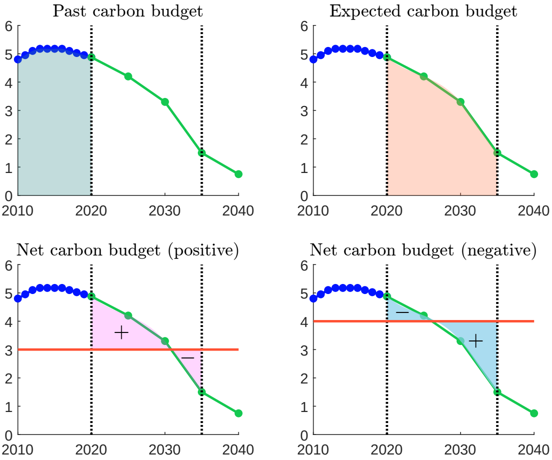
Table 16: Carbon emissions in $\mathrm{MtCO_2e}$

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

The asterisk * indicates that the company has announced a carbon target for this year

Carbon budget

Figure 20: Past, expected and net carbon budgets (Example #7)



Computation of the carbon budget

Numerical solution

- We consider the equally-spaced partition $\{[t_0, t_0 + \Delta t], \ldots, [t - \Delta t, t]\}$ of $[t_0, t]$. Let $m = \dfrac{t - t_0}{\Delta t}$ be the number of intervals
- We set $\mathcal{CE}_k = \mathcal{CE}(t_0 + k\Delta t)$
- The right Riemann approximation is:

$$\mathcal{CB}(t_0, t) = \int_{t_0}^{t} \mathcal{CE}(s)\,\mathrm{d}s \approx \sum_{k=1}^{m} \mathcal{CE}(t_0 + k\Delta t)\,\Delta t = \Delta t \sum_{k=1}^{m} \mathcal{CE}_k$$

- The left Riemann sum is:

$$\mathcal{CB}(t_0, t) \approx \Delta t \sum_{k=0}^{m-1} \mathcal{CE}_k$$

- The midpoint rule is:

$$\mathcal{CB}(t_0, t) \approx \Delta t \sum_{k=1}^{m} \mathcal{CE}\left(t_0 + \frac{k}{2}\Delta t\right)$$

Computation of the carbon budget

Analytical solution: the case of a constant reduction rate

- If we use a constant linear reduction rate $\boldsymbol{\mathcal{R}}(t_0, t) = \boldsymbol{\mathcal{R}}(t - t_0)$, we obtain the following analytical expression:

$$\boldsymbol{\mathcal{CB}}(t_0, t) = \int_{t_0}^{t} \left(\boldsymbol{\mathcal{CE}}(t_0) - \boldsymbol{\mathcal{R}}(s - t_0)\right) \mathrm{d}s = (t - t_0)\, \boldsymbol{\mathcal{CE}}(t_0) - \frac{(t - t_0)^2}{2} \boldsymbol{\mathcal{R}}$$

- In the case of a constant compound reduction rate:

$$\boldsymbol{\mathcal{CE}}(t) = (1 - \boldsymbol{\mathcal{R}})^{(t - t_0)}\, \boldsymbol{\mathcal{CE}}(t_0)$$

  we obtain:

$$\boldsymbol{\mathcal{CB}}(t_0, t) = \boldsymbol{\mathcal{CE}}(t_0) \int_{t_0}^{t} (1 - \boldsymbol{\mathcal{R}})^{(s - t_0)} \, \mathrm{d}s = \frac{(1 - \boldsymbol{\mathcal{R}})^{(t - t_0)} - 1}{\ln(1 - \boldsymbol{\mathcal{R}})} \boldsymbol{\mathcal{CE}}(t_0)$$

Computation of the carbon budget

Analytical solution: the case of a constant reduction rate

- If we assume that $\mathcal{CE}(t) = e^{-\mathcal{R}(t-t_0)}\mathcal{CE}(t_0)$, we have:

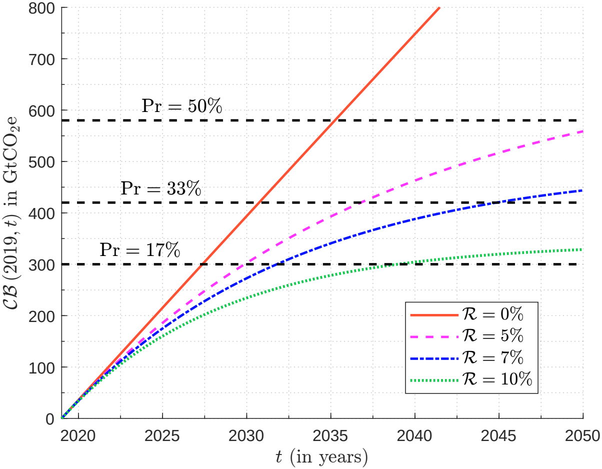
$$\mathcal{CB}(t_0,t) = \mathcal{CE}(t_0)\left[-\frac{e^{-\mathcal{R}(s-t_0)}}{\mathcal{R}}\right]_{t_0}^{t} = \mathcal{CE}(t_0)\,\frac{\left(1-e^{-\mathcal{R}(t-t_0)}\right)}{\mathcal{R}}$$

Remark

If the carbon emissions increase at a positive growth rate g, we set $\mathcal{R} = -g$.

Carbon budget and global warming

Figure 21: Probability to reach 1.5°C



IPCC (2018)

The remaining carbon budget $\mathcal{CB}(2019, t)$ is:

- 580 $GtCO_2e$ for a 50% probability of limiting warming to 1.5°C
- 420 $GtCO_2e$ for a 66% probability
- 300 $GtCO_2e$ for a 83% probability

Computation of the carbon budget
Analytical solution: the case of a Linear function

- If we assume that $\boldsymbol{\mathcal{CE}}(t) = \beta_0 + \beta_1 t$, we deduce that:

$$\begin{aligned}\boldsymbol{\mathcal{CB}}(t_0, t) &= \int_{t_0}^{t} (\beta_0 + \beta_1 s)\,\mathrm{d}s \\ &= \left[\beta_0 s + \frac{1}{2}\beta_1 s^2\right]_{t_0}^{t} \\ &= \beta_0 (t - t_0) + \frac{1}{2}\beta_1 \left(t^2 - t_0^2\right)\end{aligned}$$

- We can extend this formula to a piecewise linear function:

$$\boldsymbol{\mathcal{CB}}(t_0, t) = \ldots$$

Net zero emissions scenario (IEA)

Table 17: IEA NZE scenario (in $\mathrm{GtCO_2e}$)

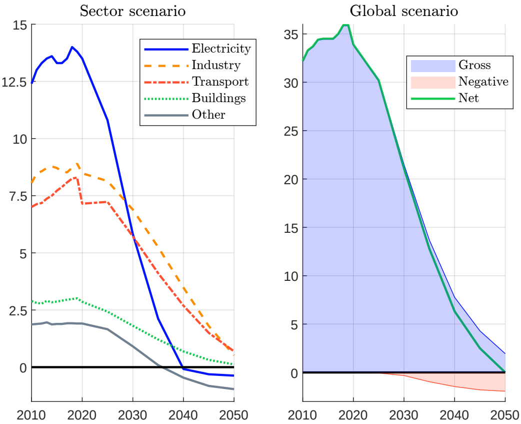
Sector	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Electricity	12.4	13	13.3	13.5	13.6	13.3	13.3	13.5	14	13.8
Buildings	2.89	2.81	2.78	2.9	2.84	2.87	2.91	2.95	2.98	3.01
Transport	7.01	7.13	7.18	7.37	7.5	7.72	7.88	8.08	8.25	8.29
Industry	8.06	8.47	8.57	8.71	8.78	8.71	8.56	8.52	8.72	8.9
Other	1.87	1.89	1.91	1.96	1.87	1.89	1.89	1.92	1.92	1.91
Gross emissions	32.2	33.3	33.7	34.4	34.5	34.5	34.5	35	35.9	35.9
BECCS/DACCS	0	0	0	0	0	0	0	0	0	0
Net emissions	32.2	33.3	33.7	34.4	34.5	34.5	34.5	35	35.9	35.9

Sector	2020	2025	2030	2035	2040	2045	2050
Electricity	13.5	10.8	5.82	2.12	−0.08	−0.31	−0.37
Buildings	2.86	2.43	1.81	1.21	0.69	0.32	0.12
Transport	7.15	7.23	5.72	4.11	2.69	1.5	0.69
Industry	8.48	8.14	6.89	5.25	3.48	1.8	0.52
Other	1.91	1.66	0.91	0.09	−0.46	−0.82	−0.96
Gross emissions	33.9	30.3	21.5	13.7	7.77	4.3	1.94
BECCS/DACCS	0	−0.06	−0.32	−0.96	−1.46	−1.8	−1.94
Net emissions	33.9	30.2	21.1	12.8	6.32	2.5	0.00

Source: IEA (2021, Figure 2.3, page 55)

Net zero emissions scenario (IEA)

Figure 22: CO_2 emissions by sector in the IEA NZE scenario (in $\mathrm{GtCO_2e}$)



Source: IEA (2021) & Author's calculations

Net zero emissions scenario (IEA)

Table 18: Carbon budget in the IEA NZE scenario (in $\mathrm{GtCO_2e}$)

t	Electricity	Buildings	Transport	Industry	Other	Gross emissions
2025	74.4	50.2	43.7	16.2	10.8	195.4
2030	115.9	87.8	76.0	26.8	17.3	324.9
2040	140.9	140.0	117.6	39.1	18.8	466.6
2045	139.9	153.2	128.1	41.6	15.6	496.8
2050	138.2	159.0	133.6	42.7	11.2	512.4

Source: IEA (2021) & Author's calculations

Carbon trend

Linear trend model

Linear trend model

- The linear trend model is defined by:

$$\mathcal{CE}\left(t\right)=\beta_{0}+\beta_{1}t+u\left(t\right)$$

where $u\left(t\right)\sim\mathcal{N}\left(0,\sigma_{u}^{2}\right)$

- OLS estimation
- The projected carbon trajectory is given by:

$$\mathcal{CE}^{\mathcal{T}rend}\left(t\right)=\widehat{\mathcal{CE}}\left(t\right)=\hat{\beta}_{0}+\hat{\beta}_{1}t$$

Carbon trend

Linear trend model

- We have:

$$\widehat{\mathcal{CE}}(0) = \hat{\beta}_0$$

- Base year: t_0
- The linear trend model becomes:

$$\mathcal{CE}(t) = \beta'_0 + \beta'_1 (t - t_0) + u(t)$$

- We have the following relationships:

$$\left\{ \begin{array}{l} \beta'_0 = \beta_0 + \beta_1 t_0 \\ \beta'_1 = \beta_1 \end{array} \right.$$

Carbon trend

Linear trend model

Example #8

Below, we report the evolution of scope $1 + 2$ carbon emissions for company A:

Table 19: Carbon emissions in $\mathrm{MtCO_2e}$ (company A)

Year	2007	2008	2009	2010	2011	2012	2013
$\mathcal{CE}(t)$	57.8	58.4	57.9	55.1	51.6	48.3	47.1
Year	2014	2015	2016	2017	2018	2019	2020
$\mathcal{CE}(t)$	46.1	44.4	42.7	41.4	40.2	41.9	45.0

Carbon trend
Linear trend model

We obtain the following estimates:

- $\hat{\beta}_0 = 2\,970.43$, $\hat{\beta}_1 = -1.4512$ and $\hat{\sigma}_u = 2.5844$
- $t_0 = 2007$, $\hat{\beta}'_0 = 57.85$, $\hat{\beta}'_1 = -1.4512$ and $\hat{\sigma}_u = 2.5844$
- $t_0 = 2020$, $\hat{\beta}'_0 = 38.99$, $\hat{\beta}'_1 = -1.4512$ and $\hat{\sigma}_u = 2.5844$
- The two estimated models are coherent:

$$\begin{aligned} \mathcal{CE}^{\mathcal{T}rend}(t) &= 38.99 - 1.4512 \times (t - 2020) \\ &= 2\,970.43 - 1.4512 \times t \end{aligned}$$

- We have:

$$\mathcal{CE}^{\mathcal{T}rend}(2025) = 38.99 - 1.4512 \times 5 = 31.73 \text{ MtCO}_2\text{e}$$

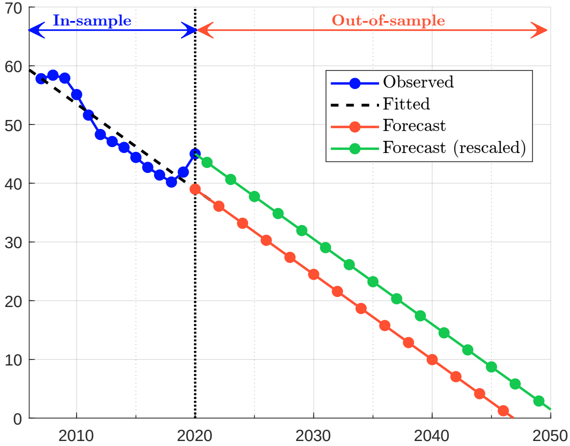
- We have $\mathcal{CE}(2020) = 45.0 \gg \widehat{\mathcal{CE}}(2020) = 38.99$
- The rescaled model has the following expression:

$$\mathcal{CE}^{\mathcal{T}rend}(t) = 45 - 1.4512 \times (t - 2020)$$

Carbon trend

Linear trend model

Figure 23: Linear carbon trend (Example #8)



Carbon trend

Log-linear trend model

Log-linear trend model

- The log-linear trend model is:

$$\ln \mathcal{CE}(t) = \gamma_0 + \gamma_1 (t - t_0) + v(t)$$

- Let $Y(t) = \ln \mathcal{CE}(t)$ be the logarithmic transform of the carbon emissions
- OLS estimation using $Y(t)$

Carbon trend

Log-linear trend model

- We have:

$$\widehat{\mathcal{CE}}\left(t\right)=\exp\left(\hat{Y}\left(t\right)\right)=\exp\left(\hat{\gamma}_0+\hat{\gamma}_1\left(t-t_0\right)\right)=\widehat{\mathcal{CE}}\left(t_0\right)\exp\left(\hat{\gamma}_1\left(t-t_0\right)\right)$$

  where $\widehat{\mathcal{CE}}\left(t_0\right)=\exp\left(\hat{\gamma}_0\right)$
- The mathematical expectation of $\mathcal{CE}\left(t\right)$ is equal to:

$$\begin{array}{rcl}\mathbb{E}\left[\mathcal{CE}\left(t\right)\right] & = & \mathbb{E}\left[e^{Y\left(t\right)}\right] \\ & = & \mathbb{E}\left[\mathcal{LN}\left(\gamma_0+\gamma_1\left(t-t_0\right),\sigma_v^2\right)\right] \\ & = & \exp\left(\gamma_0+\gamma_1\left(t-t_0\right)+\dfrac{1}{2}\sigma_v^2\right) \\ & = & \widehat{\mathcal{CE}}\left(t_0\right)\exp\left(\hat{\gamma}_1\left(t-t_0\right)\right)\end{array}$$

  where $\widehat{\mathcal{CE}}\left(t_0\right)=\exp\left(\hat{\gamma}_0+\frac{1}{2}\hat{\sigma}_v^2\right)$
- The rescaled log-linear trend model is:

$$\mathcal{CE}^{\mathcal{T}rend}\left(t\right)=\mathcal{CE}\left(t_0\right)\exp\left(\hat{\gamma}_1\left(t-t_0\right)\right)$$

Interpretation of the slope

- β_1 is the absolute variation of carbon emissions:

$$\frac{\partial\,\boldsymbol{\mathcal{CE}}\left(t\right)}{\partial\,t} = \beta_1$$

  implying that the relative variation of carbon emissions is:

$$\frac{\dfrac{\partial\,\boldsymbol{\mathcal{CE}}\left(t\right)}{\partial\,t}}{\boldsymbol{\mathcal{CE}}\left(t\right)} = \frac{\beta_1}{\boldsymbol{\mathcal{CE}}\left(t\right)}$$

- γ_1 is the relative variation of carbon emissions:

$$\frac{\dfrac{\partial\,\boldsymbol{\mathcal{CE}}\left(t\right)}{\partial\,t}}{\boldsymbol{\mathcal{CE}}\left(t\right)} = \frac{\partial\,\ln\boldsymbol{\mathcal{CE}}\left(t\right)}{\partial\,t} = \gamma_1$$

Carbon trend

Log-linear trend model

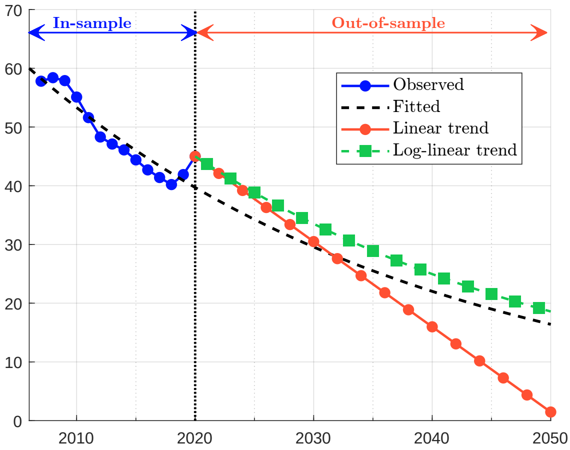
Example #8:

- We obtain the following results: $\hat{\gamma}_0 = 3.6800$, $\hat{\gamma}_1 = -2.95\%$ and $\hat{\sigma}_v = 0.0520$
- $\widehat{\mathcal{CE}}(2020) = 39.65\ \mathrm{MtCO_2e}$ without the correction of the variance bias
- $\widehat{\mathcal{CE}}(2020) = 39.70\ \mathrm{MtCO_2e}$ with the correction of the variance bias

Carbon trend

Log-linear trend model

Figure 24: Log-linear carbon trend (Example #8)



Linear vs. log-linear trend model

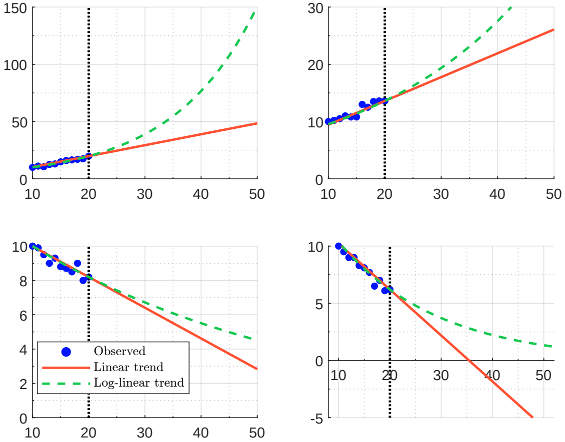
Example #9

We consider several historical trajectories of scope 1 carbon emissions:

Year	#1	#2	#3	#4
2010	10.0	10.0	10.0	10.0
2011	11.1	10.2	9.9	9.5
2012	10.5	10.5	9.5	9.0
2013	12.5	11.0	9.0	9.0
2014	13.0	10.8	9.3	8.3
2015	14.8	10.8	8.8	8.1
2016	16.0	13.0	8.7	7.7
2017	16.5	12.5	8.5	6.5
2018	17.0	13.5	9.0	7.0
2019	17.5	13.6	8.0	6.1
2020	19.8	13.6	8.2	6.2

Linear vs. log-linear trend model

Figure 25: Log-linear vs. linear carbon trend (Example #9)



Carbon trend

Stochastic trend model

Stochastic trend model

- The linear trend model can be written as:

$$\begin{cases} y(t) = \mu(t) + u(t) \\ \mu(t) = \mu(t-1) + \beta_1 \end{cases}$$

  where $u(t) \sim \mathcal{N}\left(0, \sigma_u^2\right)$
- We have $y(t) = \beta_0 + \beta_1 t + u(t)$ where $\beta_0 = \mu(t_0) - \beta_1 t_0$
- The local linear trend model is defined as:

$$\begin{cases} y(t) = \mu(t) + u(t) \\ \mu(t) = \mu(t-1) + \beta_1(t-1) + \eta(t) \\ \beta_1(t) = \beta_1(t-1) + \zeta(t) \end{cases}$$

  where $\eta(t) \sim \mathcal{N}\left(0, \sigma_\eta^2\right)$ and $\zeta(t) \sim \mathcal{N}\left(0, \sigma_\zeta^2\right)$
- The stochastic trend $\mu(t)$ and slope $\beta_1(t)$ are estimated with KF

Carbon trend

Stochastic trend model

Example #8

- We estimate the parameters $(\sigma_u, \sigma_\eta, \sigma_\zeta)$ by maximizing the Whittle log-likelihood function
- We obtain $\hat{\sigma}_u = 0.7022$, $\hat{\sigma}_\eta = 0.7019$ and $\hat{\sigma}_\zeta = 0.8350$
- The standard deviation of the stochastic slope variation $\beta_1(t) - \beta_1(t-1)$ is then equal to 0.8350 $\mathrm{MtCO_2e}$

Carbon trend

Stochastic trend model

Table 20: Kalman filter estimation of the stochastic trend (Example #8)

t	$\mathcal{CE}(t)$	$\hat{\beta}_1(t)$ (RLS)	$\beta_1(t)$ (KF)	$\mu(t)$ KF)
2007	57.80		0.0000	57.80
2008	58.40		0.2168	58.25
2009	57.90	0.0500	−0.0441	58.00
2010	55.10	−0.8600	−1.3941	55.56
2011	51.60	−1.5700	−2.6080	52.01
2012	48.30	−2.0200	−3.1288	48.47
2013	47.10	−2.0929	−2.2977	46.82
2014	46.10	−2.0321	−1.5508	45.85
2015	44.40	−1.9817	−1.5029	44.38
2016	42.70	−1.9406	−1.5887	42.73
2017	41.40	−1.8891	−1.4655	41.36
2018	40.20	−1.8329	−1.3202	40.15
2019	41.90	−1.6824	0.1339	41.41
2020	45.00	−1.4512	1.7701	44.45

Carbon momentum

- We have:

$$\mathcal{CM}^{\mathcal{L}ong}\left(t\right)=\frac{\hat{\beta}_{1}\left(t\right)}{\mathcal{CE}\left(t\right)}$$

  or:

$$\mathcal{CM}^{\mathcal{L}ong}\left(t\right)=\hat{\gamma}_{1}\left(t\right)$$

Statistics

Table 21: Statistics (in %) of carbon momentum $\mathcal{CM}^{\mathcal{L}ong}(t)$ (MSCI World index, 1995 – 2021, linear trend)

Statistics	Carbon emissions			Carbon intensity		
	$\mathcal{SC}_1$	$\mathcal{SC}_{1-2}$	$\mathcal{SC}_{1-3}^{\text{up}}$	$\mathcal{SC}_1$	$\mathcal{SC}_{1-2}$	$\mathcal{SC}_{1-3}^{\text{up}}$
Median	0.0	1.6	2.3	−4.8	−2.4	−1.3
Negative	49.9	41.1	29.4	76.0	69.6	75.6
Positive	50.1	58.9	70.6	24.0	30.4	24.4
$< -10\%$	23.4	15.8	5.8	36.0	25.0	5.7
$< -5\%$	32.1	22.2	10.6	48.6	36.7	13.4
$> +5\%$	22.9	27.5	23.6	6.2	7.3	2.7
$> +10\%$	9.2	9.5	8.0	2.3	2.6	1.0

Source: Trucost database (2022) & Authors' calculations.

Statistics

Table 22: Statistics (in %) of carbon momentum $\mathcal{CM}^{\mathcal{L}ong}(t)$ (MSCI World index, 1995 – 2021, log-linear trend)

Statistics	Carbon emissions			Carbon intensity		
	$\mathcal{SC}_1$	$\mathcal{SC}_{1-2}$	$\mathcal{SC}_{1-3}^{\text{up}}$	$\mathcal{SC}_1$	$\mathcal{SC}_{1-2}$	$\mathcal{SC}_{1-3}^{\text{up}}$
Median	−0.1	1.7	2.8	−3.6	−1.9	−1.2
Negative	50.6	40.3	29.0	76.3	69.0	75.8
Positive	49.4	59.7	71.0	23.7	31.0	24.2
$< -10\%$	13.6	8.0	2.8	20.8	12.3	2.1
$< -5\%$	26.6	16.9	7.5	42.3	29.0	8.4
$> +5\%$	29.8	35.9	37.1	9.0	10.1	4.0
$> +10\%$	16.9	19.4	19.2	4.0	4.1	1.6

Source: Trucost database (2022) & Authors' calculations.

The $\mathcal{PAC}$ framework

Participation

Ambition

Credibility

Carbon target and decarbonization scenario

The $\mathcal{PAC}$ framework requires three time series:

- The historical pathway of carbon emission
- The reduction targets announced by the company

$$\mathbb{CT} = \left\{\boldsymbol{\mathcal{R}}^{\mathcal{T}arget}\left(t_0, t_k\right), k = 1, \ldots, n_T\right\}$$

- The market-based sector scenario associated to the company that defines the decarbonization pathway

$$\mathbb{CS} = \left\{\boldsymbol{\mathcal{R}}^{\mathcal{S}cenario}\left(t_0, t_k\right), k = 1, \ldots, n_S\right\}$$

The $\mathcal{PAC}$ framework

Table 23: Reduction rates of the IEA NZE scenario (base year = 2020)

Year	Electricity	Industry	Transport	Buildings	Other	Global
2025	20.0	4.0	−1.1	15.0	13.1	10.6
2030	56.9	18.8	20.0	36.7	52.4	36.6
2035	84.3	38.1	42.5	57.7	95.3	59.6
2040	100.0	59.0	62.4	75.9	100.0	77.1
2045	100.0	78.8	79.0	88.8	100.0	87.3
2050	100.0	93.9	90.3	95.8	100.0	94.3

Source: IEA (2021) & Author's calculations.

The $\mathcal{PAC}$ framework

The 3 questions of the $\mathcal{PAC}$ framework

1. Is the trend of the issuer in line with the scenario?
2. Is the commitment of the issuer to fight climate change ambitious?
3. Is the target setting of the company relevant and robust, or is it a form of greenwashing?

The $\mathcal{PAC}$ framework

Example #10

- We consider Example #8
- Company A has announced the following targets:
  1. $\mathcal{R}^{\mathcal{T}arget}(2020, 2025) = 40\%$
  2. $\mathcal{R}^{\mathcal{T}arget}(2020, 2030) = 50\%$
  3. $\mathcal{R}^{\mathcal{T}arget}(2020, 2035) = 75\%$
  4. $\mathcal{R}^{\mathcal{T}arget}(2020, 2040) = 80\%$
  5. $\mathcal{R}^{\mathcal{T}arget}(2020, 2050) = 90\%$
- Company A is an utility corporation $\Rightarrow$ we use the IEA NZE scenario for the sector Electricity

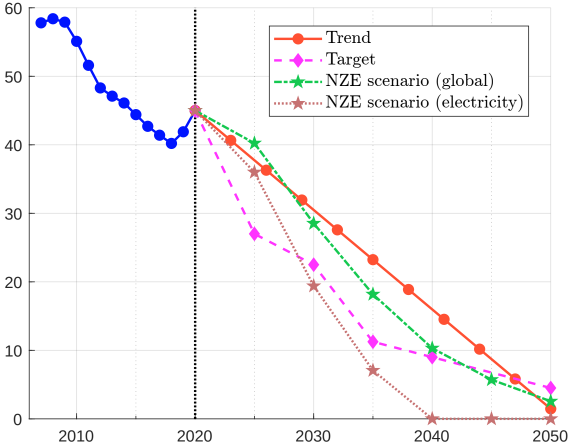
The $\mathcal{PAC}$ framework

Table 24: Comparison of carbon budgets (Example #10, base year = 2020)

Year	Trend (linear)	Trend (log-linear)	Target	Scenario (global)	Scenario (electricity)
2025	207	209	180	213	203
2030	377	390	304	385	341
2035	512	546	388	502	407
2040	610	680	439	573	425
2045	671	796	478	613	425
2050	697	896	506	634	425

The $\mathcal{PAC}$ framework

Figure 26: Carbon trend, targets and NZE scenario of company A



Source: IEA (2021) & Author's calculations.

Assessment of the $\mathcal{PAC}$ pillars

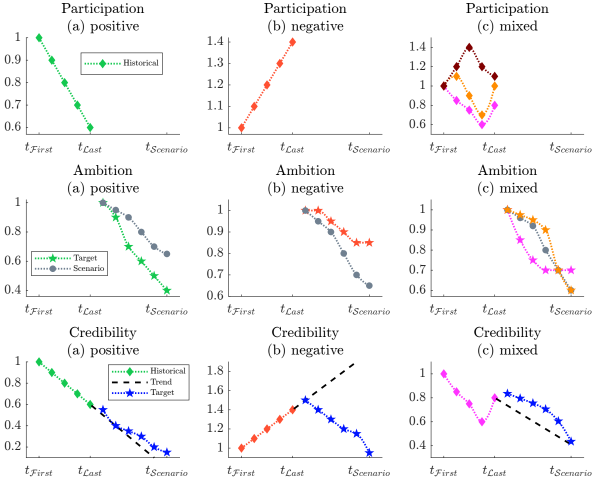
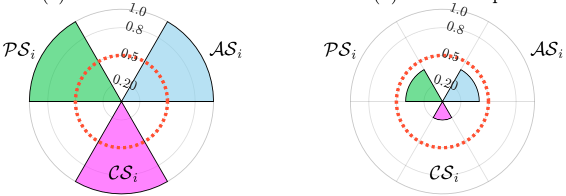


Figure 27: Illustration of the participation, ambition and credibility pillars

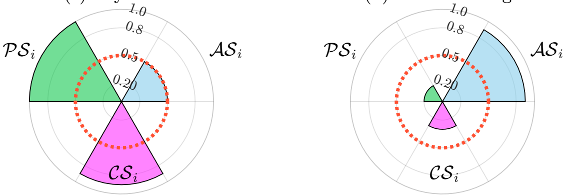
Temperature scoring system

Figure 28: The $\mathcal{PAC}$ scoring system

(a) Model student? (b) Black sheep?

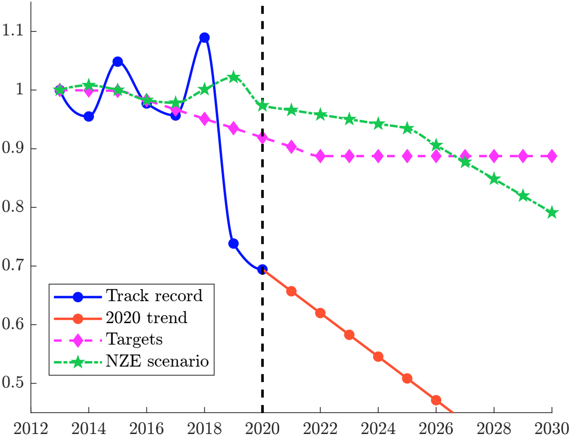


(c) Shy child? (d) Greenwashing?



Illustration

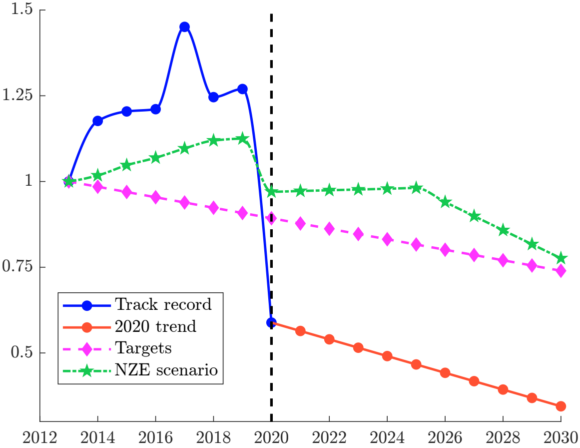
Figure 29: Carbon emissions, trend, targets and NZE scenario (Company *B*)



Source: CDP database (2021), IEA (2021) & Leguenedal *et al.* (2022)

Illustration

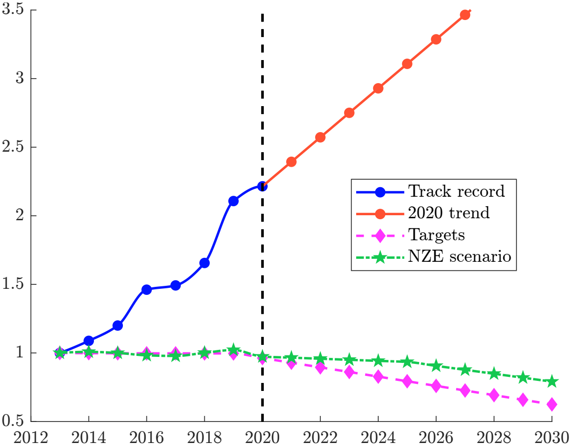
Figure 30: Carbon emissions, trend, targets and NZE scenario (Company C)



Source: CDP database (2021), IEA (2021) & Leguenedal *et al.* (2022)

Illustration

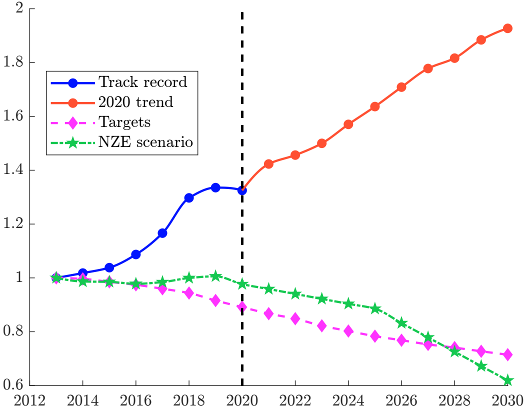
Figure 31: Carbon emissions, trend, targets and NZE scenario (Company *D*)



Source: CDP database (2021), IEA (2021) & Leguenedal *et al.* (2022)

Illustration

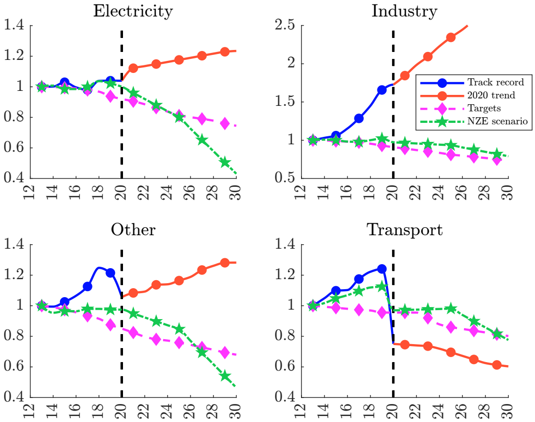
Figure 32: Carbon emissions, trend, targets and NZE scenario (median analysis, global universe)



Source: CDP database (2021), IEA (2021) & Leguenedal *et al.* (2022)

Illustration

Figure 33: Carbon emissions, trend, targets and NZE scenario (median analysis, sector universe)

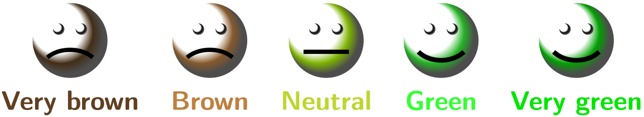


Source: CDP database (2021), IEA (2021) & Leguenedal *et al.* (2022)

Greenness measures

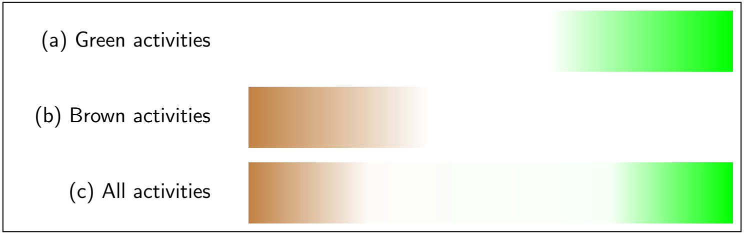
- Brown intensity: $\boldsymbol{\mathcal{BI}}$
- Green intensity: $\boldsymbol{\mathcal{GI}}$
- We have $\boldsymbol{\mathcal{BI}} \in [0,1]$, $\boldsymbol{\mathcal{GI}} \in [0,1]$ and $0 \leq \boldsymbol{\mathcal{BI}} + \boldsymbol{\mathcal{GI}} \leq 1$
- Most of the time, we have

$$\boldsymbol{\mathcal{BI}} + \boldsymbol{\mathcal{GI}} \neq 1$$



Greenness measures

Figure 34: Several taxonomies



Green taxonomy

Definition

The EU taxonomy for sustainable activities is "*a classification system, establishing a list of environmentally sustainable economic activities.*"

Green taxonomy

These economic activities must have a substantive contribution to at least one of the following six environmental objectives:

1. climate change mitigation
2. climate change adaptation
3. sustainable use and protection of water and marine resources
4. transition to a circular economy
5. pollution prevention and control
6. protection and restoration of biodiversity and ecosystem

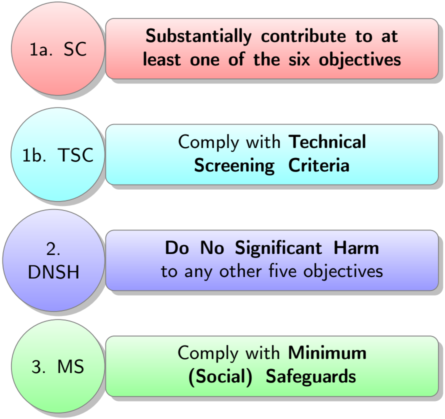
Green taxonomy

A business activity must also meet two other criteria to qualify as sustainable:

- The activity must do no significant harm to the other environmental objectives (**DNSH** constraint)
- It must comply with minimum social safeguards (**MS** constraint)

Green taxonomy

Figure 35: EU taxonomy for sustainable activities



1a. SC — **Substantially contribute to at least one of the six objectives**

1b. TSC — Comply with **Technical Screening Criteria**

2. DNSH — **Do No Significant Harm** to any other five objectives

3. MS — Comply with **Minimum (Social) Safeguards**

Green revenue share

Relationship between the green intensity and the green revenue share

We have:

$$\boldsymbol{\mathcal{GI}} = \frac{\mathcal{GR}}{\mathcal{TR}} \cdot (1 - \mathcal{P}) \cdot \mathbb{1}\left\{\boldsymbol{\mathcal{S}} \geq \boldsymbol{\mathcal{S}}^{\star}\right\}$$

where:

- $\mathcal{GR}$ is the green revenue deduced from the six environmentally sustainable objectives
- $\mathcal{TR}$ is the total revenue
- $\mathcal{P}$ is the penalty coefficient reflecting the DNSH constraint
- $\boldsymbol{\mathcal{S}}$ is the minimum safeguard score
- $\boldsymbol{\mathcal{S}}^{\star}$ is the threshold

Green revenue share

- The first term is a proxy of the turnover KPI and corresponds to the green revenue share:

$$\boldsymbol{\mathcal{GRS}} = \frac{\mathcal{GR}}{\mathcal{TR}}$$

- By construction, we have $0 \leq \boldsymbol{\mathcal{GRS}} \leq 1$
- This measure is then impacted by the DNSH coefficient
  - The two extreme cases are:

$$\left\{ \begin{array}{l} \mathcal{P} = 1 \Rightarrow \boldsymbol{\mathcal{GI}} = \boldsymbol{\mathcal{GRS}} \\ \mathcal{P} = 0 \Rightarrow \boldsymbol{\mathcal{GI}} = 0 \end{array} \right.$$

  - We have $0 \leq \boldsymbol{\mathcal{GI}} = \boldsymbol{\mathcal{GRS}} \cdot (1 - \mathcal{P}) \leq \boldsymbol{\mathcal{GRS}}$
- The indicator function $\mathbb{1}\left\{ s \geq s^{\star} \right\}$ is a binary all-or-nothing variable:

$$\boldsymbol{\mathcal{S}} < \boldsymbol{\mathcal{S}}^{\star} \Rightarrow \boldsymbol{\mathcal{GI}} = 0$$

Green revenue share

Example #11

We consider a company in the hydropower sector which has five production sites. Below, we indicate the power density efficiency, the GHG emissions, the DNSH compliance with respect to the biodiversity and the corresponding revenue:

Site	#1	#2	#3	#4	#5
Efficiency (in Watt per m^2)	3.2	3.5	3.3	5.6	4.2
GHG emissions (in $\mathrm{gCO_2e}$ per kWh)	35	103	45	12	36
Biodiversity DNSH compliance	✓	✓	✓	✓	
Revenue (in $ mn)	103	256	89	174	218

Green revenue share

- The total revenue is equal to:

$$\mathcal{TR} = 103 + 256 + 89 + 174 + 218 = \$840 \text{ mn}$$

- The fourth site does not pass the technical screening, because the power density is above 5 Watt per m^2
- The second site does not also comply because it has a GHG emissions greater than 100 $\mathrm{gCO_2e}$ per kWh
- We deduce that the green revenue is equal to:

$$\mathcal{GR} = 103 + 89 + 218 = \$410 \text{ mn}$$

- We conclude that the green revenue share is equal to 48.8%
- According to the EU green taxonomy, the green intensity is lower because the last site is close to a biodiversity area and has a negative impact:

$$\mathcal{GI} = \frac{103 + 89}{840} = 22.9\%$$

Statistics

Table 25: Statistics in % of green revenue share (MSCI ACWI IMI, June 2022)

Category	Frequency $\mathbf{F}(x)$				Quantile $\mathbf{Q}(\alpha)$				Mean	
	0	25%	50%	75%	75%	90%	95%	Max	Avg	Wgt
(1)	9.82	1.47	0.96	0.75	0.00	0.00	2.85	100.00	1.36	0.77
(2)	14.10	1.45	0.65	0.31	0.00	1.25	6.12	100.00	1.39	3.50
(3)	4.84	1.68	1.02	0.31	0.00	0.00	0.00	100.00	1.16	0.51
(4)	4.79	0.30	0.10	0.06	0.00	0.00	0.00	99.69	0.32	0.22
(5)	1.00	0.39	0.20	0.09	0.00	0.00	0.00	98.47	0.26	0.10
(6)	4.75	0.28	0.11	0.05	0.00	0.00	0.00	99.98	0.29	0.14
Total	27.85	5.82	3.17	1.68	0.42	11.82	30.36	100.00	4.78	5.24

Source: MSCI (2022) & Barahhou (2022)

$\mathbf{F}(x) = \Pr\{\mathcal{GRS} > x\}$, $\mathbf{Q}(\alpha) = \inf\{x : \Pr\{\mathcal{GRS} \leq x\} \geq \alpha\}$, arithmetic average $n^{-1}\sum_{i=1}^{n} \mathcal{GRS}_i$ and weighted mean $\mathcal{GRS}(b) = \sum_{i=1}^{n} b_i \mathcal{GRS}_i$

Statistics

- The green revenue share of the MSCI World index is equal to 5.24%
- The green revenue share of the Bloomberg Global Investment Grade Corporate Bond index is equal to 3.49%
- Alessi and Battiston (2022) estimated "*a greenness of about 2.8% for EU financial markets*"

Green capex