9.1 Carbon emissions

Carbon footprint is a generic term used to define the total greenhouse gas (GHG) emissions caused by a given system, activity, company, country, or region. Greenhouse gases are made up of water vapor (H_2O), carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), Ozone (O_3), etc. They absorb and emit radiation energy, causing the greenhouse effect. We remind that the greenhouse effect was a crucial factor for the development of human life on Earth. Indeed, without the greenhouse effect, the average temperature of Earth's surface would be about $-18°$C. With the greenhouse effect, the current temperature of Earth's surface is about $+15°$C. Nevertheless, the increasing concentration of some GHGs is an issue because it is a factor in global warming. It mainly concerns carbon dioxide, and to a lesser extent, methane and nitrous oxide.

9.1.1 Global warming potential

Carbon footprint is generally measured in carbon dioxide equivalent (CO_2e), which is a term for describing different GHGs in a common unit. In this framework, a quantity of GHG is expressed as CO_2e by multiplying the GHG amount by its global warming potential (GWP):

$$\text{equivalent mass of } CO_2 = \text{mass of the gas} \times \text{gwp of the gas}$$

where the GWP of a gas is the amount of CO_2 that would warm the earth equally. Since the mass of the gas is expressed in kilogram and the GWP has no unit, the mass of CO_2 equivalent is also expressed in kilogram. For instance, the IPCC's 5^{th} assessment report has used the following rules (IPCC, 2014a): 1 kg of methane corresponds to 28 kg of CO_2 and 1 kg of nitrous oxide corresponds to 265 kg of CO_2. The definition of a common unit allows two companies to be compared properly. To compute the carbon footprint of a system that is made up of several gases, we apply the weighted sum formula:

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

where m is the mass of CO_2 equivalent, m_i and gwp_i are the mass and the global warming potential of the i^{th} gas, and n is the number of gases. m and m_i have the same mass unit (eg., kilogram or kg, tonne or t, kilotonne or kt, megatonne or Mt, gigatonne or Gt). However, m measures a mass of CO_2 equivalent. Therefore, it better to use the following units: kgCO_2e, tCO_2e, ktCO_2e, MtCO_2e and GtCO_2e.

Example 33 *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:

$$m_A = 3017 \times 1 + 10 \times 28 + 1.8 \times 265 = 3\,774 \text{ t}CO_2\text{e}$$

and:

$$m_B = 2302 \times 1 + 32 \times 28 + 3.0 \times 265 = 3\,993 \text{ t}CO_2\text{e}$$

We notice that company B emits more carbon emissions than company A when they are measured in CO_2 equivalent. We can also compute the mass contribution of each gas:

$$c_i = \frac{m_i \cdot \text{gwp}_i}{m}$$

The mass decomposition is reported below:

Company	Mass	Absolute contribution			Relative contribution		
A	3 774	3 017	280	477	79.94%	7.42%	12.64%
B	3 993	2 302	896	795	57.65%	22.44%	19.91%

The contribution of the carbon dioxide gas is equal to 79.94% for company A and 57.65% for company B. Concerning methane gas, its contribution is respectively equal to 7.42% and 22.44%.

Box 9.1: 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.*" Since each gas differs in their capacity to absorb the energy (radiative efficiency) and how long it stays in the atmosphere (lifetime), its impact on global warming depends on these two factors. GWP is then a synthetic measure that combines radiative efficiency and lifetime.

The mathematical definition of the global warming potential is:

$$\text{gwp}_i(t) = \frac{\text{Agwp}_i(t)}{\text{Agwp}_0(t)} = \frac{\int_0^t RF_i(s)\,\mathrm{d}s}{\int_0^t RF_0(s)\,\mathrm{d}s} = \frac{\int_0^t A_i(s)\,\mathbf{S}_i(s)\,\mathrm{d}s}{\int_0^t A_0(s)\,\mathbf{S}_0(s)\,\mathrm{d}s} \tag{9.1}$$

where $A_i(t)$ is the radiative efficiency value of gas i (or the radiative forcing increase per unit mass increase of gas i in the atmosphere), $\mathbf{S}_i(t)$ is the decay function (or the fraction of gas i remaining in the atmosphere after t years following an incremental pulse of the gas) and $i = 0$ is the reference gas (e.g, CO_2). The radiative forcing $RF_i(t) = A_i(t)\,\mathbf{S}_i(t)$ is the product of the radiative efficiency and the decay function, whereas the absolute global warming potential $\text{Agwp}_i(t)$ is the cumulative radiative forcing of the gas i between 0 and t. GWP is then the ratio between the cumulative radiative forcing of the gas and this of the reference gas. We also notice that it depends on the time horizon t.

It is generally accepted to describe the decay function (or impulse response function) by exponential functions (Joos *et al.*, 2013):

$$\mathbf{S}_i(t) = \sum_{j=1}^{m} a_{i,j} e^{-\lambda_{i,j} t} \tag{9.2}$$

where $\sum_{j=1}^{m} a_{i,j} = 1$. Once we have defined the radiative efficiency function $A_i(t)$ and the set of parameters $\{(a_{i,j}, \lambda_{i,j}), j = 1, \ldots, m\}$ of the impulse function, we compute Equation (9.1) using numerical integration. In the case where $A_i(t)$ and $A_0(t)$ are constant, we obtain:

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

In Box 9.1, we explain how GWP is computed. We notice that the global warming potential value depends on the time horizon. For instance, the relative warming impact of one molecule of a greenhouse gas is not the same at 20 years than 100 years. We also notice that the estimation of GWP implies to make some assumptions about the impulse response (or decay) function and the radiative efficiency value. Let us see how the value for methane has been obtained. IPCC (2013) assumed that the radiative intensity is constant and used the following values[2]: $A_{\mathrm{CO}_2} = 1.76 \times 10^{-18}$ and $A_{\mathrm{CH}_4} = 2.11 \times 10^{-16}$. The impulse response functions were estimated by least squares and they found the following approximated curve:

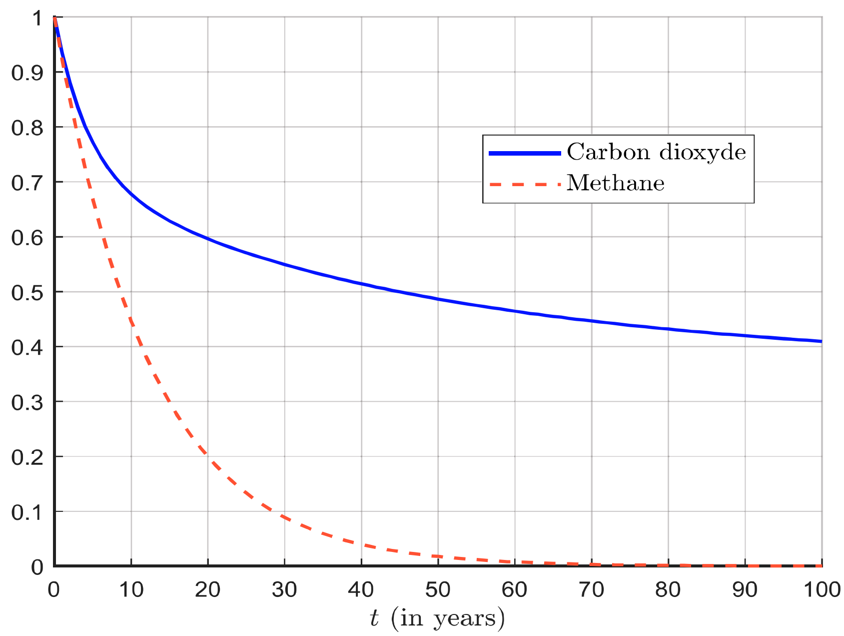
$$\mathbf{S}_{\mathrm{CO}_2}(t) = 0.2173 + 0.2240 \cdot \exp\left(-\frac{t}{394.4}\right) + 0.2824 \cdot \exp\left(-\frac{t}{36.54}\right) + 0.2763 \cdot \exp\left(-\frac{t}{4.304}\right)$$

and:

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

These two decay functions are reported in Figure 9.1. We can interpret them as survival functions[3], meaning that the density function can be computed as $f_i(t) = -\partial_t \mathbf{S}_i(t)$.

Figure 9.1: Fraction of gas remaining in the atmosphere



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

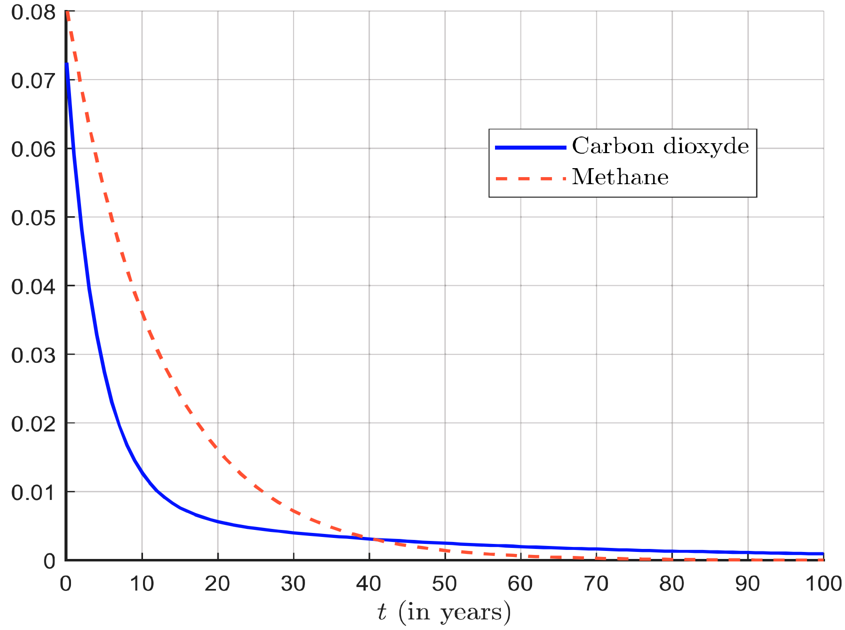
In the case of the exponential distribution $\mathcal{E}(\lambda)$, we have $\mathbf{S}_i(t) = e^{-\lambda t}$ and $f_i(t) = \lambda e^{-\lambda t}$ where λ is the rate parameter. Let τ_i be random time that the gas remains in the atmosphere. We have $\mathbb{E}[\tau_i] = 1/\lambda$ for the exponential random time. The survival function of the CH_4 gas is exponential with a mean time equal to 12.4 years ($\lambda = 1/12.4$). In the case of the general formula (9.2), the probability density function is equal to:

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

[2]The unit is $W \cdot m^{-2} g^{-1}$.

[3]This is why we use the notation $\mathbf{S}(t)$.

Figure 9.2: Probability density function of the random time



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

and the mean time $\mathcal{T}_i$ is given by:

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

Another way to find this result is to notice that $f_i(t)$ 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 and $a_{i,j}$ is the mixture weight of the j^{th} component. Therefore, we deduce that the mean time is equal to the weighted average of the mean times of the mixture components:

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

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

We can now explain why the carbon dioxide stays longer in the atmosphere than the methane. When we compare the density functions of the two gases (Figure 9.2), we observe that the disappearance probabilities are located before 50 years, since the probability to stay in the atmosphere after 50 years is less than 2%. For the CO_2 gas, we have roughly 50% that the molecule disappears and 50% that the molecule stays. In fact, we notice that one mixture component corresponds to a permanent state ($\lambda_{i,1} = 0$) with a weight of 21.73%. This explains that the CO_2 molecule can stay in the atmosphere, and we have $\mathbf{S}_{\mathrm{CO}_2}(\infty) = 21.73\%$.

We compute $\mathrm{Agwp}_{\mathrm{CO}_2}(t)$ and $\mathrm{Agwp}_{\mathrm{CH}_4}(t)$ and report their values in Figure 9.3. Even if the methane has a much shorter atmospheric lifetime than the carbon dioxide, it absorbs much more energy — because of the value of A_{CH_4} compared to the value of A_{CO_2}. Nevertheless, the absolute global warming potential is unbounded for COtwo because we have $\mathrm{Agwp}_{\mathrm{CO}_2}(\infty) = \infty$. For the methane, it reaches an upper bound, which corresponds to the ratio $A_{\mathrm{CH}_4} \times \mathcal{T}_{\mathrm{CH}_4} \propto 2.11 \times 12.4 = 26.164$. Therefore, $\mathrm{gwp}_{\mathrm{CH}_4}(t)$ is a decreasing function with respect to the time horizon (Figure 9.4). 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 $\mathrm{gwp}_{\mathrm{CH}_4}(100) = 28.3853$, which is the value calculated by IPCC (2013, 2014a). Because of the persistant regime of the carbon dioxyde, we have $\mathrm{gwp}_{\mathrm{CH}_4}(\infty) = 0$. In fact, the global warming potential of CO_2 becomes greater than this of CH_4 when $t \geq 6\,382$ years.

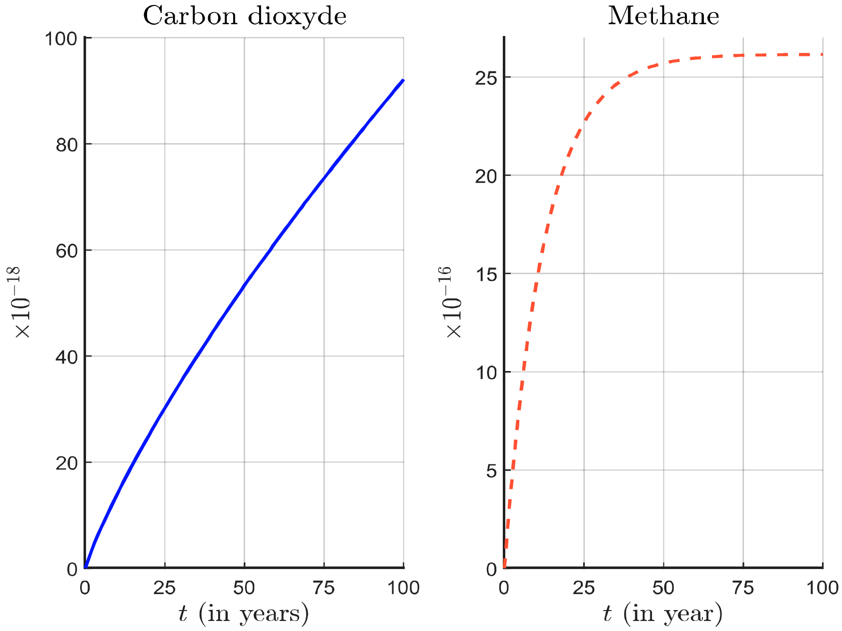
The previous analysis shows that the estimation of the global warming potential involves significant scientific uncertainty. First, the choice of a 100-year time horizon is arbitrary, and any other choice will change the GWP value. Second, the survival function $\mathbf{S}_i(t)$ is estimated and based on empirical experiments. Third, we have assumed that the radiative efficiency $A_i(t)$ is constant and equal to the initial value $A_i(0)$. In this context, we can consider that $\mathrm{gwp}_i(t)$ is stochastic or cannot be observed without any error. The GHG protocol considers the six gases listed in the Kyoto Protocol: carbon dioxide, methane, nitrous oxide, sulphur hexafluoride, hydrofluorocarbons, and perfluorocarbons. Table 9.1 gives their GWP values according to the different IPCC reports. We notice that they have continuously changed.

Table 9.1: 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.				

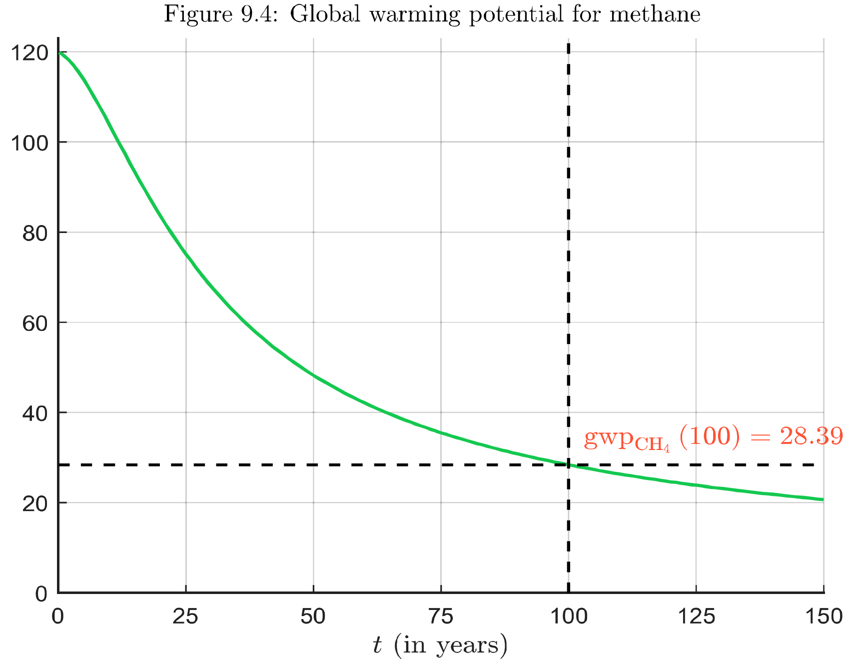
Remark 97 *The GWP has been subjected to many criticisms because it does not directly measure the impact on the temperature and it is a single-pulse emission metric (Kleinberg, 2020). The alternative metric is the global temperature potential (GTP) proposed by Shine et al. (2005). While the GWP is a measure of the energy absorbed over a given time period, the GTP is a measure of the temperature change at the end of that time period. The adoption of the GTP is however extremely rare, because its calculation is complicated and it appeared after the Kyoto Protocol.*

Figure 9.3: Absolute global warming potential



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

Figure 9.4: Global warming potential for methane



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

9.1.2 Consolidation accounting at the company level

Greenhouse gas accounting requires to define rules about what is reported and what is not reported. For instance, we have seen that the GHG protocol does not consider all greenhouse gases. In a similar way, the consolidation of GHG emissions (also named organizational boundary) follows specific principles, which are similar to those we can find in financial consolidation accounting. For corporate reporting, the GHG protocol distinguishes two approaches:

1. Equity share approach
2. Control approach

Under the first approach, a parent company must report carbon emissions of a subsidiary company according to its share of equity (or ownership ratio). This is the simplest accounting method. For example, if company A owns 25% of company B, company A have to take into account 25% of the company B's GHG emissions. Under the second approach, it can use either the financial control method or the operational control method. The company financially controls an operation if it bears the majority risks and rewards of this operation[4], whereas it has operational control if it has the full authority to implement the operation. The control approach is based on the all-or-none principle: Company A includes 100% of the company B's GHG emissions if A controls B, otherwise it includes 0%. In Table 9.2, we report the three accounting principles. By definition, the company has financial (and operational) control on group companies or subsidiaries. This explains that 100% of GHG emissions are consolidated. Associated and affiliated companies differ from the previous categories, because the company do not have the financial control. In this case, no GHG emissions are consolidated under the financial control method. Nevertheless, the company may have operational control, which explains that 100% of GHG emissions may be consolidated[5]. For joint ventures and partnerships, we apply the equity share principle for the financial control method, and we use the same rule than for associated and affiliated companies when we consider the financial control approach. Since the category fixed assets correspond to investments, the company receives dividends but has no control and GHG emissions are not consolidated. The same case applies to franchises because they are sperate legal entities and franchisers have no equity rights or control. In the opposite situation, the franchise is considered as a subsidiary.

Table 9.2: 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	Ownership ratio	100%	100%
Associated/affiliated companies	Ownership ratio	0%	0%/100%
Joint ventures/partnerships	Ownership ratio	Ownership ratio	0%/100%
Fixed asset investments	0%	0%	0%
Franchises	0%	0%	0%
	Ownership ratio	100%	100%

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

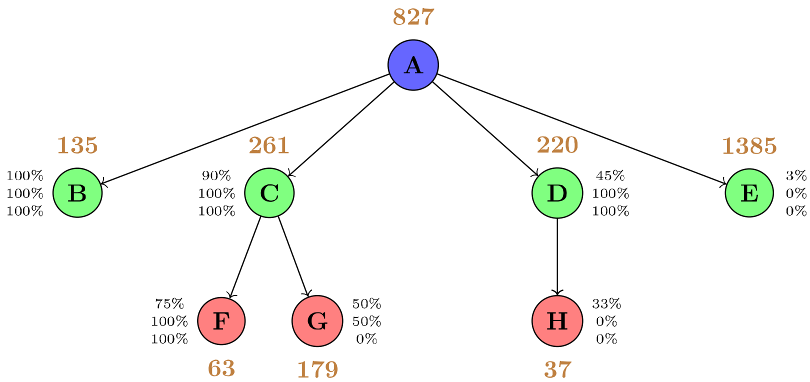
Remark 98 *An illustration of the differences between the equity share and control approaches is given in GHG Protocol (2004) on pages 22 and 23. This concerns the Holland Industries Group.*

[4] For instance when the company has more than 50% voting rights.

[5] If the company has no operational control, GHG emissions are not consolidated.

Example 34 *We report the organizational structure of company A in Figure 9.5. This industrial group has several subsidiaries, partnerships and joint ventures. For instance, Companies B and C are integrated to company A, implying that the latter has financial and operational control on them. Company D is in the same situation even if company A has not the majority of capital. Indeed, company A treats company D as a subsidiary in its financial accounts, because the remaining capital is diluted and they control the management. The participation in company E is an investment. Company C has two joint ventures. For company F, it owns 75% of the capital, while company G is held in equal proportion by company A and another partner. Finally, company H is affiliated to company D, which has no financial or operational control.*

Figure 9.5: Defining the organizational boundary of company A



For each company, the brown number corresponds to the carbon emissions in 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.

Computing the carbon emissions reported by company A will depend on the accounting method. In the case of the equity share approach, we exclude the investment in company H and obtain:

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

If we use the financial control approach, the reported carbon emissions become:

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

With the operational control approach, they are slightly different from above because of the treatment of company G:

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

Generally, an equity share of 50% or more induces a financial/operational control, which implies that 100% of carbon emissions are consolidated and reported by the parent company. By contrast, the consolidation factor may be equal to 0% if the parent company has no control, even in the case it has a significant equity share (*e.g.*, between 30% and 40%).

9.1.3 Scope 1, 2 and 3 emissions

The GHG Protocol corporate standard classifies a company's greenhouse gas emissions in three scopes[6]:

- 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[7]:
  - 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.

Scope 1 emissions are also called direct emissions, whereas indirect emissions encompass both scope 2 and 3 GHG emissions. Unlike scope 1 and 2, scope 3 is an optional reporting category.

Remark 99 *The GHG protocol defines "the operational boundary as the scope of direct and indirect emissions for operations that fall within a company's established organizational boundary. The operational boundary (scope 1, scope 2, scope 3) is decided at the corporate level after setting the organizational boundary. The selected operational boundary is then uniformly applied to identify and categorize direct and indirect emissions at each operational level. The established organizational and operational boundaries together constitute a company's inventory boundary."*

Before explaining in fine detail the different scopes and their computation, we report six examples of carbon footprint reporting in Table 9.3. We consider the CDP database, since most of companies reporting to CDP use the GHG protocol framework. The CDP reporting framework is based on a questionnaire (see Box 9.2 on page 880). We first notice all the figures are not calculated. This is normal since scope 3 is not mandatory in the GHG protocol framework. When the sub-category is empty, we don't know whether it is equal to zero or a missing value, meaning that the company has not the capacity or implemented the method to compute it. In the case of Amazon, the sub-category end-of-life treatment of sold products is equal to zero and not an empty case. A second remark concerns the definition of the scope 2, because there are two approaches: location-based and market-based. How to read this table? If we consider the first company Amazon, its scope 1 emissions are equal to 9.62 $MtCO_2e$. For the scope 2 emissions, they are equal to 9.02 $MtCO_2e$ when they are calculated with the location-based method or 5.27 $MtCO_2e$ when they are calculated

[6] The latest version of corporate accounting and reporting standard can be found at www.ghgprotocol.org/corporate-standard.

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

Table 9.3: Examples of CDP reporting (carbon emissions in tCO_2e, reporting year 2020)

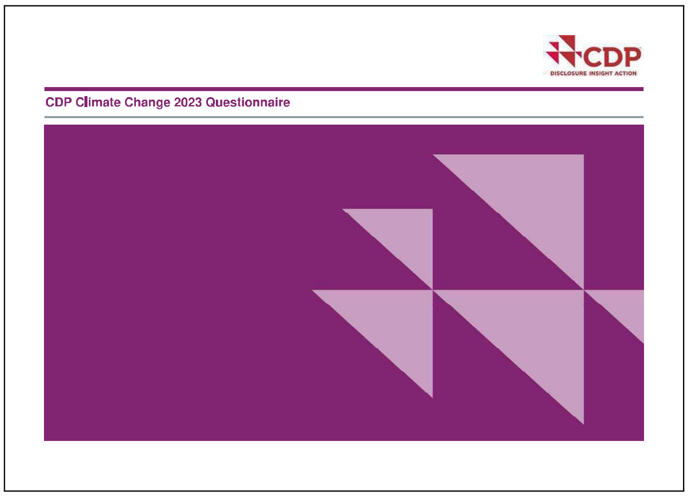
Scope	Category	Sub-category	Amazon	Danone	ENEL	Pfizer	Netflix	Walmart
1			9 623 138	668 354	45 255 000	654 460	30 883	7 236 499
2	Location-based (2a)		9 019 786	864 710	4 990 685	551 577	28 585	11 031 800
	Market-based (2b)		5 265 089	479 210	7 855 954	542 521	141	9 190 337
3	Upstream	Purchased goods 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.

with the market-based method. The fifteen sub-categories of scope 3 emissions are not aggregated, and each item is filled separately. The last of part of the table (from Scope 1 + 2a to Scope 1 + 2a + 3 is not included in the CDP questionnaire. These figures are calculated by summing the different items.

Box 9.2: CDP questionnaire for corporates

In order to report to CDP, companies must fill the CDP questionnaire on climate change, which is available at `www.cdp.net/en/guidance/guidance-for-companies` in HTML, Word and PDF formats. The full questionnaire has 129 pages and 16 sections. Emissions methodology corresponds to section C5, while emissions data are reported in section C6 with the following breakdown: scope 1 emissions (§C6.1), scope 2 emissions (§C6.3), scope 3 emissions (§C6.5) and emissions intensities (§C6.10).



Scope 1 emissions

According to GHG Protocol (2004, page 40)GHG-Protocol, once the inventory boundary has been established, "*companies generally calculate GHG emissions using the following steps: (1) Identify GHG emissions sources; (2) Select a GHG emissions calculation approach; (3) Collect activity data and choose emission factors; (4) Apply calculation tools and (5) Roll-up GHG emissions data to corporate level. The identification step helps to categorize the GHG emission sources.*" The identification step consists in categorizing the GHG emissions in the four main source categories:

1. Stationary combustion: combustion of fuels in stationary equipment (*e.g.*, boilers, turbines, heaters, incinerators);

2. Mobile combustion: combustion of fuels in transportation devices (*e.g.*, automobiles, trucks, trains, airplanes, boats);

3. Process emissions: emissions from physical or chemical processes (*e.g.*, cement manufacturing, petrochemical processing, aluminum smelting);

4. Fugitive emissions: intentional and unintentional releases as well as fugitive emissions (*e.g.*, such as equipment leaks, coal piles, wastewater treatment, cooling towers).

Concretely, the company lists all the activities that result in a GHG emission, and allocates them 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, frequency, etc. Since $E_{g,h}$ is expressed in tonne, $\boldsymbol{\mathcal{EF}}_{g,h}$ is measured in tonne per activity unit. For instance, if A_h is measured in hectare, $EF_{g,h}$ is measured in tonne per hectare. In fact, the emission factor is a coefficient that attempts to quantify how much of a greenhouse gas is released into the atmosphere by an activity that releases that gas[8]. For each gas, we calculate the total emissions:

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

where n_A is the number of activities. Finally, we estimate the carbon emissions by applying the right GWP and summing up all the gases:

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

where n_G is the number of gases[9]. Therefore, the compact formula is:

$$\boldsymbol{\mathcal{CE}} = \sum_{g=1}^{n_G} \text{gwp}_g \cdot \left(\sum_{h=1}^{n_A} A_h \cdot \boldsymbol{\mathcal{EF}}_{g,h} \right)$$

The carbon footprint of the company can be split into activities:

$$\boldsymbol{\mathcal{CE}} = \sum_{h=1}^{n_A} A_h \left(\sum_{g=1}^{n_G} \text{gwp}_g \cdot \boldsymbol{\mathcal{EF}}_{g,h} \right) = \sum_{h=1}^{n_A} A_h \cdot \boldsymbol{\mathcal{EF}}_h = \sum_{h=1}^{n_A} \boldsymbol{\mathcal{CE}}_h$$

where $\boldsymbol{\mathcal{EF}}_h$ and $\boldsymbol{\mathcal{CE}}_h$ are the global emission factor and carbon emissions related to the h^{th} activity. We can also aggregate several activities:

$$\boldsymbol{\mathcal{CE}}_{\mathcal{A}} = \sum_{h \in \mathcal{A}} \boldsymbol{\mathcal{CE}}_h = \sum_{h \in \mathcal{A}} A_h \cdot \boldsymbol{\mathcal{EF}}_h$$

where $\mathcal{A}$ is the set of activities. It may happen that some emission factors are defined without a reference to a specific gas (e.g., CO_2 or CH_4). In this case, the emission factor is a synthetic measure which already take into account the GWP of the gases:

$$\boldsymbol{\mathcal{EF}}_h = \sum_{g=1}^{n_G} \text{gwp}_g \cdot \boldsymbol{\mathcal{EF}}_{g,h}$$

[8]For example, how many kg of GHG are emitted by 1 kWh of natural gas?
[9]n_G is equal to six in the GHG Protocol.

The expression of the carbon footprint becomes:

$$\boldsymbol{\mathcal{CE}} = \sum_{h \in \mathcal{A}_1} A_h \left(\sum_{g=1}^{n_G} \mathrm{gwp}_g \cdot \boldsymbol{\mathcal{EF}}_{g,h} \right) + \sum_{h \in \mathcal{A}_2} A_h \cdot \boldsymbol{\mathcal{EF}}_h$$

where $\mathcal{A}_1$ and $\mathcal{A}_2$ are the sets of activities without and with synthetic emission factors.

The choice of data inputs is codified by IPCC (2006, 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.

We can find emission factors in several sources: IPCC Emission Factor Database (Box 9.3), National Inventory Reports[10] (NIRs), country emission factor databases[11], international agencies or academic publications. In the US, the emission factors are calculated by the Environmental Protection Agency (US EPA). In the UK, this is the National Atmospheric Emissions Inventory (NAEI) agency, which is in charge to define the emission factors. In France, the database is managed by ADEME (Agence de l'Environnement et de la Maîtrise de l'Energie) and contains about 5 300 validated emission factors. Generally, we can download these emission factors in an Excel or PDF file.

Let us see an example. We consider the GHG inventory document[12] published by Enel. The scope 1 is based on the following activities: (1) combustion of fossil fuels in electricity generation activities; (2) combustion of fossil fuels in generators used for electricity generation and distribution activities; (3) combustion of fossil fuels in vehicles under the Company's control; (4) combustion of fuels for heating offices and canteens; (5) CH_4 leakage in gas-fired thermoelectric power plants; (6) SF_6 losses in electricity generation and distribution activities; (7) HFCs gas losses from cooling systems; (8) NF_3 losses from the production of solar panels; (9) Transportation of fuel (LNG and coal) on vessels under own operational control and (10) CH_4 emissions from the decomposition of organic matter in hydroelectric basins. For the calculations, they use the parameter values of IPCC (2006) for emission factors and the GWP figures of IPCC (2014a). They obtained the following results in 2021 expressed in 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 then equal to 51.75 MtCO_2e. The contribution of CO_2 is the most important since it represents 98.4% of the total emissions, implying that the other gases have a small impact. In terms of activities, GHG emissions are mainly located in the electricity power generation. Buildings has a contribution of 0.2%.

[10]The NIR reports can be found at the UNFCCC website: https://unfccc.int/ghg-inventories-annex-i-parties/2021.

[11]Here are some websites: www.epa.gov/climateleadership/ghg-emission-factors-hub (US), https://naei.beis.gov.uk/data/ef-all (UK), https://bilans-ges.ademe.fr (France), www.dcceew.gov.au/climate-change/publications/national-greenhouse-accounts-factors-2021 (Australia), www.isprambiente.gov.it (Italy), https://publications.gc.ca/site/eng/9.911206/publication.html (Canada).

[12]Enel (2022). *Quantification and Reporting of Greenhouse Gas Emissions in Accordance with the Corporate GHG Protocol*. 12th April 2022, www.enel.com/investors/sustainability.

Box 9.3: IPCC emission factor database (EFDB)

The IPCC emission factor database[a] (EFDB) is a database on various parameters to be used in calculation of anthropogenic emissions by sources and removals by sinks of greenhouse gases. It contains the IPCC default data[b], and data from peer-reviewed journals and other publications including national inventory reports (NIRs). The database includes emission factors for five categories:

1. Energy (fuel combustion activities, fugitive emissions from fuels, carbon dioxide transport and storage);

2. Industrial processes and product use (mineral industry, chemical industry, metal industry, non-energy products from fuels and solvent use, electronics industry, product uses as substitutes for ozone depleting substances, other product manufacture and use, other);

3. Agriculture, forestry, and other land use (livestock, land, aggregate sources and non-CO2 emissions sources on land, other);

4. Waste (solid waste disposal, biological treatment of solid waste, incineration and open burning of waste, wastewater treatment and discharge, other)

5. Other (Indirect N_2O emissions from the atmospheric deposition of nitrogen in NO_x and NH_3, other)

Some figures of the library are given in Table 9.4. We notice that they may depend on the region and technical criteria. The unit is also important. For instance, if the emission factors are expressed in tCarbon/TeraJoule (tonne of carbon per terajoule energy), we multiply the emission factor $\boldsymbol{\mathcal{EF}}$ (in tC/TJ) by the energy consumption C (in TJ) to obtain the carbon content (in tonnes of carbon). Since one tonne of CO_2 contains 0.2727 tonne of carbon, we then deduce that the CO_2 emissions are equal to $\dfrac{C \cdot \boldsymbol{\mathcal{EF}}}{0.2727}$ tCO_2e. In this case, the activity data corresponds to the energy consumption.

[a] The website is www.ipcc-nggip.iges.or.jp/EFDB.

[b] Revised 1996 IPCC Guidelines, IPCC Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories, IPCC Good Practice Guidance for Land Use, Land-Use Change and Forestry, 2006 IPCC Guidelines for National Greenhouse Gas Inventories and 2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands.

Table 9.4: 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 semi-conductor	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

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, page 34). There are then four forms of energy that are tracked in scope 2:

- 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 includes indirect emissions from generation only. For instance, the distribution of energy within a grid is tracked in scope 3. In Figures 9.6–9.9, we report the different cases that are illustrated in the GHG Protocol: if the consumed electricity comes from owned/operated equipment, no scope 2 emissions are reported (Figure 9.6); if the consumed electricity comes from a direct line transfer or the grid[13], the consumer of the energy reports the emissions in scope 2 (Figures 9.7 and (Figure 9.8); if some consumed electricity comes from the owned/operated equipment, and some is purchased from the grid, the operator (company A) has both scope 1 emissions from energy generation, and scope 3 emissions from energy purchased on the grid (Figure 9.9).

Figure 9.6: Energy production and consumption from owned/operated generation

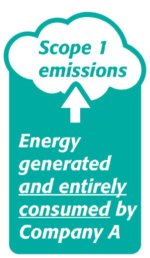
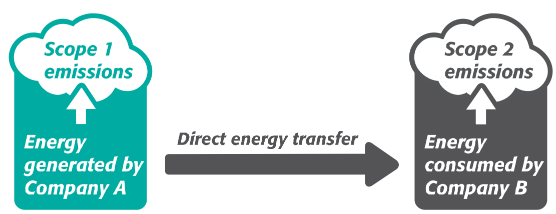


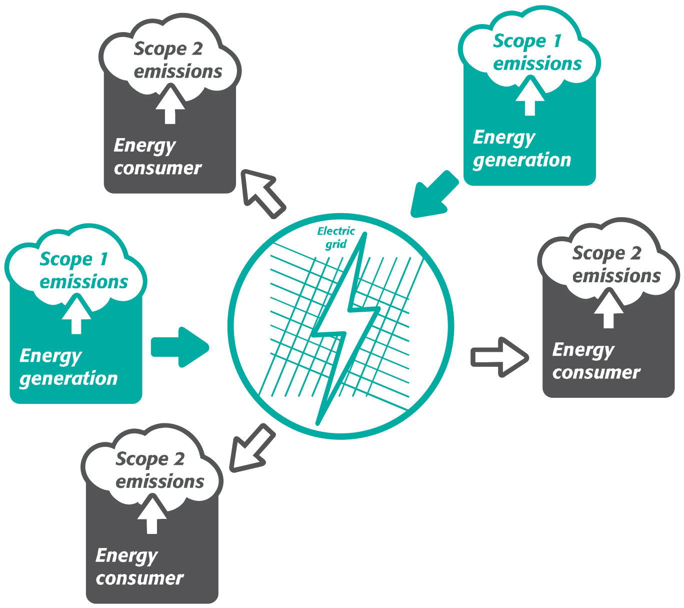
Figure 9.7: Direct line energy transfer



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

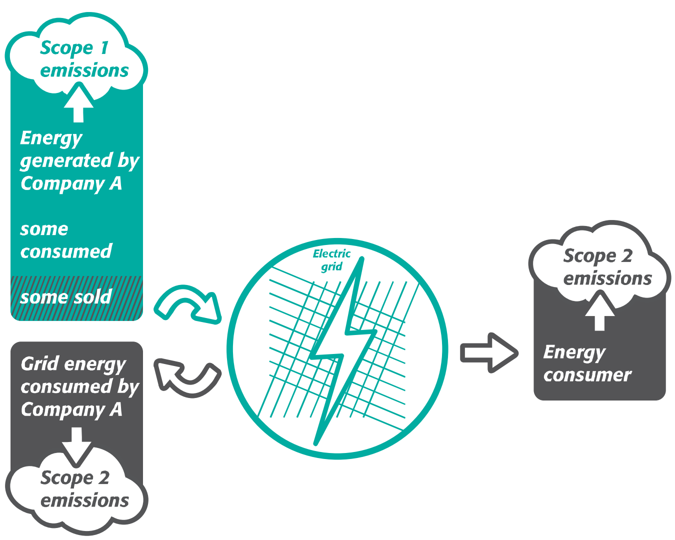
[13] A grid is "*a system of power transmission and distribution lines under the control of a coordinating entity or grid operator, which transfers electrical energy generated by power plants to energy users — also called a power grid.*" (CDP, 2022, page 8).

Figure 9.8: Electricity production on a grid



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

Figure 9.9: Facility consuming both energy generated on-site and purchased from the grid



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

Scope 2 emissions are calculated using activity data and emission factors[14] expressed in MWh and 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 and $\mathcal{EF}_s$ is the emission factor of the source s. The source can be an electricity supplier[15], a specific or country grid, a specific power station, etc.

Remark 100 *A Megawatt-hour is the common billing unit for electrical energy delivered to consumers. 1 000 MWh is equivalent to 3.6 TeraJoule (TJ). The TJ unit is used by IPCC (2006) (see Table 9.4 on page 884). A third energy unit is also used to defined emissions factors in North America (Canada and the US) and the United Kingdom: the British thermal unit or Btu (1 Btu is equivalent to 1.0551 KJ or 0.2931 Wh).*

Example 35 *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 gCO_2e/kWh.

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:

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

For the second source, we obtain:

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

We deduce that the scope 2 carbon emissions of this company is equal to 520 tCO_2e.

Let us consider again the GHG inventory report of Enel (page 882). We remind that the scope 1 emissions of Enel is equal to 51 750 265 tCO_2e. In the same document, we learn that the ratio between scope 1 emissions and the total electricity production is equal to 227 gCO_2e/kWh (or 0.227 tCO_2e/MWh). We deduce that the 2021 electricity production of Enel is [16]:

$$A = \frac{51,750\,265}{0.227} = 227\,974\,735 \text{ MWh} = 228 \text{ TWh}$$

Two main methods are available for accounting scope 2 emissions:

- 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;

[14] This approach is also known as the emission rate approach.

[15] The largest electricity companies are EDF, Enel, Engie, E.ON, Fortum, Marubeni, Siemens, State Grid Corporation of China, Tokyo Electric Power, and Uniper.

[16] In this example, we inverse the equation in order to estimate the activity data of an electricity supplier:

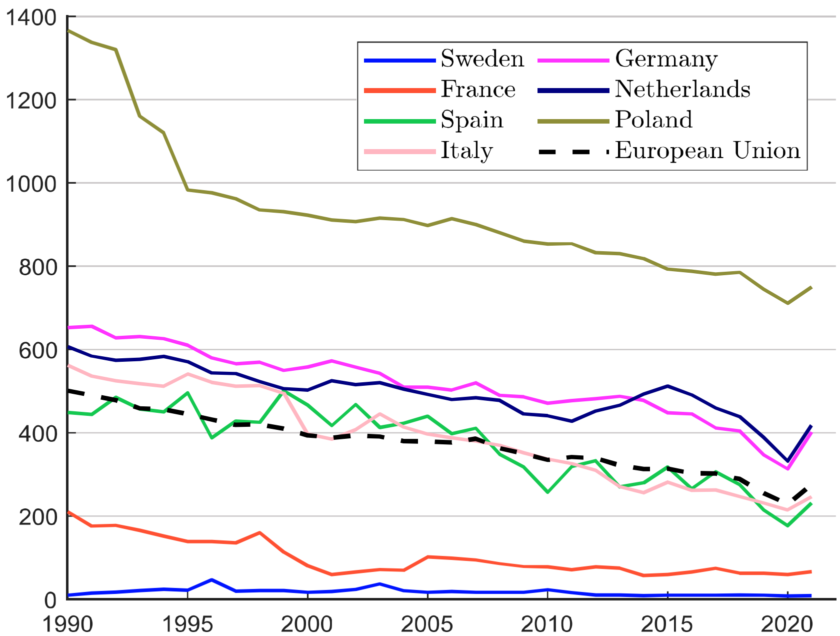
$$A = \frac{\mathcal{CE}}{\mathcal{EF}}$$

where $\mathcal{CE}$ is the scope 1 emissions of the utility company.

- 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.

Under the market-based method, an emission factor is associated to each electricity contract. To be relevant, contacts must meet some quality criteria and concern some specific instruments: energy attribute certificates [17] (*e.g.*, RECs, GOs), power purchase agreements with energy generators and green electricity products.

Figure 9.10: Emission factor in 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.

The location-based method depends on the emission factor of the regional, subnational or national grid. Its value highly depends on the energy mix and the grid infrastructure. For instance, we report the evolution of national emission factors of some European countries in Figure 9.10. We notice that they tend to decrease since thirty years and they differ from one country to another. On average, the emission factor is equal to 275 gCO_2e/kWh in the European Union in 2021. The two extreme countries are Sweden (9 gCO_2e/kWh) and Poland (750 gCO_2e/kWh). The reason is that most of Sweden's electricity supply comes from hydropower and nuclear, while Poland produces 83% of its electricity from fossil fuels (and 72% from coal). Emission factors for several region and countries in the world are given in Table 9.5. We notice the high heterogeneity of the figures. The continent with the lowest value is South America (204 gCO_2e/kWh) while Asia has the largest emission factor (539 gCO_2e/kWh). Two countries which are geographically close may have different

[17] REC (or renewable energy certificate) is an energy attribute certificate used in Australia, Canada, India and the US, while GO (guarantee of origin) is an energy attribute certificate used in Europe.

emission factors. This is the case of France and Germany (58 vs. 354 gCO_2e/kWh), Canada and the US (128 vs. 380 gCO_2e/kWh), etc.

Table 9.5: Emission factor in 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

Example 36 *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

If we consider a Tier 1 approach, we can estimate 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:

$$\begin{aligned}\mathcal{CE} &= A \cdot \mathcal{EF}_{World} \\ &= \left(2\,013{,}269 \times 10^3\right) \times 442 \\ &= 889\,864\,898\,000 \text{ gCO}_2\text{e} \\ &= 889.86 \text{ ktCO}_2\text{e}\end{aligned}$$

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 $\mathcal{CE} = 553.65$ $ktCO_2e$. The third approach uses a Tier 2 method by considering the emission factor of each country. In this case, we have to collect the data. We use figures in Table 9.5 and the following emission factors: Belgium (143); Ireland (402); Luxembourg (68) and Netherlands (331). It follows that:

$$\begin{aligned}\mathcal{CE} &= \sum_{s=1}^{12} A_s \cdot \mathcal{EF}_s \\ &= (125\,807 \times 143 + 1\,132\,261 \times 58 + \ldots + 124\,010 \times 270 + 37\,742 \times 442) \times \frac{10^3}{10^9} \\ &= 278.85 \text{ ktCO}_2\text{e}\end{aligned}$$

We notice that the estimated scope 2 emissions of this bank are sensitive to the chosen approach.

The market-based accounting approach requires to track the electricity of each supplier. For that, the company can use reliable tracking systems (North American REC, European Energy Certificate System GO, International REC standard, TIGR registry) and supplier-based contactual instruments. This Tier 1 approach is based on contract-specific emission factors. Nevertheless, when they are not available, the company can use supplier-based average and residual mix emission factors.

Example 37 *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[18], the market-based scope 2 emissions of this company are equal to:

$$\begin{aligned} \mathcal{CE} &= \frac{10^6 \times 60\% \times 1 + 10^6 \times 40\% \times 26}{10^6} \\ &= 11 \text{ ktCO}_2\text{e} \end{aligned}$$

The market-based approach may reduce the scope 2 emissions when the company purchases green electricity. For instance, the emission factors in France are the following: 6 for nuclear, 418 for natural gas, 730 for fuel oil and 1 058 for coal. In Table 9.6, we have reported the life cycle emission factors for several technologies. Even if these figures depend on many parameters (vintage, country, etc.) and the ranges are relatively wide, we clearly observe an ordering. Wind, nuclear, hydro and solar electricity generates less GHG emissions than gas, fuel oil and coal.

Table 9.6: Emission factor in $\mathrm{gCO_2e/KWh}$ from electricity supply technologies (IPCC, 2014a; UN-ECE, 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	CCUS	169	90-370	130	92–221
	Combined cycle	490	410–650	430	403–513
Fuel oil			510–1170		
Coal	CCUS	161	70–290	350	190–470
	PC	820	740–650	1 000	912–1095

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

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

Let us consider again the example of Enel (page 882). They obtained the following figures (expressed in $ktCO_2e$):

	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

The first category derives from the generation of electricity purchased and consumed by Enel (electricity consumption taken from the network for civil use or for energy generation in thermoelectric and hydroelectric plants). The second category includes indirect emissions due to dissipated energy emissions from technical losses from Enel's distribution network and from the transmission system. We notice that this second category represented 67% and 69% of scope 2 emissions. Curiously, the market-based figure is greater than the location-based approach: 7.11 vs. 4.30 $MtCO_2e$.

We consider the CDP database and compare the location-based and market-based values for the year 2020. Statistics are reported in Table 9.7. Less than 1% of issuers have declared zero scope 2 carbon emissions with the location-based approach. This figure becomes 8.78% when we consider the market-based approach. 70% of issuers have greater location-based emissions than market-based emissions. About 10% have the same value, meaning that these issuers have certainly used the mix residual approach to compute the scope 2 emissions with the market-based approach. The mean variation ratio[19] is equal to +26.59%. This result is explained by the frequency asymmetry, but also by the fact that the variation is higher for issuers that have greater location-based emissions than market-based emissions (+43.29% vs. −22.04%).

Table 9.7: 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 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. They are divided into fifteen categories of emissions: eight upstream categories and seven downstream categories (Table 9.8). We report below their description as it appears in GHG Protocol (2011, Table 5.4, pages 34-37):

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;

[19]The variation ratio is equal to $\dfrac{CE_{\mathrm{loc}} - CE_{\mathrm{mkt}}}{\max\left(CE_{\mathrm{loc}}, CE_{\mathrm{mkt}}\right)}$.

Table 9.8: The scope 3 carbon emissions categories

Upstream	Downstream
1. Purchased goods and services	1. Downstream transportation and distribution
2. Capital goods	2. Processing of sold products
3. Fuel and energy related activities	3. Use of sold products
4. Upstream transportation and distribution	4. End-of-life treatment of sold products
5. Waste generated in operations	5. Downstream leased assets
6. Business travel	6. Franchises
7. Employee commuting	7. Investments
8. Upstream leased assets	8. Other downstream
9. Other upstream	

3. Fuel- and energy-related activities (not included in scope 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;

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);

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;

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).

All these categories share the principle that there is no double counting of emissions between the scopes. For instance, the transport categories do not concern vehicles and facilities owned, controlled or operated by the company, because their GHG emissions are already reported in scope 1 and 2. This means that the transport of employees with a company's vehicle is reported in scope 1 and 2, but not in scope 3. On the contrary, the public transport of employees is reported in scope 3.

Table 9.9: 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

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.

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

The computation of scope 3 emissions requires specific emission factors. For example, Table 9.9 gives their values for business travel (category 6) and employee commuting (category 7) in the US. In the same document, we can find other scope 3 emissions factors (categories 4, 5, 9 and 12). Collecting data is not an easy task since there is no available comprehensive database at the global level. Nevertheless, we can find documented databases at the sector level. For instance, AGRIBALYSE provides references data on the environmental impacts of agricultural and food products through a database built according to the life cycle analysis (LCA) methodology[20]. Other databases can be found in the GHG Protocol website (`https://ghgprotocol.org/life-cycle-databases`). The

[20] The web site is `https://doc.agribalyse.fr`.

GHG protocol has also developed several calculation tools (cross-sector, country-specific, sector-specific and cities). With Quantis, they also provide scope 3 evaluator (S3E), which is a free web-based tool[21].

Since it may be sometimes difficult to manipulate physical units, the organizations have also developed monetary emission factors, which are expressed in $\text{kgCO}_2\text{e/k\$}$ or $\text{kgCO}_2\text{e/k€}$. Some figures are reported in Table 9.10. For example, a business air travel, whose cost is equal to \$1 000, induces a scope 3 emissions of 1 970 kgCO_2e according to the scope 3 evaluator tool.

Table 9.10: 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.

Ducoulombier (2021) highlights the importance of scope 3 emissions, but also the lack of data robustness. Since the reporting of these indirect emissions remains voluntary, we observe heterogenous data in the CDP database with scope 3 items that are partially or not calculated. In this context, most of ESG data providers estimate scope 3 upstream and downstream values using statistical model or environmentally-extended input-output (EEIO) framework[22]. This means that the reported scope 3 emissions are rarely used.

Remark 101 *In order to distinguish the different scopes, we use the following notations:* $\mathcal{SC}_1$ *for scope 1 emissions,* $\mathcal{SC}_2$ *for scope 2 emissions and* $\mathcal{SC}_3 = \mathcal{SC}_3^{\text{up}} + \mathcal{SC}_3^{\text{down}}$ *for scope 3 emissions, where* $\mathcal{SC}_3^{\text{up}}$ *and* $\mathcal{SC}_3^{\text{down}}$ *refer to upstream and downstream scope 3 emissions. The cumulative emissions are then denoted by* $\mathcal{SC}_{1-2} = \mathcal{SC}_1 + \mathcal{SC}_2$, $\mathcal{SC}_{1-3}^{\text{up}} = \mathcal{SC}_1 + \mathcal{SC}_2 + \mathcal{SC}_3^{\text{up}}$ *and* $\mathcal{SC}_{1-3} = \mathcal{SC}_1 + \mathcal{SC}_2 + \mathcal{SC}_3$.

9.1.4 Carbon emissions of investment portfolios

There are two main methods for measuring the carbon footprint of an investment portfolio. The first method if the financed emissions approach. In this case, the investor calculates the carbon emissions that are financed across both equity and debt. Generally, we use EVIC 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, 2019b). Let W be the wealth invested in the company, the financed emissions are equal to:

$$\mathcal{CE}(W) = \frac{W}{\text{EVIC}} \cdot \mathcal{CE}$$

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

$$\mathcal{CE}(W) = \sum_{i=1}^{n} \mathcal{CE}_i(W_i) = \sum_{i=1}^{n} \frac{W_i}{\text{EVIC}_i} \cdot \mathcal{CE}_i \tag{9.3}$$

[21]The tool is available at https://quantis-suite.com/Scope-3-Evaluator.
[22]This model is studied in Section 8.4 on page 807.

where EVIC_i and $\mathcal{CE}_i$ are the enterprise value and carbon emissions of company i. It follows that $\mathcal{CE}(W)$ is expressed in $\mathrm{tCO_2e}$.

A second method is to use the ownership approach (Le Guenedal and Roncalli, 2022). In this case, we break down the carbon emissions between the stockholders of the company. Equation (9.3) becomes:

$$\mathcal{CE}(W) = \sum_{i=1}^{n} \frac{W_i}{\mathrm{MV}_i} \cdot \mathcal{CE}_i = \sum_{i=1}^{n} \varpi_i \cdot \mathcal{CE}_i \tag{9.4}$$

where MV_i is the market value of company i and ϖ_i is the ownership ratio of the investor. 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:

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

and:

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

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

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

Since $\mathcal{CE}(W)$ is a linear function of W, the carbon footprint of the portfolio is generally computed with $W = \$1$ mn and is expressed in $\mathrm{tCO_2e}$ (per \$ mn invested).

Remark 102 *The second 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.*

Example 38 *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)			Debt	$\mathcal{FP}$	$\mathcal{SC}_{1-2}$
	31/12/2021	31/12/2022	31/01/2023	(in \$ bn)	(in %)	(in $\mathrm{ktCO_2e}$)
A	12.886	10.356	10.625	1.112	99.8	756.144
B	7.005	6.735	6.823	0.000	39.3	23.112
C	3.271	3.287	3.474	0.458	96.7	454.460

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

$$\mathrm{EVIC}_A = \frac{10\,356}{0.998} + 1\,112 = \$11\,489 \text{ mn}$$

We deduce that the financed emissions are equal to:

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

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:

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

Finally, we obtain the following results[23]:

	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

9.1.5 Statistics

In what follows, we use the analysis done by Barahhou *et al.* (2022). We consider the Trucost dataset of carbon emissions as of 01/06/2022 and analyze the distribution of carbon emissions in 2019 for around 15 000 companies. We prefer to use the year 2019 instead of the year 2020, because the covid-19 crisis had a significant impact on the carbon footprint. In Figure 9.11, we have reported the scope 1 and 2 carbon emissions per GICS sector. We notice that including scope 2 has a limited impact, except for some low-carbon sectors such as Consumer Services, Information Technology and Real Estate. In Table 9.11, we have calculated the breakdown of carbon emissions. Scope 1 and 2 emissions represent 17.6 GtCO_2e, and the most important sector contributors are Utilities (34.4%), Materials (31.4%), Energy (14.0%) and Industrials (10.0%). This means that these 4 strategic sectors explain about 90% of scope 1 and 2 carbon emissions.

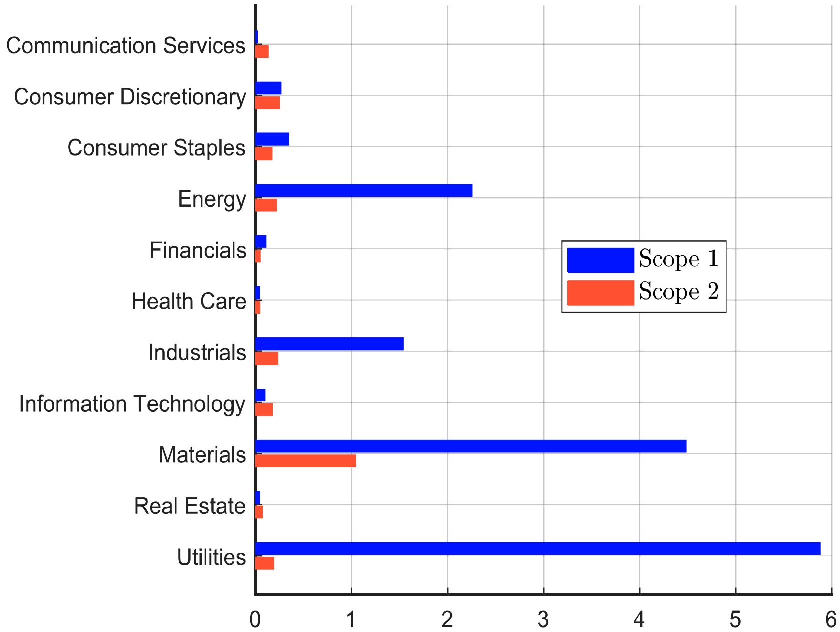
Table 9.11: Breakdown (in %) of carbon emissions in 2019

Sector	$\mathcal{SC}_1$	$\mathcal{SC}_2$	$\mathcal{SC}_{1-2}$	$\mathcal{SC}_3^{\text{up}}$	$\mathcal{SC}_3^{\text{down}}$	$\mathcal{SC}_3$	$\mathcal{SC}_{1-3}$
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 GtCO_2e)	15.1	2.6	17.6	10.3	53.7	64.0	81.6

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

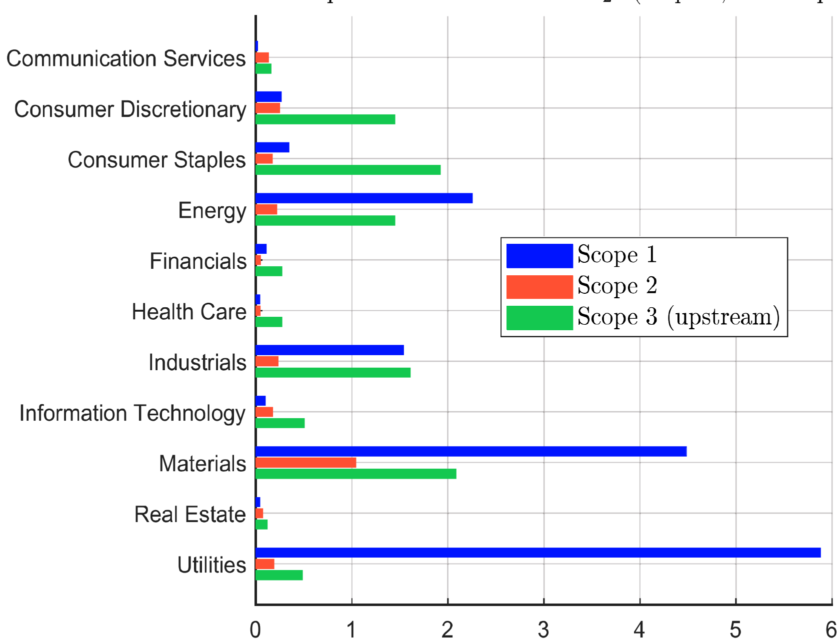
[23] For the financed emissions, we use the data as of 31 December 2022 while the ownership ratio is based on the current data (as of 31 January 2023). In this example, the data as of 31 December 2021 are never used.

Figure 9.11: 2019 carbon emissions per GICS sector in $GtCO_2e$ (scope 1 & 2)



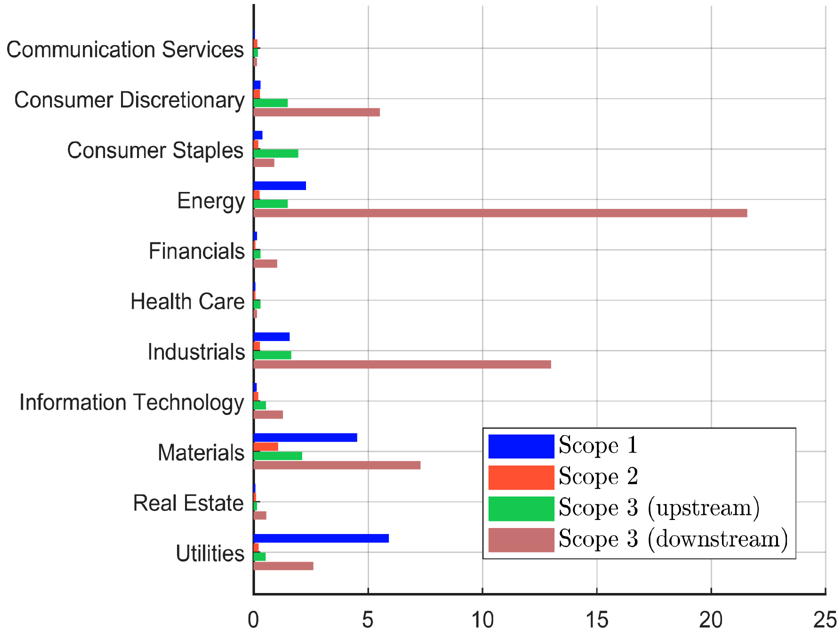
Source: Trucost (2022) & Barahhou *et al.* (2022).

Figure 9.12: 2019 carbon emissions per GICS sector in $GtCO_2e$ (scope 1, 2 & 3 upstream)



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

Figure 9.13: 2019 carbon emissions per GICS sector in $GtCO_2e$ (scope 1, 2 & 3)



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

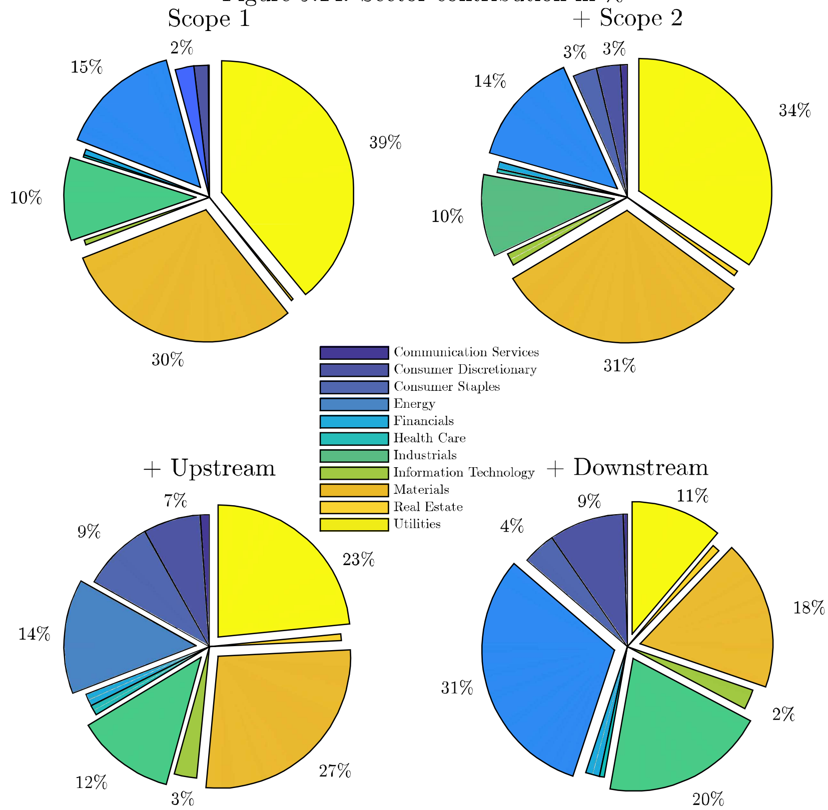
In Figure 9.12, we observe that some sectors are highly impacted by the upstream scope 3 emissions. For instance, the ratio $\dfrac{\mathcal{SC}_3^{\text{up}}}{\mathcal{SC}_{1-2}}$ is greater than 2.5 for Consumer Discretionary, Consumer Staples and Health Care, and is close to 2 for Information Technology. Among the strategic sectors, Energy and Industrials are the most penalized whereas the upstream scope 3 emissions of Utilities is relatively small compared to its scope 1 emissions.

While the impact of the upstream scope 3 is significant, the impact of the downstream scope 3 is huge as demonstrated in Figure 9.13. Four sectors have very large downstream carbon emissions: Consumer Discretionary, Energy, Industrials and Materials. While Utilities has the most important contribution in terms of scope 1 and 2 since it represents 34.4% of carbon emissions, its contribution to scope 3 is relatively modest and is equal to 4.8%. Including or not scope 3, in particular the downstream carbon emissions, changes the whole picture of the breakdown between the sectors. Figure 9.14 is a visualisation of the sector contribution by considering the addition of several scopes. At each step, the contribution of Materials and Utilities decreases whereas it increases for Consumer Discretionary, Energy, Industrials and Information Technology. Among the most significant sectors[24], the behavior of Consumer Staples is singular since its contribution increases when adding scope 2 and upstream scope 3, but decreases when considering downstream scope 3.

Remark 103 *When considering scope 3 emissions, double counting is a real issue. According to Table 9.11, the total carbon emissions is* 17.6 $GtCO_2e$ *for scope* $1+2$*, and* 81.6 $GtCO_2e$ *for scope* $1+2+3$*, while we estimate that the world emits about* 36 $GtCO_2e$ *per year.*

[24]They correspond to sectors that have a contribution greater than 2%.

Figure 9.14: Sector contribution in %



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

In Figure 9.15, we draw the histogram of carbon emissions and indicate the 5% and 95% percentile values. We need to use a logarithmic scale, because the range is between some tonnes of CO_2e to several dozen tonnes of CO_2e. This graph shows that it is difficult to compute the carbon footprint of a portfolio based on carbon emissions, because this metric is not homogeneous to the company size. This is why the carbon intensity metric is preferred in financial markets.

9.1.6 Negative emissions, avoided emissions, and carbon offsetting

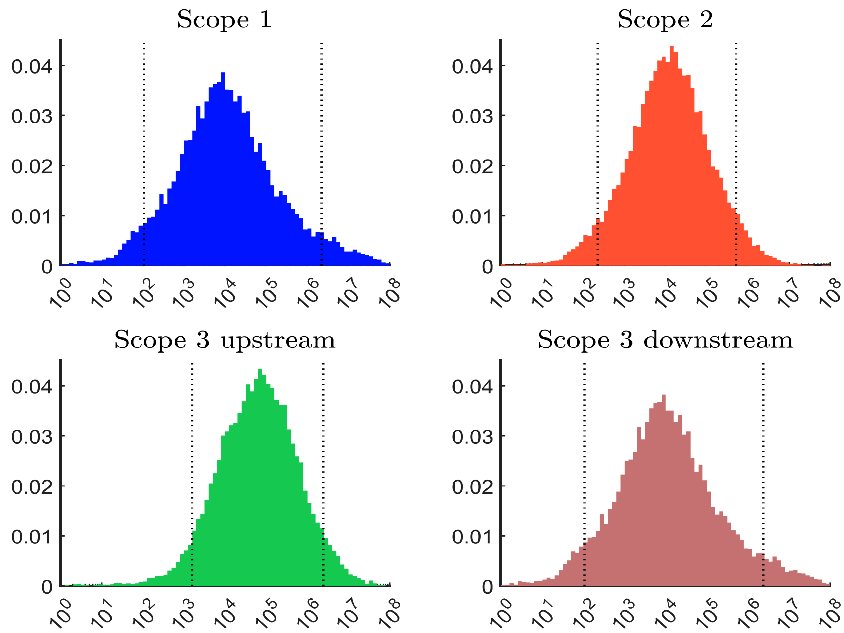
Negative emissions, also known as carbon dioxide removal or CDR, is the process of removing CO_2 from the atmosphere. There are two main categories of negative emissions:

1. Natural climate solutions
   Examples include forest restoration and afforestation[25], reducing soil disturbance[26], etc.

[25] 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.

[26] This 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.

Figure 9.15: Histogram of 2019 carbon emissions (logarithmic scale, tCO_2e)



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

2. Negative emission technologies
   Examples are direct air capture with carbon storage[27] (DACCS), bioenergy with carbon capture and storage[28] (BECCS), enhanced weathering[29], ocean fertilization[30], etc.

Tanzer and Ramírez (2019) gives a more formal definition of negative emissions by considering four minimum criteria for determining whether a technology induces negative emissions:

> "*[...] (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)

In a series of three review papers, Jan Minx and his co-authors provided a comprehensive overview of negative emissions (Minx *et al.*, 2018; Fuss *et al.*, 2018; Nemet *et al.*, 2018). They emphasized

[27] This technology uses special filters to capture CO_2 directly from the air, while the captured CO_2 is then stored underground or used in other applications.

[28] This process involves capturing and storing the CO_2 emissions from burning biomass, such as wood or grasses.

[29] This process 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.

[30] This technology involves adding nutrients to the ocean, which can stimulate the growth of phytoplankton in the ocean, which then absorbs CO_2 through photosynthesis.

that the efficiency, capacity, and cost of different technologies vary widely. A typical example is direct air capture technology[31]. The rationale for the technology is presented in the book published by National Academies of Sciences, Engineering, and Medicine (2019). There are two general types of DAC processes: DAC with liquid solvents (L-DAC) and DAC with solid sorbents (S-DAC). In an L-DAC process, there are four stages: absorption, regeneration, purification and separation. Each phase involves a chemical reaction:

$$\begin{aligned} 2\,\mathrm{KOH} + \mathrm{CO_2} &\longrightarrow \mathrm{H_2O} + \mathrm{K_2CO_3} \\ \mathrm{CaO} + \mathrm{H_2O} &\longrightarrow \mathrm{Ca\,(OH)_2} \\ \mathrm{K_2CO_3} + \mathrm{Ca\,(OH)_2} &\longrightarrow 2\,\mathrm{KOH} + \mathrm{CaCO_3} \\ \mathrm{CaCO_3} &\longrightarrow \mathrm{CaO} + \mathrm{CO_2} \end{aligned}$$

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. 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, which is high compared to the price of carbon traded on CO_2 markets. Another factor in assessing the relevance of DAC technologies is the measurement of carbon efficiency, which depends on the amount and carbon intensity of electricity used to remove atmospheric CO_2. Today, the carbon efficiency of the best DAC plans is less than 70%. This is, of course, the current situation and many improvements are expected in the coming years. For instance, IEA (2022) estimated that DAC costs could fall below \$100/tCO_2 by 2030.

Box 9.4: 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.

A related concept to negative emissions is avoided emissions, often incorrectly referred to as Scope 4 emissions. According to Russell (2023), "*comparative impacts are estimated as 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*":

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

Avoided emissions can be positive ($\mathcal{AE} \geq 0$) or negative ($\mathcal{AE} < 0$). For example, an electric car emits CO_2, especially when we consider the life cycle of the batteries, but electric cars do not emit

[31] DAC and DACCS are two interchangeable terms because carbon storage is implicit in all carbon dioxide capture, use, and storage (CCUS) technologies.

greenhouse gases from burning gasoline. In this example, the reference product is the gasoline-powered car and the assessed product is the electric car, and we expect the avoided emissions to be positive. However, there are two issues in calculating avoided emissions. First, which car should we choose to represent the gasoline car or the reference product? Second, what is the use of the electric car? In fact, the avoided emissions depend on many factors, such as the carbon intensity of the electricity, recycling assumptions, etc.

In addition to negative emissions and avoided emissions, carbon offsetting includes a third concept: carbon credits. Carbon credits are transferable financial instruments that represent one tonne of carbon dioxide or another greenhouse gas. They are traded on carbon markets where companies, governments and individuals can buy and sell credits to meet their emission reduction targets. The price of carbon credits can vary depending on supply and demand, as well as the type of project and the region in which it is located. There are two main types of carbon credit systems:

- 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.

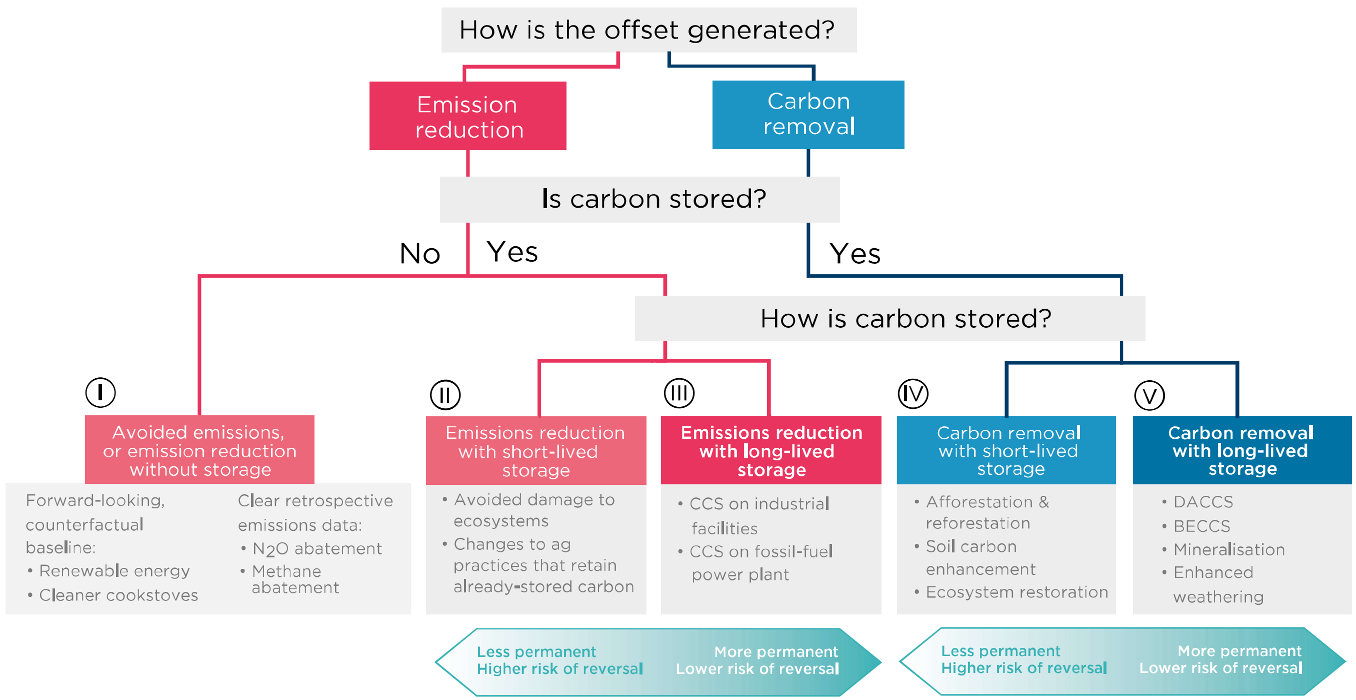
- Voluntary carbon markets
  These markets are not regulated by the government, and companies can voluntarily buy carbon credits to offset their emissions. Voluntary carbon markets are often used to offset emissions from activities not covered by cap-and-trade systems. In this case, the avoided emissions 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.

We can now give a precise definition of carbon offsetting. Carbon offsetting is when a company offsets its own carbon emissions by providing emission reductions outside of its own operations. This means that the company purchases a verified carbon credit in a voluntary carbon market that funds a negative emission project. Carbon offsetting does not involve avoided emissions because they concerns the company's own operations and are associated with a change in the company's business strategy. Carbon offsets also do not include carbon credits purchased in a cap-and-trade system because these carbon credits do not necessarily result in negative emissions. Because carbon offsetting involves reducing a company's carbon footprint, it is commonly associated with the race to net-zero emissions. However, we need to make a clear distinction between the two concepts. It is now accepted that some activities will continue to emit GHGs in 2050 due to a lack of carbon-free alternatives, even in the most stringent net-zero scenario. In such situations, carbon offsets must be used primarily by companies exposed to these hard-to-abate sectors, such as cement or airlines. In Figure 9.16 we reproduce the taxonomy of carbon offsets proposed by Allen *et al.* (2020). Based on our definition, only categories IV and V fall under the strict definition of carbon offsetting.

Allen *et al.* (2020) proposed a framework for assessing the relevance of carbon offsets to ensure that they contribute to a net-zero economy. The Oxford principles for net-zero aligned carbon offsetting are:

1. Cut emissions, use high quality offsets, and regularly revise offsetting strategy as best practice evolves
   Companies' first priority is to reduce their own emissions, not to purchase carbon offsets. If they do, they need to buy offsets that ensure environmental integrity, high standards and certification in line with accounting practices. The largest GHG offset programs are the Verified

Figure 9.16: Taxonomy of carbon offsets

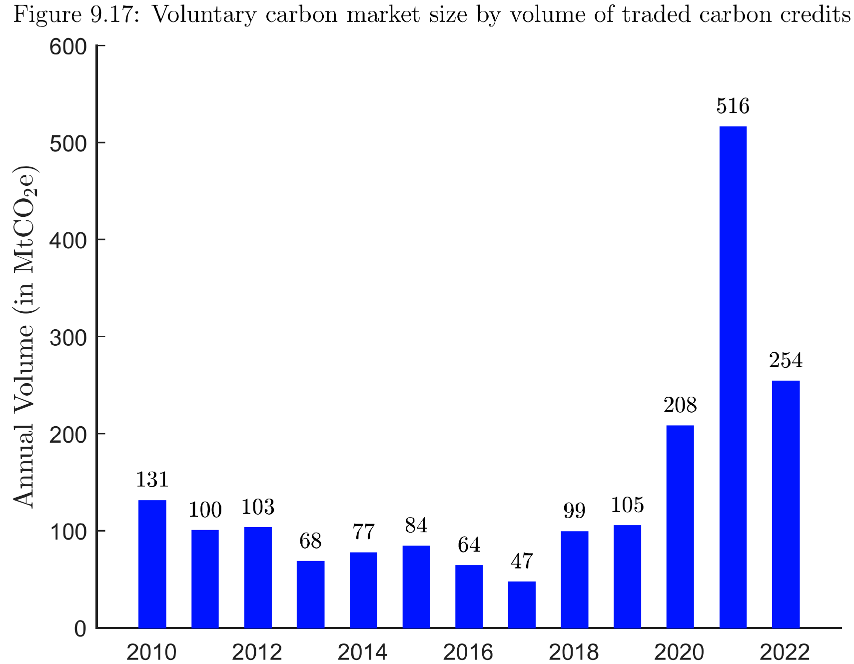


Source: Allen *et al.* (2020, Figure 1, page 7).

Carbon Standard (VCS) and the Gold Standard (GS). The status of projects that meet these standards can be tracked through official registries whose goal is to certify the ownership of each negative emissions project. Specifically, ownership is transferred to the buyer of the carbon credits and then canceled when the credits are sold. The purpose of registries is to ensure that negative emissions are not counted twice.

2. Shift to carbon removal offsetting
There is clearly an imbalance between the supply of certified negative emissions projects and the projects needed to achieve net zero in the long term. Creating demand for carbon removal offsets today will send the necessary market signal to increase supply. Figure 9.17 shows the size of the voluntary carbon market (VCM). It has been multiplied by two after 2019. According to Ecosystem Marketplace (2023b), the cumulative volume has reached 2.3 $GtCO_2e$ with a value of $10 billion. This implies an average price of $4.35 per tonne of CO_2. From 2021, the average price is more likely to be between $7 and $8 per tonne of CO_2. The market is largely dominated by renewable energy projects and forestry & land use. Since 2020, projects on household & community devices have also been promoted. Although developing, the voluntary carbon market remains relatively small and immature, with many intermediaries and few end users[32]. For example, the energy sector is the main buyer of voluntary carbon credits, accounting for more than 50% of the market. However, the market is expected to reach between $10 billion and $40 billion by 2030, up from a record $2.1 billion in 2021 (BCG, 2023a).

Figure 9.17: Voluntary carbon market size by volume of traded carbon credits



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

[32] In fact, it is concentrated in a few companies. According to Ecosystem Marketplace (2023a), the top 10 buyers in 2021 were Delta Air Lines, TotalEnergies, Shell, Volkswagen, Takeda Pharmaceuticals, Comcast, Diamondback Energy, La Poste, Telstra and Eni.

3. Shift to long-lived storage
The issue of CO_2 storage and sequestration is an important one. As noted by Allen *et al.* (2020), "*short-lived storage involves methods that have a higher risk of being reversed over decades. Long-lived storage refers to methods of storing carbon that have a low risk of reversal over centuries to millennia, such as storing CO2 in geological reservoirs or mineralising carbon into stable forms. Short-lived storage offsets help buy time to reduce emissions and invest in long-lived storage, but they are not a long-term solution for achieving balance between sinks and sources.*" Measuring the efficiency of a technology is not straightforward and is highly dependent on the lifetime of the project (Terlouw *et al.*, 2021) and the system boundary. Figure 9.18 shows an example taken from Tanzer and Ramírez (2019). Chiquier *et al.* (2022) proposed to evaluate the efficiency of carbon dioxide removal by considering the amount of CO_2 stored (or removed) and the amount of CO_2 leaked (or emitted) over the supply chain:

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

The metric $\eta(t)$ depends on the lifetime t expressed in years. In general, it is a decreasing function of time t, which means that the efficiency is maximum at the beginning of the project. In the case of an afforestation/reforestation project implemented in 2020 in the UK, Chiquier *et al.* (2022) estimates $\eta(10) = 87.1\%$, $\eta(30) = 98.8\%$, $\eta(100) = 98.9\%$, and $\eta(1000) = 61.9\%$. Here, the CDR efficiency increases in the beginning because the forest establishment emits CO_2 and the trees are young. Then the trees grow and the efficiency is close to 100% between 30 and 100 years. In the long term, the efficiency decreases due to the risk of forest fires. A summary of key features for each CDR pathway is provided in Table 9.12.

Table 9.12: Summary of key features for each CDR pathway

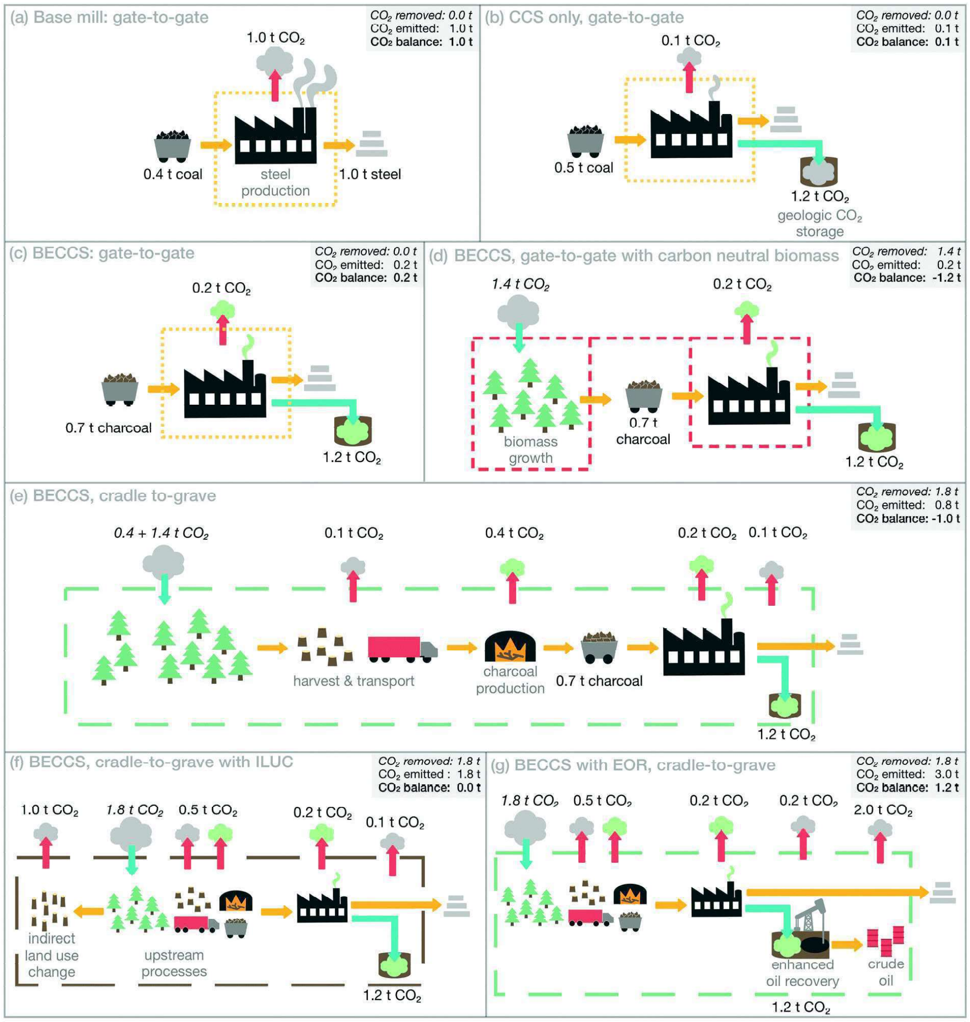
CDR	$\eta(100)$	$\eta(1000)$	Timing	Permanence
Afforestation	63 to 99%	31 to 95%	Decades	Very low
Reforestation	63 to 99%	31 to 95%	Decades	Very low
BECCS	52 to 87%	78 to 87%	Immediate to decades	High/very high
Biochar	20 to 39%	−3 to 5%	Immediate	Low/very low
DACCS	−5 to 90%	−5 to 90%	Immediate	Very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

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

4. Support the development of net-zero aligned offsetting
The fourth principle is to promote carbon offsetting. To develop this market, companies can enter into long-term agreements, form sector-specific alliances, support the restoration and protection of natural and semi-natural ecosystems, and incorporate these principles into regulation.

Carbon accounting for negative emission technologies is still an open question (Brander *et al.*, 2021; Kaplan *et al.*, 2023). It is closely related to the issue of certification and credibility of CDR projects. Accounting for carbon offsets also challenges the economic incentives of these projects from the perspective of buyers of carbon credits. Microsoft's experience described in *Nature* is an interesting testimony from an end user and provides some insights to improve the ecosystem of negative emission technologies and carbon offsetting (Joppa *et al.*, 2021).

Figure 9.18: Perceived CO_2 emissions of a simplified steel production system when viewed from different system boundaries



The dashed line in each sub-figure represents the system boundaries used to estimate the total CO_2 emissions in the upper right corner of each figure. The system design and numbers used are greatly simplified for illustrative purposes. (a-c) show the gate-to-gate CO_2 emissions of a steel mill, considering only the CO_2 produced at the mill itself for normal production (a), with the use of carbon capture and storage (b), and with the use of bioenergy with carbon capture and storage (c). (d) extends the system boundaries to include photosynthetic uptake of the exact amount of CO_2 released by combustion, assuming the charcoal is carbon neutral. (e) is a simplified cradle-to-grave system that includes in its boundaries the CO_2 absorbed by the wood that is lost in the charcoal production process, the CO_2 emissions from biomass harvesting and transportation, the CO_2 emissions from charcoal production, and the CO_2 emissions from CO_2 storage. (f) is a variant where biomass production has significant indirect land use change emissions. (g) is a variant where geological storage of CO_2 results in the production and combustion of fossil fuels whose CO_2 emissions exceed the CO_2 stored.

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

9.2 Carbon intensity

While carbon emissions measure the carbon footprint in an absolute value, the carbon intensity is a relative metric of the carbon footprint. The underlying idea is to normalize the carbon emissions by a size or activity unit. For instance, we can measure the carbon footprint of countries by tCO_2e per capita, watching television by CO_2e emissions per viewer-hour, washing machines by $kgCO_2e$ per wash, cars by $kgCO_2e$ per kilometer driven, companies by $ktCO_2e$ per \$1 mn revenue, etc. We distinguish two types of carbon intensity: carbon intensities whose activity units are physical and carbon intensities whose activity units are monetary.

9.2.1 Physical intensity ratios

The product carbon footprint (PCF) measures the relative carbon emissions of a product throughout its life cycle. This approach, which is called life cycle assessment (LCA), distinguishes two methods:

- 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;
- In contrast, cradle-to-grave covers the entire life cycle of a product, including the use-phase and recycling.

Below, we report some examples of product carbon footprint computed by ADEME.

Table 9.13: Examples of product carbon footprint (in $kgCO_2e$ 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).

The previous analysis can be extended to corporate carbon footprint (CCF). For instance, we can measure the CCF of a cement manufacturer by the amount of GHG emissions per tonne of cement. In the airline sector, the main traffic metric is the revenue passenger kilometers (RPK), which is calculated by multiplying the number of paying passengers by the distance traveled. Therefore, the CCF of airlines can be measured by the amount of GHG emissions per RPK (Table 9.14).

Table 9.14: Physical carbon intensity per production unit

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

9.2.2 Monetary intensity ratios

From a financial point of view, it does not make sense to compare and aggregate the carbon emissions of a large cap company with the carbon emissions of a small cap company. Carbon intensity is then a more relevant metric. ESG analysts can then compare companies that belong to the same activity sector by using physical intensity ratios. For example, they can compare all the cement manufacturers, because they can normalize the carbon emissions by the volume of cement production. In a similar way, they can compare all the airline companies, because they can normalize the carbon emissions by the RPK metric. Nevertheless, the physical intensity ratios are not relevant when we consider a portfolio that is invested in several sectors. How to compare a cement-based carbon intensity with a RPK-based carbon intensity? How to aggregate the two metrics? Until now, nobody has the answer.

Therefore, portfolio managers will 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. For instance, we can use revenues, sales, etc. to normalize carbon emissions:

- Revenue:
$$\mathcal{CI}^{\text{Revenue}} = \frac{\mathcal{CE}}{\text{Revenue}}$$
- Sales:
$$\mathcal{CI}^{\text{Sales}} = \frac{\mathcal{CE}}{\text{Sales}}$$
- Enterprise value including cash:
$$\mathcal{CI}^{\text{EVIC}} = \frac{\mathcal{CE}}{\text{EVIC}}$$
- Market value:
$$\mathcal{CI}^{\text{MV}} = \frac{\mathcal{CE}}{\text{MV}}$$

Even the previous carbon emission metrics based on EVIC and market value can be viewed as carbon intensity metrics.

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. We notice that the carbon intensity satisfies the additivity property. In a similar way, we obtain:

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

Let us now consider the revenue-based carbon intensity (also called the economic carbon intensity). We denote by Y_i the revenue of issuer i. The carbon intensity of the portfolio becomes:

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

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

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

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

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

We deduce that:

$$\begin{aligned}
\mathcal{CI}^{\mathrm{Revenue}}(w) &= \frac{\sum_{i=1}^{n}\frac{w_i}{\mathrm{MV}_i}\cdot\mathcal{CE}_i}{\sum_{i=1}^{n}\frac{w_i}{\mathrm{MV}_i}\cdot Y_i} \\
&= \sum_{i=1}^{n} w_i\cdot\omega_i\cdot\mathcal{CI}_i^{\mathrm{Revenue}}
\end{aligned}$$

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:

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

Except when all the companies have the same revenue per market value ratio, we deduce that the revenue-based carbon intensity does not satisfy the additivity property since we have $\mathcal{CI}^{\text{Revenue}}(w) \neq \sum_{i=1}^{n} w_i \cdot \mathcal{CI}_i^{\text{Revenue}}$. In order to avoid this problem, we generally use the weighted average carbon intensity (WACI) of the portfolio:

$$\mathcal{CI}^{\text{Revenue}}(w) = \sum_{i=1}^{n} w_i \cdot \mathcal{CI}_i^{\text{Revenue}} \tag{9.5}$$

This method is the standard approach in portfolio management.

Remark 104 *Carbon intensity is additive when we consider a given issuer:*

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

Example 39 *We assume that* $\mathcal{CE}_1 = 5 \times 10^6$ CO_2e, $Y_1 = \$0.2 \times 10^6$, $\text{MV}_1 = \$10 \times 10^6$, $\mathcal{CE}_2 = 50 \times 10^6$ CO_2e, $Y_2 = \$4 \times 10^6$ *and* $\text{MV}_2 = \$10 \times 10^6$. *We invest* $W = \$10$ *mn.*

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 $\mathcal{CI}_2 = 12.5$ $\text{tCO}_2\text{e/\$ mn}$. Since we have:

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

We obtain the following results:

w_1	w_2	$\mathcal{CE}(w)$ ($\times 10^6$ 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. Let us assume that we buy the two companies, implying that $W = \$20$ mn, $w_1 = 50\%$ and $w_2 = 50\%$. In this case, we obtain $\mathcal{CE}(w) = 55 \times 10^6$ and $Y(w) = \$4 \times 10^6$. The economic carbon intensity is then equal to $55/4 = 13.10$ while the WACI is 18.75.

Remark 105 *For sovereign issuers, the economic carbon intensity is measured in mega-tonnes of* CO_2e *per million dollars of GDP while the physical carbon intensity unit is* tCO_2e *per capita.*