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Carbon Footprint for Dynamically Rebalanced Portfolios

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With the recent Paris Agreement in 2015 (see UN Treaties-XXVII [2015]), global consciousness of climate change risk has reached the status of a legally binding framework for countries to limit the "increase in the global average temperature to 2°C above preindustrial level, and to pursue effort to limit such increase to 1.5°C." The Agreement's objective is a long-term global effort in the management of a public super-national good (the climate) and will have significant impacts on governments, policymakers, households and consumers, corporations, and investors. For investors specifically, climate change represents a threefold challenge: duty, risk, and opportunity.

First, as per their role in societies, investors are asked to redirect significant investments (directly, with equity investments, and indirectly, via financing governments and companies through bonds) to meet the objectives of the Paris Agreement and other national or regional regulations already in place.

Second, climate change represents a nontrivial risk, from the increasing likelihood of natural disasters to the impact on long-term economic growth. Indeed, climate change has a clear impact on nations' economic health, which in turn is transmitted to financial markets through the standard channels (resources and commodity prices, long-term debt, political risks, and expectations). Understanding and managing these risks will be key for investors. For this, a large stream of literature has already pointed out how the extraordinary and unprecedented economic growth of the last 60 years is not sustainable in a Hicksian sense (see Hicks [1946], Rees [1992], and Dewan [2006] for further details). As a matter of fact, the new policies needed to tackle climate change could have a significant impact on global economic paths. With a closer focus on the energy sector, in particular oil and other fossil resources, there is a significant risk that part of the actual reserves cannot be burnt if we want to keep the trajectory of global temperature in line with the Paris Agreement. The Carbon Tracker Initiative [2011] reported that if the top 100 listed companies in the coal and oil and gas sectors were to burn their reserves over the next 40 years, we would deviate significantly from the 2°C trajectory. Stevens [2016] also recorded similar conclusions. For companies in this business, however, market prices and valuations strongly reflect current reserves. If these reserves cannot be burnt, the financial impact will be huge and likely disruptive, causing systemic risk for all financial players (on this topic, see also the speech by Bank of England's Governor Carney [2015]).

Third, this new framework is expected to initiate and reinforce tectonic shifts in capital allocation toward renewable energy production, sustainable industrial processes, and efficient allocation of resources. The probable outcome will be, on the one hand, the emergence of new industries and corporations that will take advantage of new policies and environmental constraints, while, on the other hand, noncompetitive industries could be negatively affected. Opportunities will arise, and investors should integrate this dimension to detect new trends and allocate their investments accordingly.

To face these challenges, investors need a precise measurement on the risk they face and their contributions to the objectives of a low-carbon economy. Among the class of ecological footprint measurements (see Wackernagel and Rees [1998]), carbon footprint (CF) is a powerful tool that enables governments, households, and corporations to measure their contribution to global warming as well as the efficiency of policies deployed to limit it. CF is universally admitted to stand for the total amount of greenhouse gas (GHG) emissions with potential global warming impact (i.e., it is usually measured in mass units [tons of CO_2 or equivalent] rather than being area based [the amount of land necessary to absorb the emissions]). Notwithstanding the popularity CF enjoys in the media, political debates, and academia, there has been significant work to converge toward a standardized definition of what a CF should be and how corporations, households, and governments should calculate it. It is out of the scope of this article to reproduce a complete review of the literature on this, so we refer to the ISO Guidelines (ISO/TS 14067:2013 [2013]), the Global Reporting Initiative, Wiedmann and Minx [2008], Singh et al. [2009], Herva et al. [2011], and Čuček, Klemeš, and Kravanja [2012] for further details.

This article does not focus on a specific measure of carbon emission. Our contribution is instead a unified framework for investors with dynamic allocations through which they can measure the impact of their investments on global warming and monitor the transition to a low-carbon economy. With respect to this approach, we use a generic collection of carbon measures, each of which captures a specific side of a complete CF. Indeed, as pointed out by Galli et al. [2012], no single indicator is able to give a representative indication of the real impact; a better picture can be drawn from a collection of indicators. Our framework is therefore flexible to the choice of measures each investor finds adapted to her investments.

Although we advocate for institutionalization and standardization of CFs, we believe that the optimal choice of measure should depend on the type of investment. For example, as shareholders, equity investors can have an active role in the way corporations manage their climate-change risk and the transition to a low-carbon economy. On the other side, fixed-income investors have very little impact on corporate management, but they can have a significant impact if they favor climate-change-related projects (impact investing). As such, the same indicator may not work for both categories of investors. Within our framework, investors will select a family of carbon measures as their inputs, according to their preferences and needs, and produce a global set of CFs, each giving a representative and synthetic view of the portfolio's carbon risk.

Although not restrictive, this article takes the point of view of an equity fund, but the same ideas can be adapted to fixed-income funds. We define the absolute and relative (intensity) contributions that are attributable to the fund by taking into account both dynamic changes in the fund's compositions (rebalancings) and inflow/outflows. The framework is well adapted to carbon footprinting for exchange-traded funds and other index funds, especially those that change their composition regularly (among others, trackers of alternative beta and factor-based strategies). We also derive CF attribution that, in line with the standard performance attribution, should allow investors (and fund managers) to understand the main drivers of their CF. The application of our framework is shown using two practical examples.

DATA

Let F_t be the value (assets under management) of a fund invested in equities whose weights within the portfolio, at time t, are denoted by w_t^F. We assume that B_t is a reference index to which the fund is benchmarked, and the fund solely consists of stock from the reference index. Stocks' weights in the reference index are denoted by w_t^B. We shall assume that the reference index weights are proportional to their total equities' market capitalizations adjusted by their free floats, the standard for market indexes like the Stoxx Europe 600 Index or the S&P 500 Index. B_t represents the total market value of the benchmark at time t, and it is driven by market fluctuations; F_t moves according to market fluctuations and, from

EXHIBIT 1
Measures of GHG Emissions

Variable	GHG	Description
CB^1	Scope 1	GHG emissions generated from burning fossil fuels and production processes that are owned or controlled by the company
CB^2	Scope 2	GHG emissions from consumption of purchased electricity, heat, or steam by the company
CB^3	Scope 3	Other indirect GHG emissions, both upstream and downstream, excluded by Scope 2
CB^4	Direct + First Tier Indirect	GHG Scope 1 + Scope 2 emissions plus the GHG emissions of direct suppliers

Note: All are expressed in thousands of tons of CO_2-equivalent.
Sources: TruCost, GHG Protocol.

time to time, jumps following inflows/outflows activity from investors. By definition, then, $w_{t,i}^B = 0 \Rightarrow w_{t,i}^F = 0$ for all stock (indexed by i). Although not necessary, this assumption simplifies the analysis.

For each stock in the reference index, we denote by CB the vector of different carbon-related measures:

$$CB_{i,y} = (CB_{i,y}^1, CB_{i,y}^2, \ldots, CB_{i,y}^j)$$

where i indexes all the stocks in the reference index, y denotes the year the measurer refers to, and j denotes all specific measures at disposal (e.g., GHG emissions, energy production and their sources, reserves). We denote by $R_{i,y}$ the revenue of company i for year y. Stocks' revenues are expressed in millions of the reference index currency.

Exhibit 1 describes some of the most used measures of GHG emissions. With any of these measures, investors can easily obtain the standard CFs. For practical purposes, we shall follow a variant of the definition given by Wiedmann and Minx [2008], specifically adapted to corporations: The CF is a measure of the exclusive total amount of GHG emissions that is directly and indirectly upstream caused by the business activity of the corporation.

With respect to the definition by Wiedmann and Minx [2008], we include all greenhouse gases, as defined by the Kyoto Protocol, rather than carbon dioxide (CO_2) alone. Other gases are adjusted by a global warming coefficient, and all are measured in thousands of tons of CO_2-equivalent ($ktCO_2e$). Furthermore, we attribute to each corporation the total amount of emissions directly attributable to its activities (Scope 1), its energy purchases (Scope 2), and other GHG emissions from its direct suppliers (upstream Scope 3). We believe that the addition of Scope 3 emissions is necessary to have a comprehensive view of the total carbon impact, although we are aware that this measure is often difficult to obtain (see, e.g., Huang, Weber, and Matthews [2009] and Downie and Stubbs [2013]). However, we do not include Scope 3 downstream emissions because they are usually not easily manageable by corporate management. On the other side, corporate management can take actions to limit carbon emissions and pressure their suppliers to do so as well. Exhibit 2 collects the variables we use for energy producers in the reference index and GHG emissions associated with energy production from fossil sources.

EXHIBIT 2
Measures of Energy Production from Different Sources

Renewable		Fossil	
Variable	**Source**	**Variable**	**Source**
CB^5	Biomass	CB^{11}, $CB^{11,e}$	Coal
CB^6	Geothermal	CB^{12}, $CB^{12,e}$	Liquefied Natural Gas
CB^7	Hydroelectric	CB^{13}, $CB^{13,e}$	Liquefied Petroleum Gas
CB^8	Solar	CB^{14}, $CB^{14,e}$	Natural Gas
CB^9	Wave and Tidal	CB^{15}, $CB^{15,e}$	Nuclear
CB^{10}	Wind	CB^{16}, $CB^{16,e}$	Petroleum

Notes: The measures of production are expressed in GWh. For fossil sources, we also have the measure of emissions linked to production, denoted by $CB^{11,e}$, ..., $CB^{16,e}$ expressed in $ktCO_2e$.
Sources: TruCost, GHG Protocol.

Finally, Exhibit 3 collects the variables we use to measure fossil reserves, both 1P (i.e., proven reserves that can be extracted profitably with a 90% probability) and

EXHIBIT 3
Measures of Energy Reserves

Variable	Source	Breakdown	Description
CB^{17}	Coal	Metallurgical	GHG emissions if the company's metallurgical coal (typically for steel production),
CB^{18}	Coal	Other	thermal coal (typically for power and heat generation), and other coal (all other
CB^{19}	Coal	Thermal	industrial utilization in the chemical, pharmaceutical industries, and refineries) reserves were burnt.
CB^{20}	Gas	Natural	GHG emissions if the company's natural gas (extracted with conventional methods,
CB^{21}	Gas	Shale	typically as a by-product of oil extraction) and shale gas (extracted from rocks using nonconventional methods, such as fracking) reserves were burnt.
CB^{22}	Oil	Conventional	GHG emissions if the company's conventional (i.e., using standard extraction
CB^{23}	Oil	Unconventional	processes) or unconventional oil reserves (using nonstandard processes, such as tar sand or bitumen) were burnt.

Notes: Metallurgical coal and oil are expressed in millions of barrels (MMbbl); other and thermal coal in ktCO$_2$e; and gases in billions of cubic feet equivalent (bcf). The related GHG emissions are instead given in ktCO$_2$e.
Sources: TruCost, GHG Protocol.

2P (i.e., probable reserves with at least 50% probability of being present), broken down according to their sources and the associated GHG emissions. Carbon measures are usually disclosed in the companies' yearly statements, with some delay. The same is true for revenues, although partial quarterly data may be available early. Therefore, $CB_{i,y}$ is usually known with some delay during the course of year $y + 1$.

Because the portfolio's weights may change over time as a result of regular rebalancing and its market value can be affected by inflows/outflows, fair accounting of carbon emissions related to the fund would require daily data. This can be achieved by equally spreading yearly measures on each trading day: $CB_{t,i}^{j,daily} = CB_{y,i}^{j}/n(y)$,where *Jan* 1st $\leq t \leq$ *Dec* 31 of year y and $n(y)$ is the number of trading days in the year. In what follows, we drop the daily notation as we consider daily data.

Absolute and Relative Contributions

Assume that on trading day t, the daily-adjusted carbon measure for company i is $CB_{t,i}^{1}$. We recall that following the definition given in Exhibit 1, this measure corresponds to Scope 1 GHG emissions in ktCO$_2$e. We define the proportion of these daily emissions attributable to fund F as the fund's daily contribution $DC_t^F(CB^1)$. This can be calculated on an ownership-ratio basis: If $\theta_{t,i}^{B}$ is the total number of free-floating shares available in the market and $\theta_{t,i}^{F}$ is the number of shares held by the fund, then

$$DC_t^F(CB^1) = \sum_{i=1}^{N} \frac{\theta_{t,i}^F}{\theta_{t,i}^B} CB_{t,i}^1 = \frac{F_t}{B_t} \sum_{i=1}^{N} \frac{w_{t,i}^F}{w_{t,i}^B} CB_{t,i}^1$$

where the second equality comes from the definition of the weight and N is the number of securities in the reference index. It should be noticed that, within this framework, we attribute all emissions linked to stocks to their shareholders only. First, it could be argued that debtholders should also be entitled to a proportion of the carbon emissions. An alternative could be to calculate the ownership ratio relative to companies' assets rather than equities only. Second, it is widely accepted that, when it comes to carbon accounting, the shared responsibility among producers and customers should prevail (on this, see, for example, Lenzen et al. [2007]). In particular, it could be argued that, at least for special sectors (e.g., utilities with public-related business or electricity producers), part of the emissions should not be accounted to the shareholders only.

For the first point, it is possible in theory to use both debt and equity to build fair CFs. However, this would require more data on the capital structure for each stock in the reference index. For the second point, although we agree in principle, we prefer to use the simple method and then attribute all emissions to the shareholders because, for this point to be addressed, one would require subjective assumptions that, in turn, would give subjective CFs. In any case, investors usually monitor their CFs over time to measure the impact of their investments, and they benchmark their actions to the market portfolio. Because we can reasonably think in relative terms, we believe that the simple accounting method is appropriate.

Now let X be one of the 23 carbon measures CB^j detailed in Exhibits 1 to 3 or the revenue measure R. We define the absolute contribution A of the fund F relative to the measure X over the period $[T_1, T_2]$ as the sum of daily values of X attributable to the fund:

$$A^F(T_1, T_2, X) := \sum_{t=T_1}^{T_2} DC_t^F(X) = \sum_{t=T_1}^{T_2} \frac{F_t}{B_t} \sum_{i=1}^{N} \frac{w_{t,i}^F}{w_{t,i}^B} X_{t,i} \quad (1)$$

Throughout the rest of the article, we will drop the time dependence of A when doing so is not misleading and write $A^F(X)$ as the absolute contribution of the fund for the measure X.

The relative contribution or intensity $I^F(X)$ of the fund for the measure X is defined as the ratio between the absolute contribution for the measure X and the absolute contribution for the measure $X = Revenue$:

$$I^F(X) := \frac{\sum_{t=T_1}^{T_2} \frac{F_t}{B_t} \sum_{i=1}^{N} \frac{w_{t,i}^F}{w_{t,i}^B} X_{t,i}}{\sum_{t=T_1}^{T_2} \frac{F_t}{B_t} \sum_{i=1}^{N} \frac{w_{t,i}^F}{w_{t,i}^B} R_{t,i}} \quad (2)$$

or in vector form

$$I^F(X) := \frac{A^F(X)}{A^F(R)} \quad (3)$$

For GHG emission measures (CB^j, $j = 1, \ldots, 6$), intensity I provides the amount of emissions for one million revenue.

Remark. When we look at the intensity on a given trading day ($t = T_1 = T_2$) from Equation (2), we have

$$I^F(X) := \frac{\sum_{i=1}^{N} \frac{w_{t,i}^F}{w_{t,i}^B} X_{t,i}}{\sum_{i=1}^{N} \frac{w_{t,i}^F}{w_{t,i}^B} X_{t,i}} = \sum_{i=1}^{N} \lambda_{t,i} \frac{X_{t,i}}{R_{t,i}}$$

$$\text{where } \lambda_{t,i} = \frac{\frac{w_{t,i}^F}{w_{t,i}^B} R_{t,i}}{\sum_{i=1}^{N} \frac{w_{t,i}^F}{w_{t,i}^B} R_{t,i}}$$

We remark that X/R is the stock's intensity measure, and $\lambda_{t,i}$ is the fraction of fund's revenue attributable to stock i. In other words, the instantaneous fund's intensity is given by the weighted average of its stocks' intensities, where the weights are given by the fraction of the fund's revenue attributable to each stock. We highlight that weighted averages of stocks' intensities, where the weights are those in the fund as opposed to the revenues, will give a biased measure of the fund's intensity.

Carbon Attributions

As in a standard Brinson-like performance attribution (see Brinson and Fachler [1985] and Brinson, Hood, and Beebower [1986]), we propose a simple framework in which the difference in absolute (resp. intensity) measures A (resp. I) between the fund and the benchmark can be broken down into user-given categories. For this, let us assume that all stocks in the universe can be classified according to a given categorical scheme S, as, for example, industrial sectors or countries. We can also consider the case of dynamic categorical schemes, meaning that a stock can belong to different categories at different times. Typical examples are the categorical schemes based on companies' size, valuation, volatility, or any other dynamic measure. To simplify the notation, we will assume that the categorical scheme S is indeed static, although the method applies for dynamic schemes too. For the sake of simplicity, we denote each category as a sector. The goal of the attribution is to study the difference between the fund's CF and that of the reference index through the prism of allocation and selection effect within each sector. In what follows, we denote $|S|$ as the number of sectors in the scheme S, and the notation $i \in S_k$ means that stock i belongs to the sector S_k.

The natural benchmark. Let X be one of the carbon measures introduced in Exhibits 1 to 3, and assume that, over a given period, the fund has significantly outperformed the benchmark. The fund could then have a higher measure $A^F(X)$ simply because its market value is higher than the benchmark. More generally, we recognize that the difference in financial performance between the fund and the benchmark could imply higher measures $A^F(X)$. In line with our fair accounting approach, we propose a specific benchmark that neutralizes differences between the fund and the reference index market values (i.e., financial performance differences). For this, we introduce a family of theoretical funds, denoted by $(BF)_h$, $T_1 \leq h \leq T_2$, such that at time t the t^{th} fund of the family has the same market value as the fund F: $(BF_t)_t = F_t$, and $w_{t,i}^{BF} = w_{t,i}^{B}$. Basically, the t^{th} fund of the family BF invests, on day t, the amount F_t according to the weights in the reference index at time t. We call BF the *natural benchmark* of F. The use of the natural benchmark allows us to neutralize the differences in CFs arising from differences in the performance of the fund with respect to the benchmark.

Absolute measures. From Equation (1), we can write

$$A^F(X) = \sum_{t=T_1}^{T_2} \frac{F_t}{B_t} \sum_{k=1}^{|S|} \sum_{i \in S_k} \frac{w_{t,i}^F}{w_{t,i}^B} X_{t,i}$$

If $W_t^{S_k,F} := \Sigma_{i \in S_k} w_{t,i}^F$ is the weight of the sector S_k in the fund and $w_{t,i}^F / W_t^{S_k,F}$ is the relative weight of each stock within its own sector, then

$$A^F(X) = \sum_{t=T_1}^{T_2} \sum_{k=1}^{|S|} W_t^{S_k,F} \left(\frac{F_t}{B_t} \sum_{i \in S_k} \frac{w_{t,i}^F}{W_t^{S_k,F}} \frac{1}{w_{t,i}^B} X_{t,i} \right)$$

If we denote by $F_{k,t}$ a family of funds that, at each time t, all have the same market value of F_t ($(F_{k,t})_t = F_t$) but have only invested in stocks of sector S_k with the same weighting scheme (basically by taking initial weights w^F and scaling it to sum to 1), then from Equation (1) we can write

$$\frac{F_t}{B_t} \sum_{i \in S_k} \frac{w_{t,i}^F}{W_t^{S_k,F}} \frac{1}{w_{t,i}^B} X_{t,i} = A^{F_{k,t}}(t,t,X)$$

so that finally

$$A^F(X) = \sum_{t=T_1}^{T_2} \sum_{k=1}^{|S|} W_t^{S_k,F} A^{F_{k,t}}(t,t,X) \tag{4}$$

Equation (4) simply states that the absolute contribution of the fund for the measure X is the sum of the instantaneous weighted average of the sectors' contributions. The same holds true for the natural benchmark BF:

$$A^{BF}(X) = \sum_{t=T_1}^{T_2} \sum_{k=1}^{|S|} W_t^{S_k,BF} A^{BF_{k,t}}(t,t,X)$$

The excess contribution $E(X)$ of the fund over its natural benchmark is then

$$E(X) := A^F(X) - A^{BF}(X) \tag{5}$$

For example, if $X = CB^1$, then $E(X) > 0$ means that the Scope 1 GHG emissions attributable to the fund are higher than the emissions attributable to its natural benchmark. Because

$$E(X) := \sum_{t=T_1}^{T_2} E_t(X) \tag{6}$$

where

$$E_t(X) := \sum_{k=1}^{|S|} W_t^{S_k,F} A^{BF_{k,t}}(t,t,X) - \sum_{k=1}^{|S|} W_t^{S_k,BF} A^{BF_{k,t}}(t,t,X) \tag{7}$$

we can concentrate on $E_t(X)$ and then add up all daily excess contributions to obtain the total excess contribution. As for the standard Brinson performance attribution, Equation (8) decomposes the daily excess contribution into three separate effects. The allocation effect measures the ability of the strategy to underweight (overweight) sectors with higher (lower) absolute contributions than the natural benchmark. Unlike the standard Brinson performance attribution, here we focus on negative contributions rather than positive. The selection effect measures the ability of the strategy to select, among each sector, companies that make the final absolute contribution lower than the benchmark. The interaction effect measures the ability of the strategy to underweight (overweight) the sectors with higher (lower) absolute contributions than the sectors in the natural benchmark.

$$\begin{aligned} E_t(X) = & \underbrace{\sum_{k=1}^{|S|} (W_t^{S_k,F} - W_t^{S_k,BF})(A^{BF_{k,t}}(t,t,X) - A^{BF}(t,t,X))}_{\text{Allocation Effect}} \\ & + \underbrace{\sum_{k=1}^{|S|} W_t^{S_k,BF} (A^{F_{k,t}}(t,t,X) - A^{BF_{k,t}}(t,t,X))}_{\text{Selection Effect}} \\ & + \underbrace{\sum_{k=1}^{|S|} (W_t^{S_k,F} - W_t^{S_k,BF})(A^{F_{k,t}}(t,t,X) - A^{BF_{k,t}}(t,t,X))}_{\text{Interation Effect}} \end{aligned} \tag{8}$$

Equation (8) highlights the importance of the choice of the natural benchmark in the carbon attribution: Because $(F_{k,t})_t = F_t$ and $BF_t = F_t$, the instantaneous allocation, selection, and interaction effects will not depend on the potential differences between the market values of the fund and the reference index. Without such adjustment, these effects would have been biased by the difference in market value, making the instantaneous portfolio's carbon attribution positive (negative) if its market value were lower (higher), all other things being equal.

Intensity measures. The decomposition for intensity measures is slightly different. From Equation (3), we have

$$\begin{aligned} EI(X) &:= \frac{A^F(X)}{A^F(R)} - \frac{A^{BF}(X)}{A^{BF}(R)} \\ &= \frac{A^{BF}(R)(A^F(X) - A^{BF}(X))}{A^F(R)A^{BF}(R)} \\ &\quad + A^{BF}(X)\frac{(A^{BF}(R) - A^F(R))}{A^F(R)A^{BF}(R)} \end{aligned}$$

and from Equations (5) and (6)

$$EI(X) := \frac{1}{A^F(R)}(E(X) - I^{BF}(X)E(R)) = \frac{1}{A^F(R)}\sum_{t=T_1}^{T_2} EI_t(X) \tag{9}$$

where $EI_t(X) := E_t(X) - I^{BF}(X)E_t(R)$. For example, if $X = CB^1$, then $EI(X) > 0$ means that the Scope 1 GHG emissions intensity of the fund is higher than the emissions intensity of the natural benchmark. In other words, the fund is less carbon efficient because it is accountable for more GHG emissions per million of revenue than its natural benchmark. We see that large differences in terms of the absolute contributions between the fund and the natural benchmark $E(X) > 0$ tend to increase intensity differences, all other things being equal. On the other side, large differences in the absolute revenue $E(R)$ tend to decrease intensity differences, all other things being equal. In particular, $EI(X) = 0$ implies $E(X) = I^{BF}(X)E(R) = 0$; thus, for the fund to have the same intensity as the natural benchmark, the excess absolute contribution must grow linearly with the excess in revenue, the constant being given by the benchmark intensity. Equation (10) breaks down the instantaneous excess intensity. The allocation and selection terms have the same interpretation as for the absolute measure attribution, but this time, we have to consider both the effect of the carbon measure X and the revenue R. It should be noted that the revenue effects (allocation and selection) have negative effects on the intensity, meaning that their increases tend to lower the total excess intensity, which in turn translates into lower carbon intensity for the fund compared to the benchmark.

$$\begin{aligned} &EI_t(X) \\ &= \underbrace{\sum_{k=1}^{|S|}(W_t^{S_k,F} - W_t^{S_k,BF})(A^{BF_{k,t}}(t,t,X) - A^{BF}(t,t,X))}_{X-\text{Allocation Effect}} \\ &\quad \underbrace{- I^{BF}(X)\sum_{k=1}^{|S|}(W_t^{S_k,F} - W_t^{S_k,BF})(A^{BF_{k,t}}(t,t,R) - A^{BF}(t,t,R))}_{R-\text{Allocation Effect}} \\ &\quad \underbrace{+ \sum_{k=1}^{|S|} W_t^{S_k,BF}(A^{F_{k,t}}(t,t,X) - A^{BF_{k,t}}(t,t,X))}_{X-\text{Selection Effect}} \\ &\quad \underbrace{- I^{BF}(X)\sum_{k=1}^{|S|} W_t^{S_k,BF}(A^{F_{k,t}}(t,t,R) - A^{BF_{k,t}}(t,t,R))}_{R-\text{Selection Effect}} \\ &\quad \underbrace{+ \sum_{k=1}^{|S|}(W_t^{S_k,F} - W_t^{S_k,BF})(A^{F_{k,t}}(t,t,X) - A^{BF_{k,t}}(t,t,X))}_{X-\text{Interaction Effect}} \\ &\quad \underbrace{- I^{BF}(X)\sum_{k=1}^{|S|}(W_t^{S_k,F} - W_t^{S_k,BF})(A^{F_{k,t}}(t,t,R) - A^{BF_{k,t}}(t,t,R))}_{R-\text{Interaction Effect}} \end{aligned} \tag{10}$$

APPLICATIONS

In this section, we propose two simple applications of the carbon analysis developed in the previous sections. For both applications, the reference index is the Stoxx Europe 600 Index. The period of study goes from December 30, 2005, to December 30, 2016. Carbon measures are taken from Exhibit 1, and we also introduce the following:

Energy production from fossil sources $:= \sum_{i=11}^{16} CB^i$ in GWh

GHG emissions from fossil sources

$:= \sum_{i=11}^{16} CB^{i,e}$ in $ktCO_2e$

Green energy production

$:= \sum_{i=5}^{10} CB^{i}$ in GWh

The Size Effect

We consider two portfolios invested in the largest and the smallest tiers of the investment universe. More precisely, at each rebalancing date (the third Friday of March, June, September, and December) the first portfolio invests in the top-tier stocks of the reference index. We denote this portfolio as Large. Similarly, the Small portfolio will invest in the small-tier stocks of the reference index. Stocks are weighted as in the reference index (scaled up so that they add to 1). Outside of rebalancing dates, stocks that are removed from the reference index are also removed from the two portfolios, and their weights are distributed over the other stocks on a pro rata basis. Portfolios are calculated in euros. Finally, dividends are reinvested in the index according to the Stoxx methodology. We assume that two investors are buying and holding these two portfolios for 1,000,000 EUR at inception (December, 30, 2005).

Exhibit 4 gives an overview of the carbon performance of the hypothetical investments in the Large and Small portfolios compared to their natural benchmarks. It should be noted that, because the Large and Small portfolios do not have the same financial return over the period, it follows that their natural benchmarks are different. The GHG direct plus first-tier indirect emissions associated with the Large portfolio are 0.76 $ktCO_2e$ lower than those of its natural benchmark. However, the revenue associated with the natural benchmark is higher (18.08 million EUR versus 16.21 million EUR) so that all intensity measures for the natural benchmark and the Large portfolio are very similar. Finally, this portfolio accounts for almost 10 $ktCO_2e$ more GHG emissions from reserves than the natural benchmark (55.78 $ktCO_2e$ vs. 45.75 $ktCO_2e$).

The Small portfolio instead is responsible for significantly higher GHG direct plus first-tier indirect emissions (15.91 $ktCO_2e$ vs. 9.31 $ktCO_2e$ for its natural benchmark). Although emissions are higher, its intensities are very similar to the natural benchmark, given the higher proportion of revenue associated with this portfolio. It is interesting to note that the GHG emissions from reserves are almost 10 times lower than the natural benchmark because these reserves are often associated with oil and gas companies that, usually, rank among the biggest capitalizations of the reference index.

EXHIBIT 4

Carbon Measures Associated with the Large and Small Portfolios and Their Natural Benchmark

	Natural Benchmark	Large Portfolio	Natural Benchmark	Small Portfolio
GHG direct plus first-tier indirect	8.46	7.70	9.31	15.91
GHG Scope 1	5.50	4.99	6.04	10.63
GHG Scope 2	0.79	0.71	0.88	1.30
GHG Scope 3	4.83	4.42	5.32	8.58
Energy production from fossil sources	0.82	0.49	0.98	1.72
GHG emissions from fossil sources	0.39	0.30	0.46	0.53
Green energy production	0.23	0.17	0.27	0.43
Revenue	18.08	16.21	20.07	33.54
GHG emission from reserves	45.75	55.78	53.48	6.64
Intensity Scope 1	0.30	0.31	0.30	0.32
Intensity Scope 2	0.04	0.04	0.04	0.04
Intensity Scope 3	0.27	0.27	0.27	0.26
Intensity direct plus first-tier indirect	0.47	0.48	0.46	0.47

Notes: GHG emissions are measured in $ktCO_2e$, revenues in millions of EUR, and intensities in $ktCO_2e/mEUR$.

Sources: DataStream, Stoxx, TruCost.

Exhibits 5 and 6 show the carbon attributions of the Large and Small portfolios with respect to their natural benchmarks when we consider the GHG direct plus first-tier indirect emissions. The first four columns (allocation, selection, interaction, and total) contain the different components given in Equations (7) and (8). The other columns show the values given in Equation (4): the average sector weights, the cumulated GHG emission of each sector, and their product (contribution), for both the portfolios and their natural benchmarks.

For the Large portfolio, we see that the difference in GHG emissions (−0.76 $ktCO_2e$) is largely explained by a good selection effect (−0.59 $ktCO_2e$) and allocation effect (−0.19 $ktCO_2e$). In more detail, the Large portfolio has a good selection effect in the basic material and consumer services sectors, signaling that large

EXHIBIT 5
GHG Emission Attributions for the Large Portfolio over Its Natural Benchmark

Sector	Allocation	Selection	Interaction	Total	Avg. Weight, Large	GHG Sector Emissions	Contrib.	Avg. Weight, Natural Bench.	GHG Sector Emissions	Contrib.
Total	–0.19	–0.59	0.01	–0.76		7.70			8.46	
Basic Materials	–0.01	–0.27	0.00	–0.28	8.14%	17.83	1.43	8.22%	21.12	1.71
Cons. Goods	–0.05	–0.17	–0.01	–0.22	16.31%	3.50	0.54	15.26%	4.73	0.68
Cons. Discretionary	0.04	–0.27	0.05	–0.17	5.75%	1.83	0.10	7.16%	5.57	0.40
Financials	–0.05	–0.09	0.00	–0.14	24.52%	0.25	0.06	23.98%	0.65	0.14
Health Care	–0.09	–0.01	0.00	–0.09	11.55%	0.37	0.04	10.46%	0.43	0.04
Industrials	–0.09	0.22	–0.05	0.08	9.33%	14.18	1.29	11.86%	12.36	1.42
Oil & Gas	0.09	0.07	0.00	0.16	9.54%	21.15	1.97	8.74%	20.40	1.74
Technology	0.02	–0.01	0.00	0.01	3.13%	0.52	0.02	3.38%	0.69	0.02
Telecom	–0.05	0.00	0.00	–0.05	6.36%	0.74	0.05	5.71%	0.74	0.04
Utilities	0.00	–0.08	0.01	–0.07	5.33%	43.11	2.20	5.24%	45.04	2.25

EXHIBIT 6
GHG Emission Attributions for the Small Portfolio over Its Natural Benchmark

Sector	Allocation	Selection	Interaction	Total	Avg. Weight, Small	GHG Sector Emissions	Contrib.	Avg. Weight, Natural Bench.	GHG Sector Emissions	Contrib.
Total	–0.69	9.37	–2.09	6.60		15.91			9.31	
Basic Materials	–0.15	2.55	–0.35	2.04	6.96%	53.3	3.81	8.22%	23.21	1.88
Cons. Goods	0.26	1.99	–0.57	1.68	9.86%	19.28	1.94	15.26%	5.15	0.75
Cons. Discretionary	–0.24	0.61	0.67	1.04	14.92%	14.75	2.19	7.16%	6.12	0.44
Financials	–0.09	0.33	0.06	0.29	25.53%	2.16	0.58	23.98%	0.72	0.16
Health Care	0.40	0.07	–0.03	0.44	5.83%	1.13	0.06	10.46%	0.47	0.05
Industrials	0.49	0.06	0.33	0.88	22.38%	14.68	3.43	11.86%	13.43	1.56
Oil & Gas	–0.38	0.37	–0.22	–0.23	5.43%	26.19	1.38	8.74%	22.59	1.91
Technology	–0.11	0.02	0.00	–0.08	4.58%	1.28	0.06	3.38%	0.75	0.03
Telecom	0.29	0.03	–0.02	0.3	2.37%	1.31	0.03	5.71%	0.82	0.05
Utilities	–1.15	3.34	–1.95	0.24	2.11%	126.5	2.43	5.24%	50.28	2.49

companies in these sectors tend to have lower GHG emissions compared to the natural benchmark. On the other side, the portfolio has a bad selection effect in the industrial sector, which is consistent with the fact that such large industries may have larger GHG emissions.

For the Small portfolio (Exhibit 4), we know that the difference in GHG emissions is positive (6.6 $ktCO_2e$), and it is mainly explained by negative selection effect (9.30 $ktCO_2e$) with a marginal good interaction effect (−2.09 $ktCO_2e$) and allocation effect (−0.69 $ktCO_2e$), as is shown in Exhibit 6. This is due to the poor selection effect in the basic materials, consumer goods, and utilities sectors, which in turn proves that small companies in these sectors tend to have larger GHG emissions. The GHG emission contribution of the industrial sector in particular is quite high (3.43 $ktCO_2e$) compared to the equivalent in the natural benchmark (1.56 $ktCO_2e$), although the absolute emissions of the sector in the portfolio and the natural benchmark are similar (14.68 $ktCO_2e$ versus 13.43 $ktCO_2e$). This translates into a negative allocation effect with a very small selection effect. In other words, industrials may have larger GHG emissions than the benchmark, but the Small portfolio amplifies this fact because industrial stocks usually have smaller capitalizations than stocks in other sectors, meaning that the portfolio is finally overweighted on this sector. It is noticeable that the utilities sector is by far the biggest absolute GHG contributor, for both the Large (43.11 ktCO_2e for 5.33% average weight) and Small (126.50 ktCO_2e for 2.11% average weight) portfolios. Indeed, the other sectors in the Small portfolio have higher GHG emissions than Large, even if—except for basic materials—the differences are less pronounced.

From this simple example, we can conclude that, across sectors, a company's size has a direct impact on total GHG emissions. In other words, smaller companies tend to have higher GHG emissions than their larger counterparts, although this is not uniform within sectors. Finally, we note that the single-sector emissions in the natural benchmark for the Large and Small portfolios (GHG emissions columns in Exhibits 5 and 6) are not the same. This is because the portfolios do not have the same financial performance.

Eurozone versus Rest of Europe

Our second example considers two portfolios invested, respectively, in all stocks in the Eurozone and in the rest of Europe (Switzerland, the United Kingdom, Sweden, Norway, Denmark, Iceland, and the Czech Republic) from the reference index (Stoxx Europe 600 Index). Portfolios are rebalanced quarterly (the third Friday of March, June, September, and December), and stocks are weighted as in the reference index (with a scaling factor so that final weights sum to 1). We denote these portfolios as Euro and Ex-Euro. Portfolios are calculated in euros, and their maintenance is the same as before. Again, we assume that 1,000,000 EUR is invested at the inception of both portfolios.

From Exhibit 7, we see that the Euro portfolio is characterized by higher GHG emissions, especially Scope 1 emissions, which in turn translates into higher direct plus first-tier indirect emissions. Companies in the Eurozone tend to be higher GHG emitters than the natural benchmark, but their emissions are linked to their industrial processes rather than upstream or downstream GHG emissions. Indeed, they have almost double the energy production from fossil sources and relatively double the GHG emissions from fossil sources compared with the natural benchmark. They also have higher green energy production. Finally, the revenues associated with the Eurozone companies are higher than the natural benchmark, but this is not enough to compensate for higher GHG emissions, leading then to higher intensities: for the direct plus first-tier indirect, the Euro portfolio produces 0.5 ktCO_2e per 1 million EUR of revenue, and this number is 0.47 ktCO_2e for the natural benchmark.

The Ex-Euro portfolio is instead characterized by lower GHG emissions than its natural benchmark (Exhibit 7). These companies are usually responsible for a lower level of energy production and emissions from fossil sources, but also lower levels of renewable green energy production. The share of revenue associated with Ex-Euro is also lower than its natural benchmark (14.58 million EUR versus 19.86 million EUR). Overall, its intensity is lower than the natural benchmark (0.41 ktCO_2e compared to 0.46 ktCO_2e for its natural benchmark).

Exhibit 7

Carbon Measures Associated with the Euro and Ex-Euro Portfolios and Their Natural Benchmark

	Natural Benchmark	Euro Portfolio	Natural Benchmark	Ex-Euro Portfolio
GHG direct plus first-tier indirect	8.13	11.13	9.16	6.02
GHG Scope 1	5.29	7.88	5.93	3.23
GHG Scope 2	0.76	0.88	0.87	0.74
GHG Scope 3	4.62	5.66	5.26	4.17
Energy production from fossil sources	0.75	1.46	0.97	0.16
GHG emissions from fossil sources	0.35	0.67	0.46	0.10
Green energy production	0.21	0.40	0.27	0.05
Revenue	17.18	22.21	19.86	14.58
GHG emission from reserves	41.46	14.41	53.80	84.15
Intensity Scope 1	0.31	0.35	0.30	0.22
Intensity Scope 2	0.04	0.04	0.04	0.05
Intensity Scope 3	0.27	0.26	0.26	0.29
Intensity direct plus first-tier indirect	0.47	0.50	0.46	0.41

Notes: GHG emissions are measured in ktCO_2e; revenues in millions of EUR; and intensities in ktCO_2e/mEUR.

Sources: DataStream, Stoxx, TruCost.

Exhibit 8

GHG Emission Attributions for the Euro Portfolio over Its Natural Benchmark

Sector	Allocation	Selection	Interaction	Total	Avg. Weight, Euro	GHG Sector Emissions	Contrib.	Avg. Weight, Natural Bench.	GHG Sector Emissions	Contrib.
Total	0.97	1.89	0.14	3.00		11.13			8.13	
Basic Materials	0.07	0.39	0.00	0.46	8.81%	25.09	2.14	8.22%	20.27	1.64
Cons. Goods	0.02	0.18	–0.01	0.19	14.57%	5.92	0.79	15.26%	4.61	0.66
Cons. Discretionary	0.02	0.09	–0.01	0.1	6.69%	6.52	0.43	7.16%	5.34	0.38
Financials	–0.10	0.07	0.00	–0.03	25.18%	0.93	0.21	23.98%	0.60	0.14
Health Care	0.43	0.02	–0.01	0.44	4.75%	0.63	0.03	10.46%	0.41	0.04
Industrials	0.08	0.19	0.03	0.30	14.00%	13.65	1.85	11.86%	11.98	1.37
Oil & Gas	–0.19	0.44	–0.09	0.15	6.95%	24.72	1.70	8.74%	19.77	1.70
Technology	–0.13	0.00	0.00	–0.13	5.13%	0.73	0.04	3.38%	0.66	0.02
Telecom	–0.03	0.01	0.00	–0.02	6.10%	0.88	0.05	5.71%	0.70	0.04
Utilities	0.82	0.49	0.22	1.53	7.79%	53.35	3.89	5.24%	42.46	2.15

Exhibit 9

GHG Emission Attributions for the Ex-Euro Portfolio over Its Natural Benchmark

Sector	Allocation	Selection	Interaction	Total	Avg. Weight, Ex-Euro	GHG Sector Emissions	Contrib.	Avg. Weight, Natural Bench.	GHG Sector Emissions	Contrib.
Total	–1.02	–2.60	0.49	–3.14		6.02			9.16	
Basic Materials	–0.08	–0.42	0.01	–0.49	7.75%	17.69	1.33	8.22%	22.90	1.86
Cons. Goods	–0.02	–0.17	–0.01	–0.20	15.97%	3.86	0.60	15.26%	5.02	0.73
Cons. Discretionary	–0.02	–0.08	0.00	–0.10	7.62%	4.91	0.37	7.16%	6.03	0.43
Financials	0.11	–0.08	0.00	0.03	22.71%	0.35	0.08	23.98%	0.72	0.16
Health Care	–0.45	–0.01	0.00	–0.46	15.69%	0.40	0.06	10.46%	0.46	0.05
Industrials	–0.08	–0.29	0.05	–0.32	9.89%	10.67	1.04	11.86%	13.19	1.53
Oil & Gas	0.20	–0.28	–0.06	–0.14	10.41%	18.81	1.87	8.74%	21.95	1.86
Technology	0.13	–0.01	0.00	0.13	1.77%	0.56	0.01	3.38%	0.74	0.02
Telecom	0.03	–0.01	0.00	0.02	5.34%	0.64	0.03	5.71%	0.81	0.05
Utilities	–0.85	–1.27	0.51	–1.61	2.82%	22.41	0.63	5.24%	49.93	2.46

Exhibit 8 reproduces the carbon emissions attribution detailed in Equations (7) and (8) for the Euro portfolio against its natural benchmark when we consider the GHG direct plus first-tier indirect measure. We see that the difference (3 ktCO_2e) is explained by the 0.97 ktCO_2e for the allocation effect and 1.89 ktCO_2e for the selection effect. The major contribution of the allocation effect is by far the utilities sector with 0.82 ktCO_2e. This sector represents, on average, 7.79% of the Euro portfolio and only 5.24% of the natural benchmark and usually is associated with very high levels of GHG emissions, as can be seen in the GHG emission columns in Exhibit 8. Noteworthy, this sector is also responsible for a significant part of the selection effect (0.49 ktCO_2e). We may argue that utility companies are a significant contributor to the total GHG emissions of the Euro portfolio, both because they are big emitters and because they represent a significant part of the Eurozone financial market. The oil and gas sector also contributes to the portfolio's larger emissions through the selection effect: although this sector is underweighted in the portfolio (6.95% versus 8.74%), the selected stocks indeed have higher emissions than the natural benchmark (24.72 ktCO_2e for the sector in the portfolio versus 19.77 ktCO_2e in the natural benchmark). The same is also true for basic materials. For the Ex-Euro portfolio, we see that its lower GHG emissions are due to the selection effect for −2.60 ktCO_2e and the allocation effect for −1.02 ktCO_2e, as shown in Exhibit 9. The utility sector represents half of the GHG emissions reduction: −0.85 ktCO_2e in the allocation effect and −1.27 ktCO_2e in the selection effect. Indeed, the Ex-Euro portfolio is underweighted in this sector, and the stocks that it selects have lower emissions than the stocks in the same sector selected by the natural benchmark.

A similar conclusion can be drawn for the basic material sector: stocks in this sector outside the Eurozone tend to have lower emissions than the natural benchmark. The finding is then symmetric with respect to the combined effect of these two sectors for the Euro portfolio. In conclusion, we find that the geographic distinction has a clear effect in the GHG emissions of the portfolios: the Euro portfolio has higher GHG emissions than the benchmark (and the Ex-Euro), mainly because it usually overweights the utility sector, and utility stocks in the Eurozone have higher GHG emissions than their peers in the rest of Europe. The same applies for stocks in the basic material sector, although there is no overweighting of this sector for either portfolio.

CONCLUSIONS

This articles provides a unified framework for calculating CF and carbon emissions attributions for dynamically rebalanced funds with respect to their benchmarks. The procedure applies for emissions measures, risk measures (typically measures of coal, oil, and gas reserves), and impact measures (typically measures of green energy production or impact investing). This range of indicators can be calculated within a unique and coherent framework, thus improving standardization and aiding comparisons between different opportunities and investments. All together, they constitute a complete CF and give a full picture of investors' portfolio exposure to climate change risk.

Following the literature and standard practice, we distinguish between absolute and relative (intensity) measures, where the latter normalizes absolute measures over total revenues. For both measures, we present carbon performance attributions with respect to the benchmark, from which investors can disentangle the excess contribution over the benchmark into an allocation effect and a selection effect. As for financial performance attributions, these exercises highlight excess contributions across specific categories (typically industrial sectors or countries) and could help investors redirect their investments (by over- or underweighting given categories or by changing the selection within them) to improve their total contributions or their portfolios' intensities.

We provide two examples of carbon footprinting and carbon emission attribution for European stocks. The first shows that company size is an important factor to take into account. Indeed, small companies tend to have higher GHG emissions than their larger counterparts, but not necessarily higher intensities. The second compares the differences between Eurozone stocks and stocks in the rest of Europe. As a matter of fact, the geographic factor is also important: Eurozone stocks do have higher GHG emissions than the rest of Europe, and this is mainly explained by the significant role played by utilities stocks in the Eurozone.

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