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PERSPECTIVES

Hedging Climate Risk

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We present a simple dynamic investment strategy that allows long-term passive investors to hedge climate risk without sacrificing financial returns. We illustrate how the tracking error can be virtually eliminated even for a low-carbon index with 50% less carbon footprint than its benchmark. By investing in such a decarbonized index, investors in effect are holding a "free option on carbon." As long as climate change mitigation actions are pending, the low-carbon index obtains the same return as the benchmark index; but once carbon dioxide emissions are priced, or expected to be priced, the low-carbon index should start to outperform the benchmark.

Whether or not one agrees with the scientific consensus on climate change, both climate risk and climate change mitigation policy risk are worth hedging. The evidence on rising global average temperatures has been the subject of recent debates, especially in light of the apparent slowdown in global warming over 1998–2014.[1] The perceived slowdown has confirmed the beliefs of climate change doubters and fueled a debate on climate science widely covered by the media. This ongoing debate is stimulated by three important considerations.

The first and most obvious consideration is that not all countries and industries are equally affected by climate change. As in other policy areas, the introduction of a new regulation naturally gives rise to policy debates between the losers, who exaggerate the costs, and the winners, who emphasize the urgency of the new policy. The second consideration is that climate mitigation has typically not been a "front burner" political issue. Politicians often tend to "kick the can down the road" rather than introduce policies that are costly in the short run and risk alienating their constituencies—all the more so if there is a perception that the climate change debate is not yet fully settled and that climate change mitigation may not require urgent attention. The third consideration is that although the scientific evidence on the link between carbon dioxide (CO_2) emissions and the greenhouse effect is overwhelming, there is considerable uncertainty regarding the rate of increase in average temperatures over the next 20 or 30 years and the effects on climate change. There is also considerable uncertainty regarding the "tipping point" beyond which catastrophic climate dynamics are set in motion.[2] As with financial crises, the observation of growing imbalances can alert analysts to the inevitability of a crash but still leave them in the dark as to when the crisis is likely to occur.

This uncertainty should be understood as an increasingly important risk factor for investors, particularly long-term investors. At a minimum, the climate science consensus tells us that the risks of a climate disaster are substantial and rising. Moreover, as further evidence of climate events linked to human-caused emissions of CO_2 accumulates and global temperatures keep rising, there is an increased likelihood of policy intervention to limit these emissions.[3] The prospect of such interventions has increased significantly following the Paris Climate Change Conference and the unanimous adoption of a new universal agreement on climate change.[4] Of course, other plausible scenarios can be envisioned whereby the Paris agreement is not followed by meaningful policies. From an investor's perspective, there is therefore a risk with respect to both climate change and the timing of climate mitigation policies. Still, overall, investors should—and some are beginning to—factor carbon risk into their investment policies. It is fair to say, however, that there is still little awareness of this risk factor among (institutional)

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investors.[5] Few investors are aware of the carbon footprint and climate impact of the companies in their portfolios. Among investors holding oil and gas stocks, few are aware of the risks they face with respect to those companies' stranded assets.[6]

In this article, we revisit and analyze a simple, dynamic investment strategy that allows long-term passive investors—a huge institutional investor clientele that includes pension funds, insurance and re-insurance companies, central banks, and sovereign wealth funds—to significantly hedge climate risk while essentially sacrificing no financial returns. One of the main challenges for long-term investors is the uncertainty with respect to the timing of climate mitigation policies. To use another helpful analogy with financial crises, it is extremely risky for a fund manager to exit (or short) an asset class that is perceived to be overvalued and subject to a speculative bubble because the fund could be forced to close as a result of massive redemptions before the bubble has burst. Similarly, an asset manager looking to hedge climate risk by divesting from stocks with high carbon footprints bears the risk of underperforming his benchmark for as long as climate mitigation policies are postponed and market expectations about their introduction are low. Such a fund manager may well be wiped out long before serious limits on CO_2 emissions are introduced.

A number of "green" financial indexes have existed for many years. These indexes fall into two broad groups: (1) pure-play indexes that focus on renewable energy, clean technology, and/or environmental services and (2) "decarbonized" indexes (or "green beta" indexes), whose basic construction principle is to take a standard benchmark, such as the S&P 500 or NASDAQ 100, and remove or underweight the companies with relatively high carbon footprints.[7] The "first family" of green indexes offers no protection against the timing risk of climate change mitigation policies. But the "second family" of decarbonized indexes does: An investor holding such a decarbonized index is hedged against the timing risk of climate mitigation policies (which are expected to disproportionately hit high-carbon-footprint companies) because the decarbonized indexes are structured to maintain a low tracking error with respect to the benchmark indexes.

Thus far, the success of pure-play indexes has been limited. One important reason, highlighted in **Table 1**, is that since the onset of the financial crisis in 2007–2008, these index funds have significantly underperformed market benchmarks.

Besides the fact that clean tech has been overhyped,[8] one of the reasons why these indexes have underperformed is that some of the climate mitigation policies in place before the financial crisis have been scaled back (e.g., in Spain). In addition, financial markets may have rationally anticipated that one of the consequences of the financial crisis would be the likely postponement of the introduction of limits on CO_2 emissions. These changed expectations benefited the carbon-intensive utilities and energy companies more than other companies and may explain the relative underperformance of the green pure-play indexes. More importantly, the reach of the pure-play green funds is very limited because they concentrate investments in a couple of subsectors and, in any case, cannot serve as a basis for building a core equity portfolio for institutional investors.

The basic point underlying a climate risk–hedging strategy that uses decarbonized indexes is to go beyond a simple divestment policy or investments in only pure-play indexes and instead keep an aggregate risk exposure similar to that of standard market benchmarks. Indeed, divestment of high-carbon-footprint stocks is just the first step. The second key step is to optimize the composition and weighting of the decarbonized index in order to minimize the tracking error (TE) with the reference benchmark index. It turns out that TE can be virtually eliminated, with the overall carbon footprint of the decarbonized index remaining substantially lower than that of the reference index (close to 50% in terms of both carbon intensities and absolute carbon emissions). Decarbonized indexes have thus far essentially matched or even outperformed the benchmark index.[9] In other words, investors holding a decarbonized index have been able to significantly

Table 1. Pure-Play Clean Energy Indexes vs. Global Indexes

	S&P 500	NASDAQ 100	PP 1	PP 2	PP 3	PP 4	PP 5
Annualized return	4.79%	11.40%	5.02%	–8.72%	2.26%	–8.03%	–1.89%
Annualized volatility	22.3	23.6	24.1	39.3	30.2	33.8	37.3

Notes: Table 1 gives the financial returns of several ETFs that track leading clean energy pure-play indexes. Pure Play 1 refers to Market Vectors Environmental Services ETF, Pure Play 2 to Market Vectors Global Alternative Energy ETF, Pure Play 3 to PowerShares Cleantech Portfolio, Pure Play 4 to PowerShares Global Clean Energy Portfolio, and Pure Play 5 to First Trust NASDAQ Clean Edge Green Energy Index Fund. Annualized return and volatility were calculated using daily data from 5 January 2007 to the liquidation of Pure Play 1 on 12 November 2014.
Sources: Amundi and Bloomberg (1 September 2015).

reduce their carbon footprint exposure without sacrificing any financial returns. In effect, these investors are holding a "free option on carbon": So long as the introduction of significant limits on CO_2 emissions is postponed, they can obtain the same returns as on a benchmark index. But from the day CO_2 emissions are priced meaningfully and consistently and limits on CO_2 emissions are introduced, the decarbonized index should outperform the benchmark.[10] A climate risk–hedging policy around decarbonized indexes is essentially an unlevered minimum risk arbitrage policy that takes advantage of a currently mispriced risk factor (carbon risk) in financial markets. Although larger arbitrage gains are obtainable by taking larger risks (and this climate risk–hedging strategy errs on the side of caution), the strategy is particularly well suited for long-term passive investors who seek to maximize long-term returns while limiting active stock trading over time.

A Green Index without Relative Market Risk: The Basic Concept

Investor perceptions of lower financial returns from green index funds could explain why green indexes have thus far remained a niche market. Another reason might be the design of most green indexes, which lend themselves more to a bet on clean energy than a hedge against carbon risk. In contrast, the design we support allows passive long-term investors to hedge carbon risk. Thus, the goal is not just to minimize exposure to carbon risk by completely divesting from any company with a carbon footprint exceeding a given threshold, but also to minimize the tracking error of the decarbonized index with the benchmark index. We support this design because it implements a true dynamic hedging strategy for passive investors and can easily be scaled to significantly affect not only portfolios' footprints but also (eventually) the real economy.[11]

The basic idea behind index decarbonization is to construct a portfolio with fewer composite stocks than the benchmark index but with similar aggregate risk exposure to all priced risk factors. This approach is possible because, as Koch and Bassen (2013) showed, carbon risk is asymmetrically concentrated in a few firms.[12] Ideally, the only major difference in aggregate risk exposure between the two indexes would be with respect to the carbon risk factor, which would be significantly lower for the decarbonized index. So long as carbon risk remains unpriced by the market, the two indexes will generate similar returns (i.e., offer the same compensation for risk demanded by the representative investor), thus achieving no or minimal TE. But once carbon risk is priced or is expected to be priced by the market, the decarbonized index should start outperforming the benchmark.

The central underlying premise of this strategy is that financial markets currently underprice carbon risk. Moreover, our fundamental belief is that eventually, if not in the near future, financial markets will begin to price carbon risk. Our premise leads inevitably to the conclusion that a decarbonized index is bound to provide higher financial returns than the benchmark index. We believe that the evidence in support of our premise is overwhelming. Currently, virtually all financial analysts overlook carbon risk. Only in 2014 did a discussion about stranded assets make it into a report from a leading oil company for the first time, and the report mostly denied any concern that a fraction of proven reserves might ever become stranded assets.[13] Only a few specialized financial analysts[14] factor stranded assets into their valuation models of oil company stocks. Nor, apart from a few exceptions,[15] do financial analysts ever evoke carbon-pricing risk in their reports to investors. In sum, current analysts' forecasts assume by default that there is no carbon risk. Under these circumstances, it takes a stretch of the imagination to explain that financial markets somehow currently price carbon risk correctly. Even more implausible is the notion that financial markets currently price carbon risk excessively. Only in this latter scenario would investors in a decarbonized index face lower financial returns than in the benchmark index.

Some might object that our fundamental belief that financial markets will price carbon risk in the future is not particularly plausible. After all, the evidence from many climate talks' failures following Kyoto suggests, if anything, that global carbon pricing in the near future is extremely unlikely. If that should be the case, our investor in the decarbonized index would simply match the returns of the benchmark index—a worst-case scenario. Any concrete progress in international negotiations—and the implementation of nationally determined independent contributions agreed to in Paris—will change financial market expectations about carbon risk and likely result in higher financial returns on the low-TE index relative to the benchmark index.

The Decarbonized Index Optimization Problem. Given our basic premise and fundamental belief, the next question is how to go about constructing the green index. There are several possible formulations of the problem in practice. One formulation is to eliminate high-carbon-footprint composite stocks, with the objective of meeting a target carbon footprint reduction for the green index, and then to reweight the remaining stocks in order to minimize tracking error with the benchmark index. The dual formulation is to begin by imposing a constraint on maximum allowable tracking error with the benchmark index and then, subject to this constraint, exclude and reweight composite stocks in the benchmark index to maximize the green index's carbon footprint reduction. Although there is no compelling reason to choose one formulation over the other, we favor the second formulation, which seeks to minimize tracking error subject to meeting a carbon footprint reduction target.

Another relevant variation in the design of the constrained optimization problem is whether to (1) require at the outset the complete exclusion of composite stocks of the worst performers in terms of carbon footprint or (2) allow the green index to simply underweight high-carbon-footprint stocks without completely excluding them. Although the latter formulation is more flexible, it has drawbacks, which we discuss later in the article.

We confine our analysis to essentially two alternatives among the many possible formulations of the constrained optimization problem for the construction of a decarbonized index that trades off exposure to carbon, tracking error, and expected returns. We describe both formulations formally, under the simplifying assumption that only one sector is represented in the benchmark index.

The two portfolio optimization problems can be simply and easily represented. Suppose that there are N constituent stocks in the benchmark index and that the weight of each stock in the index is given by $w_i^b = \left[\frac{\text{Mkt cap}(i)}{\text{Total mkt cap}}\right]$. Suppose next that each constituent company is ranked in decreasing order of carbon intensity, q_l^i, with company $l = 1$ having the highest carbon intensity and company $l = N$ the lowest (each company is thus identified by two numbers $[i,l]$, with the first number referring to the company's identity and the second to its ranking in carbon intensity).

In the first problem, the green portfolio can be constructed by choosing new weights, w_i^g, for the constituent stocks to solve the following minimization problem:

$$\text{Min TE} = sd\left(R^g - R^b\right),$$

where

$$w_l^g = 0 \text{ for all } l = 1,\ldots k$$

$$0 \le w_l^g \text{ for all } l = k+1,\ldots N$$

sd = standard deviation

That is, the decarbonized index is constructed by first excluding the k worst performers in terms of carbon intensity and reweighting the remaining stocks in the green portfolio to minimize TE.[16] This decarbonization method follows transparent rules of exclusion, whatever the threshold k.

In the second problem formulation, the first set of constraints $(w_j^g = 0 \text{ for all } j = 1,\ldots k)$ is replaced by the constraint that the green portfolio's carbon intensity must be smaller than a given threshold: $\sum_{l=1\ldots N} q_l w_l^g \le Q$. In other words, the second problem is a design, which potentially does not exclude any constituent stocks from the benchmark index and seeks only to reduce the carbon intensity of the index by reweighting the stocks in the green portfolio. Although the second problem formulation (pure optimization) dominates the first (transparent rules) for the same target aggregate carbon intensity, Q, because it has fewer constraints, it has a significant drawback in terms of the methodology's opacity and the lack of a clear signal for which constituent stocks to exclude on the basis of their relatively high carbon intensity.

Optimization Procedure. For both problem formulations, the *ex ante* TE—given by the estimated standard deviation of returns of the decarbonized portfolio from the benchmark—is estimated by using a multifactor model of aggregate risk (see Appendix D for more detailed information). This multifactor model significantly reduces computations, and the decomposition of individual stock returns into a weighted sum of common factor returns and specific returns provides a good approximation of individual stocks' expected returns. More formally, under the multifactor model the TE minimization problem has the following structure:

$$\text{Min}\left[\sqrt{\left(W^p - W^b\right)'\left(\boldsymbol{\beta}\boldsymbol{\Omega}_f\boldsymbol{\beta}' + \boldsymbol{\Delta}^{AR}\right)\left(W^p - W^b\right)}\right],$$

where

$$w_l^g = 0 \text{ for all } l = 1,\ldots k$$

$$0 \le w_l^g \text{ for all } l = k+1,\ldots N$$

$\left(W^p - W^b\right)$ = the vector of the difference in portfolio weights of the decarbonized portfolio and the benchmark

$\boldsymbol{\Omega}_f$ = the variance–covariance matrix of factors

$\boldsymbol{\beta}$ = the matrix of factor exposures

$\boldsymbol{\Delta}^{AR}$ = the diagonal matrix of specific risk variances

Risk Mitigation Benefits of Low Tracking Error. To explore more systematically the potential benefits of achieving a bounded tracking error, we ran a number of simulations with the pure optimization methodology and determined a

TE–carbon efficiency frontier for a decarbonized index constructed from the MSCI Europe Index. As illustrated in **Figure 1**, achieving a nearly 100% reduction in the MSCI Europe carbon footprint would come at the price of a huge tracking error of more than 3.5%.[17]

Such a large TE would expose investors in the decarbonized index to significant financial risk relative to the benchmark—even in a good scenario whereby the decarbonized index is expected to outperform the benchmark as a result of climate mitigation policies. **Figure 2** depicts the risk that a large TE might expose investors to and how that risk can be mitigated by lowering the TE. We first posit a scenario whereby the expected yearly return of the green index is 2.5% higher than that of the benchmark[18] and show (with a confidence interval of two standard deviations) that a 3.5% TE could expose investors to losses relative to the benchmark in the negative scenario.

As Figure 2 illustrates, if we lower the TE of the decarbonized index from 3.5% to 1.2%, the decarbonized index generates returns at least as high as those of the benchmark *even in the worst-case scenario*.

Illustrative Example. A simple example can illustrate in greater detail how a low-carbon, low-TE index might be constructed and how its financial returns—relative to the benchmark—would vary with (expectations of) the introduction of carbon taxes. Let us consider a portfolio of four stocks (A, B, C, D), each priced at 100. The first two stocks (A, B) are, say, oil company stocks; stock C is outside the oil industry but its price is perfectly correlated with the oil industry stock price; and stock D is a company whose stock price is uncorrelated with the oil industry. The pre–carbon taxation returns on these stocks are 20%, 20%, 20%, and 30%, respectively. On the one hand, we assume that stocks A and B have a relatively high carbon footprint, which would expose them to relatively high implied carbon taxation—40% and 10% of earnings, respectively. On the other hand, we assume that stocks C and D have no carbon tax exposure. We then construct the low-carbon, low-TE index as follows: (1) We filter out entirely stocks A and B, (2) we treble the weighting of stock C to maintain the same overall exposure to the oil sector as the benchmark portfolio, and (3) we leave the weighting of stock D unchanged. If the introduction of carbon taxes is expected, the price of stock A will drop to 72 and the price of stock B will increase to 108, whereas the price of stock C will increase to 120 and the price of stock D will rise to 130. What are the implications for returns on the low-carbon, low-TE index relative to the benchmark? In this scenario, the low-TE index would outperform the benchmark by 14%.

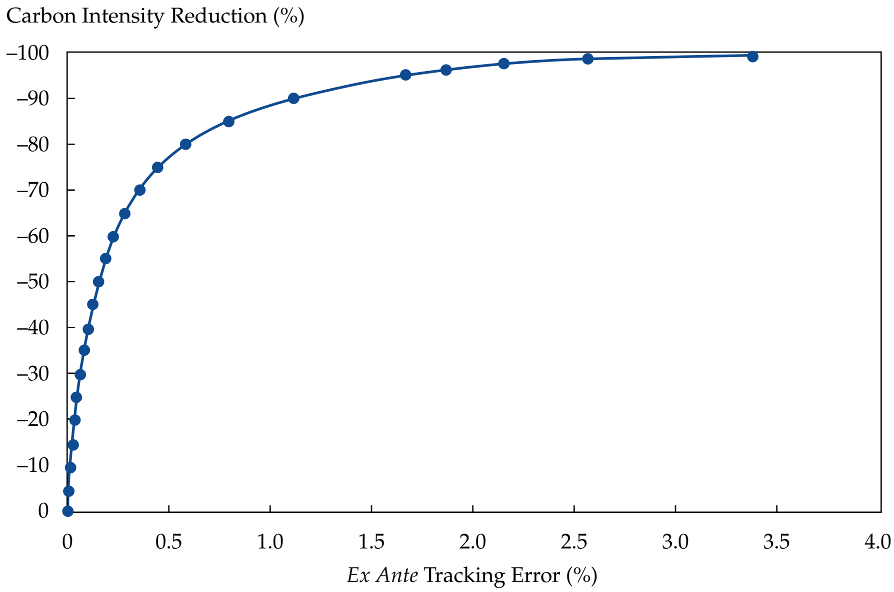
Tracking Error Management and Carbon Risk Repricing. Index managers seek to limit *ex ante* TE. However, some enhanced indexes, such as decarbonized indexes, also seek to increase returns relative to the benchmark. Although the two goals may seem in conflict, we note that the optimization procedure focuses on *ex ante* TE and excess returns are necessarily measured *ex post*. Therefore, if the risk model used to limit *ex ante* TE does not take into account carbon risk (or any factor responsible for a divergence of returns), a small *ex ante* TE can be compatible with active returns *ex post*. Two polar carbon-repricing scenarios can be considered: (1) a smooth repricing with moderate regulatory and technological changes that progressively impair the profitability of carbon-intensive companies and (2) a sharp repricing caused by unanticipated disruptive technologies or regulations. In the first scenario, investors could experience active positive returns with *ex post* TE in line with *ex ante* TE. In the second scenario, investors in a decarbonized index could experience a peak in *ex post* TE with active positive returns.

Beyond Optimization: Methodological Considerations and Caveats

In this section, we consider other issues besides portfolio optimization, including the benefits of clear signaling via transparent rules, trade-offs involved in different designs of decarbonized indexes and different normalizations of carbon footprints, how to deal with anticipated changes in companies' carbon footprints, and a few caveats.

Benefits of Clear Signaling through Transparent Rules. As all issuers well understand, inclusion in or exclusion from an index matters and is a newsworthy event. We believe that inclusion in a decarbonized index ought to have similar value. Clearly communicating which constituent stocks are in the decarbonized index would not only reward the included companies for their efforts in reducing their carbon footprint but also help discipline the excluded companies. This pressure might induce excluded companies to take steps to reduce their carbon footprint and to reward their CEOs for any carbon footprint reductions.[19] Because companies' exclusion from the index would be reevaluated yearly, it would also induce healthy competition to perform well with respect to carbon footprints, with the goal of rejoining the index.[20] Finally, clear communications concerning exclusion criteria based on carbon footprints would inspire a debate on whether greenhouse gas (GHG) emissions are properly measured and would lead to improvements in the

Figure 1. Carbon Frontier on the MSCI Europe Index



Source: Amundi (30 June 2015).

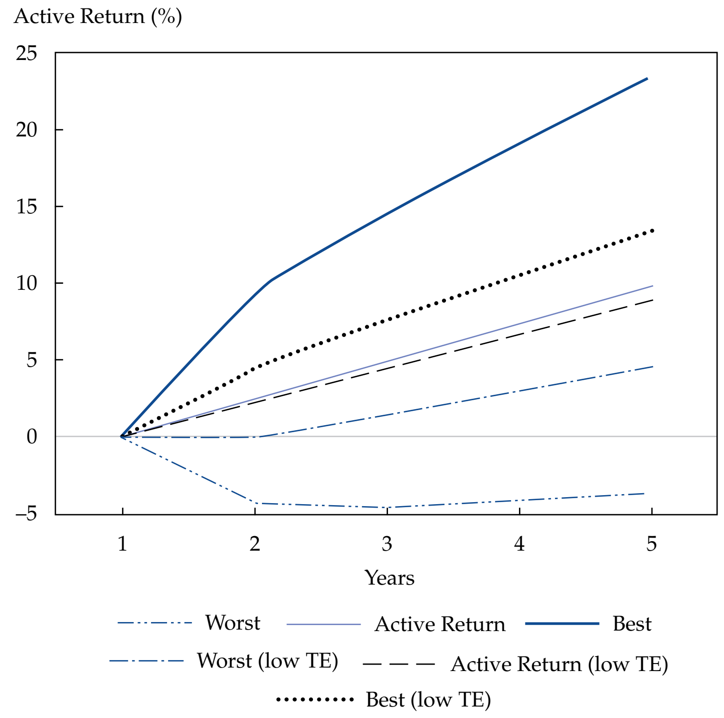
methodology for determining companies' carbon footprints.

Design Trade-Offs. A number of trade-offs are involved in the design of a decarbonized index. For example, an obvious question about balancing concerns the sector composition of the benchmark index. To what extent should the decarbonized index seek to preserve the sector balance of the benchmark? While seeking to preserve sector composition, should the filtering out of high-carbon-footprint stocks be performed sector by sector or across the entire benchmark index portfolio? Some believe that a sector-blind filtering out of companies by the size of their carbon footprint would result in an unbalanced decarbonized index that essentially excludes most of the fossil energy sector, electric utilities, and mining and materials companies. Obviously, such an unbalanced decarbonized index would have a very high tracking error and would be undesirable. Interestingly, however, a study of the world's 100 largest companies has shown that more than 90% of the world's GHG emissions are attributable to sectors other than oil and gas (see Climate Counts 2013). Hence, a sector-by-sector filtering approach could result in a significantly reduced carbon footprint while still maintaining a sector composition roughly similar to that of the benchmark. Later in the article, we show more concretely how much carbon footprint reduction can be achieved by decarbonizing the S&P 500 and MSCI Europe indexes.

One simple way to address this issue is to look at the decarbonized portfolio's TE for the different optimization problems and pick the procedure that yields the decarbonized index with the lowest TE. But there may be other relevant considerations besides TE minimization. For example, one advantage of a sector-by-sector filtering approach with transparent rules (subject to the constraint of maintaining roughly the same sector balance as that of the benchmark index) is that excluded companies can more easily determine their carbon footprint ranking in their industry and how much carbon footprint reduction it would take for their stock to be included in the decarbonized index. In other words, a sector-by-sector filtering approach would foster greater competition within each sector for companies to lower their carbon footprint. Another related benefit is that the exclusion of the worst GHG performers in the sector would also reduce exposure to companies that fare poorly on other material sustainability factors (given that carbon footprint reduction is a good proxy for investments in other material sustainability factors).[21]

Normalization of the Carbon Footprint. Because the largest companies in the benchmark index are likely to be the companies with the highest GHG emission levels, a filtering rule that excludes the stocks of companies with the highest absolute emission levels will tend to be biased against the largest companies, which could result in a high TE for the decarbonized index. Accordingly, some normalization of companies' carbon footprints is appropriate. Another reason to normalize the absolute carbon footprint measure is that a filter based on a normalized measure would be better at selecting the least wasteful companies in terms of GHG

Figure 2. Returns and Risk with Low Tracking Error



Source: Amundi.

emissions. That is, a normalized carbon footprint measure would better select companies on the basis of their energy efficiency. A simple and comprehensive, if somewhat rudimentary, normalization would be to divide each company's carbon footprint by sales. Normalizations adapted to each sector are preferable and could take the form of dividing CO_2 emissions by (1) tons of output in the oil and gas sector, (2) revenue from transporting one tonne over a certain distance in the transport sector, (3) total GWh (gigawatt-hour) electricity production in the electric utility sector, (4) square footage of floor space in the housing sector, or (5) total sales in the retail sector.

Changes in Companies' Carbon Footprints. Ideally, the green filter should take into account expected future carbon footprint reductions resulting from current investments in energy efficiency and reduced reliance on fossil fuels. Similarly, the green filter should penalize oil and gas companies that invest heavily in exploration with the goal of increasing their proven reserves, which raises the risk of stranded assets for such companies. This "threat" would provide an immediate incentive to any company with an exceptionally high carbon footprint to make investments to reduce it and would boost the financial returns of the decarbonized index relative to the benchmark.

Caveats. Whenever an investment strategy that is expected to outperform a market benchmark is pitched, a natural reaction is to ask, what's the catch? As explained earlier, the outperformance of the decarbonized index is premised on the fact that financial markets currently do not price carbon risk. Thus, an obvious potential flaw in our proposed climate risk–hedging strategy is the possibility that financial markets currently *overprice* carbon risk. While this overpricing is being corrected, the decarbonized index would underperform the benchmark index. We strongly believe this argument to be implausible because the current level of awareness of carbon risk remains very low outside a few circles of asset owners, a handful of brokers, and asset managers. Another highly implausible scenario is that somehow today's high-carbon-footprint sectors and companies will be tomorrow's low-carbon-footprint sectors and companies. One story to back such a scenario could be that the high-GHG emitters have the most to gain from carbon sequestration and will thus be the first to invest in that technology. Under this scenario, the decarbonized index would underperform the benchmark precisely when carbon taxes are introduced. This scenario is not in itself a crushing objection because the green filter can easily take into account investments in carbon sequestration as a criterion for inclusion in the index. In the end, this scenario simply suggests a reason for the carbon filter to take into account measures of companies' predicted carbon footprints.

A more valid concern is whether companies' carbon footprints are correctly measured and whether the filtering based on carbon intensity fits its purpose. Is there a built-in bias in the way carbon footprints are measured, or is the measure so noisy that investors could be exposed to many carbon measurement risks? A number of organizations—Trucost, CDP (formerly Carbon Disclosure Project), South Pole Group, and MSCI ESG Research—provide carbon footprint measures of the largest publicly traded companies, measures that can sometimes differ from one organization to another.[22] For example, it has been observed that GHG emissions associated with hydraulic fracturing for shale gas are significantly underestimated because the high methane emissions involved in the hydraulic fracturing process are not counted. Thus, what would appear to be—according to current carbon footprint measurements—a welcome reduction in carbon footprints following the shift from coal to shale gas could be just an illusion. Consequently, a green filter that relies on this biased carbon footprint measure risks exposing investors to more rather than less carbon risk.

As described in greater detail in Appendix C, GHG emissions are divided into three scopes: Scope 1, which measures direct GHG emissions; Scope 2, which concerns indirect emissions resulting from the company's purchases of energy; and Scope 3, which covers third-party emissions (suppliers and consumers) tied to the company's sales. Although Scope 3 emissions may represent the largest fraction of GHG emissions for some companies (e.g., consumer electronics companies and car manufacturers),[23] there is currently no systematic, standardized reporting of these emissions. This lack is clearly a major limitation and reduces the effectiveness of all existing decarbonization methodologies. For example, excluding the most-polluting companies in the automobile industry and the auto components industry on the basis of current emission measures would lead mostly to the exclusion of auto components companies. Automobile manufacturers would largely be preserved because most of the carbon emissions for a car maker are Scope 3 emissions. As reliance on decarbonized indexes grows in scale, however, more resources will likely be devoted to improving the quality of Scope 3 and the other categories of GHG emissions. The inclusion of Scope 3 emissions would also better account for green product innovations by materials companies that bolster the transition toward a low-carbon economy. For instance, aluminum producers might be excluded under the current GHG measures owing to their high carbon intensity even though aluminum will fare better than other materials in the transition to renewable energy.

There are three evident responses to these existing measurement limitations. First, drawing an analogy with credit markets, we know that a biased or noisy measure of credit risk by credit-rating agencies has never been a decisive reason for abolishing credit ratings altogether. Credit ratings have provided an essential reinforcement of credit markets for decades despite important imprecisions in their measurements of credit risk, which have been pointed out by researchers of credit markets over time. Second, as with credit ratings, methodologies for measuring carbon footprints will be improved, especially when the stakes involved in measuring carbon footprints correctly increase because of the role of these measures in any green filtering process. Third, the design of the decarbonized index itself offers protection against carbon footprint measurement risk; if there is virtually no tracking error with the benchmark, investors in the decarbonized index are partly hedged against this risk.

Finally, a somewhat more technical worry is that the stocks excluded from the decarbonized index could also be the most volatile stocks in the benchmark index because these stocks are the most sensitive to speculation about climate change and climate policy. If that is the case, tracking error cannot be eliminated entirely, but that should not be a reason for deciding not to invest in the decarbonized index. On the contrary, the decarbonized index will then have a higher Sharpe ratio than the benchmark, commensurate with a higher TE.[24]

To summarize, our proposed strategy for hedging climate risk is especially suitable for passive long-term investors. Rather than a risky bet on clean energy (at least in the short run), we have described a decarbonized index with minimal tracking error that offers passive investors a significantly reduced exposure to carbon risk, allowing them to "buy time" and limit their exposure with respect to the timing of the implementation of climate policy and a carbon tax. Thus, a key difference between this approach and existing green indexes is switching the focus from the inevitable transition to renewable energy to the timing risk with respect to climate policy. As we show later in the article, carbon exposure can be reduced significantly—with maximum insurance against the timing of climate policy—by minimizing tracking error with the benchmark index. We believe that this approach is essentially a win-win strategy for all passive asset owners and managers. Moreover, should this strategy be adopted by a large fraction of passive index investors—a market representing close to $11 trillion in assets, according to a recent study[25] (Boston Consulting Group 2015)—companies will feel the pressure to improve their performance on GHG emissions and debates about carbon emissions will surely be featured prominently in the financial press.[26] It constitutes, therefore, an easy entry point for a wide clientele of investors and could trigger the mobilization of a much broader ecosystem dedicated to the analysis and understanding of climate-related transition risks.

Decarbonized Indexes in Practice: How Small Are Their Carbon Footprints?

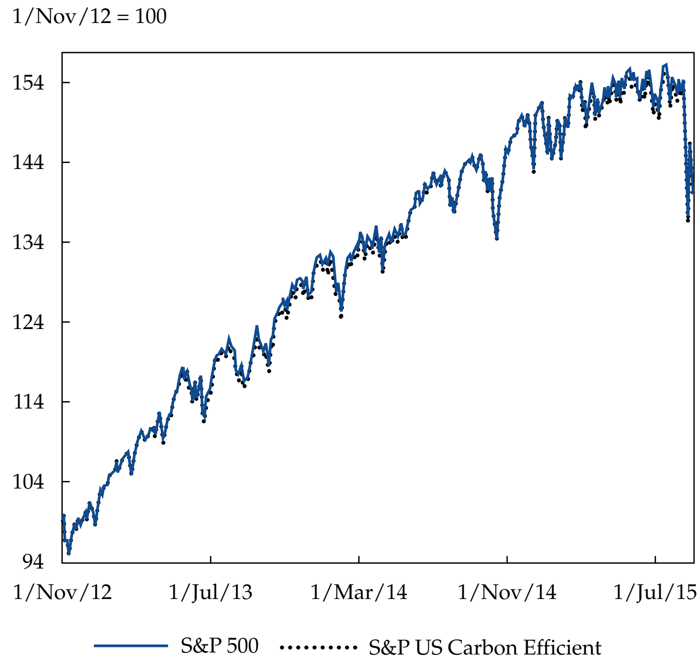
There are several examples of decarbonized indexes. AP4, the Fourth Swedish National Pension Fund (Fjärde AP-fonden), is, to our knowledge, the first institutional investor to adopt a systematic approach that uses some of these decarbonized indexes to significantly hedge the carbon exposure of its global equity portfolio. In 2012, AP4 decided to hedge the carbon exposure of its US equity holdings in the S&P 500 by switching to a decarbonized portfolio with a low TE relative to the S&P 500 through the replication of the S&P 500 Carbon Efficient Select Index. This index excludes the 20% worst performers in terms of carbon intensity (CO_2/Sales) as measured by Trucost, one of the leading companies specializing in the measurement of the environmental impacts of publicly traded companies. An initial design constraint on the decarbonized index is to ensure that stocks removed from the S&P 500 do not exceed a reduction in the Global Industry Classification Standard (GICS) sector weight of the S&P 500 by more than 50%. A second feature of the S&P 500 Carbon Efficient Select Index is the readjustment of the weighting of the remaining constituent stocks to minimize TE with the S&P 500. Remarkably, this decarbonized index reduces the overall carbon footprint of the S&P 500 by roughly 50%,[27] with a TE of no more than 0.5%. This first model of a decarbonized index strikingly illustrates that significant reductions in carbon exposure are possible without sacrificing much in the way of financial performance or TE. In fact, AP4's S&P 500 Carbon Efficient Select Index portfolio has outperformed the S&P 500 by about 24 bps annually since it first invested in the decarbonized index in November 2012, as **Figure 3** shows, which is in line with the 27 bp annual outperformance of the S&P 500 Carbon Efficient Select Index since January 2010.

AP4 has extended this approach to hedging climate risk to its equity holdings in emerging markets.[28] Relying on carbon footprint data from MSCI ESG Research, AP4 has sought to exclude from the MSCI EM Custom ESG Index not only the companies with the highest GHG emissions but also the worst companies in terms of stranded asset risk. Turning to its Pacific-ex-Japan stock holdings, AP4 has applied a similar methodology in constructing its decarbonized portfolio, excluding the companies with the largest reserves and highest carbon emissions intensity while maintaining both sector and country weights in line with its initial index holdings in the region.

More recently, AP4, FRR (Fonds de réserve pour les retraites, or the French pensions reserve fund), and Amundi have worked with MSCI to develop another family of decarbonized indexes, with a slightly different design. The result is the MSCI Global Low Carbon Leaders Index family—based on existing MSCI equity indexes (e.g., MSCI ACWI, MSCI World, and MSCI Europe)—which addresses two dimensions of carbon exposure. It excludes from the indexes the worst performers in terms of both carbon emissions intensity and fossil fuel reserves intensity while maintaining a maximum turnover constraint as well as minimum sector and country weights. The remaining constituent stocks are then rebalanced to minimize TE with the respective benchmarks.[29] **Table 2** compares the performance of the resulting decarbonized indexes, based on a backtest, with that of the MSCI Europe Index. As Table 2 shows, the Low Carbon Leaders Index delivers a remarkable 90 bp annualized outperformance over the MSCI Europe Index for November 2010–February 2016, with a similar volatility and a 0.7% tracking error.

At the end of January 2016, we conducted a performance attribution analysis, after the MSCI Europe Low Carbon Leaders Index was launched, for the period November 2014–January 2016,[30] when the outperformance was particularly strong (an overall 189 bps[31]). Our analysis shows how to distinguish which part of the performance is due to sector allocation (allocation effect[32]) and which part is due to stock selection within sectors (selection effect[33]). At the sector level (using the GICS[34] taxonomy), the allocation effect is responsible for 37 bps of outperformance, with the underweighting of the energy and materials sectors responsible for 40 bps and 20 bps, respectively. More importantly, the effect of screening out the worst GHG performers within a sector is greater than the allocation effect, with a 120 bp outperformance. Interestingly, the positive screening effect is concentrated in two sectors, Materials (127 bps) and Utilities (25 bps; see **Table E1** in Appendix E). The largest negative contributor, Consumer Staples, had an allocation effect of –37 bps and a selection effect of –8 bps.

Figure 3. S&P 500 and S&P US Carbon Efficient Indexes



Sources: Amundi and Bloomberg (31 August 2015).

We conducted a second-level analysis (industry level; see **Table E2** and **Table E3** in Appendix E) that focused on the largest contributor, the materials sector, and found that the index was strongly underweighted in the diversified metals and mining (DM&M) stocks, with a 68 bp allocation effect and a 36 bp selection effect. The reason behind this underweighting is that coal represents the major part of DM&M reserves. As for the utilities sector, the index was underweighted on multi-utilities because of their high emissions (an 11 bp selection effect and an 8 bp allocation effect). Stock performance for these two sectors was related to trends in the energy sector (mostly a fall in coal prices).

AP4, MSCI, FRR, and Amundi have further explored the robustness of these decarbonized indexes to other exclusion rules and to higher carbon footprint reductions. They found that there is not much to be gained by using more flexible criteria that permit less than 100% exclusion of high-carbon-footprint stocks. **Table 3** compares the performances of a fully “optimized” portfolio, with no strict exclusion of the worst performers, and a portfolio based on the “transparent exclusion rules” outlined earlier. Whether in terms of reduced exposure to carbon or overall tracking error, the two portfolios deliver similar results.

Interestingly, however, the two methods for constructing the decarbonized index yield substantial sector differences in TE contribution, which is concentrated in two sectors (Materials and Energy) for the fully optimized index. In contrast, the limit put on total sector exclusion in the Low Carbon Leaders Index (with transparent rules) spreads the effort across several sectors (see **Figure F1** in Appendix F for a detailed breakdown of the contributions to specific risks).

Conclusion

Our decarbonized index investment strategy stands on its own as a simple and effective climate risk–hedging strategy for passive long-term institutional investors, but it is also an important complement to climate change mitigation policies. Governments have thus far focused mostly on introducing policies to control or tax GHG emissions and to build broad international agreements for the global implementation of such policies (for a discussion of the pros and cons of cap-and-trade mechanisms versus a GHG emissions tax, see Guesnerie and Stern 2012).[35] Governments have also provided subsidies to the solar and wind energy sectors, thereby boosting a small-business constituency that supports climate change mitigation policies. Similarly, index decarbonization can boost support for such policies from a large fraction of the investor community. In addition, as more and more funds are allocated to decarbonized indexes, stronger market incentives will materialize, inducing the

Table 2. Financial Performance of Transparent Rules on MSCI Europe

Key Metrics	MSCI Europe Index	MSCI Europe Low Carbon Leaders Index
Total return[a]	7.8%	8.7%
Total risk[a]	13.2%	13.2%
Return/risk	0.59	0.65
Sharpe ratio	0.57	0.63
Active return[a]	0%	0.9%
Tracking error[a]	0%	0.7%
Information ratio	NA	1.16
Historical beta	1.00	1.16
Turnover[b]	1.8%	9.9%
Securities excluded	NA	93
Market cap excluded	NA	21.4%
Reduction in carbon emissions intensity (tCO$_2$/US$ millions)	NA	52%
Reduction in carbon reserves intensity (tCO$_2$/US$ millions)	NA	66%

NA = not applicable.
Notes: The index of low-carbon leaders is reviewed and updated every six months (in May and November). This table was created after the November 2015 review of the list of index constituents.
[a]Gross returns were annualized in euros for 30 November 2010–29 February 2016.
[b]Annualized one-way index turnover for 30 November 2010–29 February 2016.
Source: MSCI (30 November 2010–29 February 2016).

Table 3. Carbon and Financial Performances of Transparent Rules on MSCI Europe

	Optimized Index (low-carbon target)	Transparent Rules (low-carbon leaders)
Reduction in carbon emissions intensity (tCO$_2$/US$ millions)	82%	62%
Reduction in carbon reserves intensity (tCO$_2$/US$ millions)	90%	81%
Tracking error[a]	0.9%	0.72%

Note: Backtests were run over a four-year period, from 30 November 2010 to 30 June 2014.
[a]Gross returns were annualized in euros for 30 November 2010–31 July 2015.
Source: MSCI.

world's largest corporations—the publicly traded companies—to invest in reducing GHG emissions. Moreover, the encouragement of climate risk hedging can have real effects on reducing GHG emissions even before climate change mitigation policies are introduced. The mere expectation that such policies will be introduced will affect the stock prices of the highest-GHG emitters and reward those investors that have hedged climate risk by holding a decarbonized index. Finally, the anticipation of the introduction of climate change mitigation policies will create immediate incentives to initiate a transition to renewable energy.

A simple, costless policy in support of climate risk hedging that governments can adopt immediately is to mandate disclosure of the carbon footprint of their state-owned investment arms (public pension funds and sovereign wealth funds). Such a disclosure policy would have several benefits.

Given that climate change is a financial risk, disclosure provides investors (and citizens) with relevant information on the nature of the risks they are exposed to. Remarkably, some pension funds have already taken this step by disclosing their portfolios' carbon footprint—in particular, ERAFP and FRR in France; KPA Pension, the Church of Sweden, and the AP funds in Sweden; APG in the Netherlands; and the Government Employees Pension Fund (GEPF) in South Africa.

Given that citizens and pensioners will ultimately bear the costs of climate change mitigation, disclosure of their carbon exposure through their pension or sovereign wealth funds helps internalize the externalities of climate change. Indeed, investment by a public pension fund in polluting companies generates a cost borne by its government and trustees and thereby lowers the overall returns on investment. The China Investment Corporation

(CIC), China's sovereign wealth fund, has already made some statements in that direction.

Disclosure of the carbon footprint of a sovereign wealth fund's portfolio can be a way for sovereign wealth funds of oil- and gas-exporting countries to bolster risk diversification and hedging of commodity and carbon risk through their portfolio holdings. The basic concept underlying a sovereign wealth fund is to diversify the nature of the country's assets by extracting the oil and gas under the ground and thereby "transforming" these assets into "above-ground" diversifiable financial assets. Thus, it makes sense to follow up this policy by diversifying investments held by the sovereign wealth fund away from energy companies and other stock holdings that have a large carbon exposure. Interestingly, the French government recently approved a law on energy transition that requires French institutional investors to disclose their climate impact and carbon risk exposure.[36]

A more direct way to support investment in low-carbon, low-TE indexes is to push public asset owners and their managers to make such investments. Governments could thus play an important role as catalysts to accelerate the mainstream adoption of such investment policies. In this respect, it is worth mentioning the interesting precedent of the recent policy of the Shinzō Abe administration in Japan to support the development of the JPX-Nikkei Index 400. What is particularly noteworthy is that the Abe administration sees this index as an integral part of its "third arrow" plan to reform Japan's companies. GPIF—by far the largest Japanese public investor, with more than $1.4 trillion of assets under management—has adopted the new index. This example illustrates how the combination of a newly designed index with a policymaking objective and the adoption of that index by a public asset owner can be a catalyst for change.

In his book *Finance and the Good Society*, Robert J. Shiller (2012, p. 7) advances a welcome and refreshing perspective on financial economics:

> Finance is not about "making money" per se. It is a "functional" science in that it exists to support other goals—those of society. The better aligned society's financial institutions are with its goals and ideals, the stronger and more successful the society will be.

It is in this spirit that we have pursued our research on how investors can protect their savings from the momentous risks associated with GHG emissions and their long-term, potentially devastating effect on climate change. Climate change has mostly and appropriately been the bailiwick of scientists, climatologists, governments, and environmental activists. There has been relatively little engagement by finance with this important issue, but investors and financial markets cannot continue to ignore climate change. The effects of rising temperatures, the increasingly extreme weather events climate change generates, and the climate change mitigation policy responses it could provoke may have dramatic consequences for the economy and thus investment returns. Therefore, financial innovation should be explored so that the power of financial markets can be used to address one of the most challenging global threats faced by humankind.

Besides offering investors a hedging tool against the rising risks associated with climate change, a decarbonized index investment strategy can mobilize financial markets to support the common good. As a larger and larger fraction of the index-investing market is devoted to decarbonized indexes, a virtuous cycle will be activated and enhanced whereby the greater awareness of carbon footprints and GHG emissions will exert a disciplining pressure to reduce CO_2 emissions and will gradually build an investor constituency that supports climate change mitigation policies. Governments, businesses, technology innovators, and society will thus be encouraged to implement changes that accelerate the transition to a renewable energy economy.

Our basic premise/working assumption is that to foster the engagement of financial markets with climate change, it is advisable to appeal to investors' rationality and self-interest. Our argument is simply that even if some investors are climate change skeptics, the uncertainty surrounding climate change cannot be used to dismiss climate change and related mitigation policies as a zero probability risk. Any rational investor with a long-term perspective should be concerned about the absence of a market for carbon and the potential market failures that could result from this incompleteness. A dynamic decarbonized index investment strategy seeks to fill this void, offering an attractive hedging tool even for climate change skeptics.

Finally, the decarbonization approach we have described for equity indexes can also be applied to corporate debt indexes. Although the focus in fixed-income markets has been on green bonds, corporate debt indexes—decarbonized along the same lines as equity indexes (screening and exclusion based on carbon intensity and fossil fuel reserves while maintaining sector neutrality and a low TE)—could be a good complement to green bonds. Similarly, low-water-use indexes and other environmental leader indexes can be constructed in the same way as our decarbonized index.

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Appendix A. Current Context of Climate Legislation

The United Nations Framework Convention on Climate Change (UNFCCC) coordinates global policy efforts toward the stabilization of GHG concentrations in the atmosphere, with a widely accepted policy target for the upcoming decades of limiting GHG emissions to keep average temperatures from rising more than 2°C by 2050. However, no concrete policies limiting GHG emissions have yet been agreed to that make this target a realistic prospect. To give an idea of what this target entails, scientists estimate that an overall limit on the concentration of CO_2 in the atmosphere between 350 parts per million (ppm) and 450 ppm should not be exceeded if we are to have a reasonable prospect of keeping temperatures from rising by more than 2°C (IPCC 2014). Maintaining CO_2 concentrations under that limit would require keeping global CO_2 emissions below roughly 35 billion tons a year, which is more or less the current rate of emissions; it was 34.5 gigatons (Gt) in 2012, according to the European Commission.

Although the process led by the UNFCCC stalled during many years following the adoption of the Kyoto Protocol, a number of countries have taken unilateral steps to limit GHG emissions in their jurisdictions. Thus, a very wide array of local regulations, as well as legislation focused on carbon emission limits and clean energy, has been introduced in the past decade—for example, 490 new regulations were put in place in 2012 as opposed to only 151 in 2004 and 46 in 1998 (UNEP FI 2013). Moreover, after promising signs of greater urgency concerning climate policies in both the United States[37] and China, the "Paris agreement" negotiated during the climate conference in Paris in December 2015 marked "an unprecedented political recognition of the risks of climate change."[38]

The Paris agreement, however, does not detail a course for action and entails many non-binding provisions with no penalties imposed on countries unwilling or unable to reach their targets. But if the prospect of a global market for CO_2 emission permits—or even a global carbon tax—also seems far off, the establishment of a national market for CO_2 emission permits in China in the next few years could be a game changer. Indeed, in the U.S.–China Joint Announcement on Climate Change and Clean Energy Cooperation, China has pledged to cap its CO_2 emissions around 2030 and to increase the non-fossil-fuel share of its energy consumption to around 20% by 2030.[39] Moreover, following the launch of seven pilot emissions-trading schemes (ETSs), which are currently in operation, China's National Development and Reform Commission (NDRC) stated that it aimed to establish a national ETS during its five-year plan (2016–2020).[40]

Yet, despite China's impressive stated climate policy goals and the Paris agreement, substantially more reductions in CO_2 emissions need to be implemented globally to have an impact on climate change. In particular, the global price of CO_2 emissions must be significantly higher to induce economic agents to reduce their reliance on fossil fuels or to make carbon capture and storage worthwhile (current estimates indicate that a minimum carbon price of $25–$30 per ton of carbon dioxide equivalent [CO_2e] is required to cover the cost of carbon capture).[41] Therefore, with the continued rise in global temperatures and the greater and greater urgency regarding strong climate mitigation policies in the coming years, policymakers may at last realize that they have little choice but to implement radical climate policies, resulting in a steep rise in the price of carbon. On top of national governments' mobilization and international agreements, major religious authorities have recently expressed their concerns about climate change, urging both governments and civil society to act.[42]

Appendix B. Risk of Stranded Assets

The notion of stranded assets was introduced by the Carbon Tracker Initiative (2011, 2013)[43] and the Generation Foundation (2013). It refers to the possibility that not all known oil and gas reserves will be exploitable should the planet reach the peak of sustainable concentrations in the atmosphere before all oil and gas reserves have been exhausted. A plausible back-of-the-envelope calculation goes as follows: According to the Carbon Tracker Initiative (2011), Earth's proven fossil fuel reserves amount to approximately 2,800 Gt of CO_2 emissions. But to maintain the objective of no warming greater than 2°C by 2050 (with at least a 50% chance), the maximum amount of allowable emissions is roughly half, or 1,400 Gt of CO_2. In other words, oil companies' usable proven reserves are only about half of reported reserves. Responding to a shareholder resolution, ExxonMobil published in 2014, for the first time ever, a report describing how it assesses the risk of stranded assets.[44] Much of the report is an exercise in minimizing shareholders' and analysts' concerns about stranded asset risk by pointing to the International Energy Agency's projections on growing energy demand without competitive substitutes leading to higher fossil fuel prices. Nonetheless, it cannot be entirely ruled out that investors will see a growing fraction of proven reserves as unexploitable because they are simply too costly—whether because of the emergence of cheap, clean, and reliable substitutes in the form of competitive clean energy or because climate mitigation policies become an increasingly binding reality (or, most likely, both).

Appendix C. Carbon Data

In this appendix, we offer further details on the available carbon emissions and carbon reserves data as well as the main providers of the carbon data we used.

Nature of Carbon Emissions and Carbon Reserves Data

Carbon emissions and carbon reserves relate to a wide array of greenhouse gases (GHGs) and hydrocarbon reserves. The standard unit of measurement is the metric ton of carbon dioxide equivalent ($MtCO_2e$), usually shortened to tons of carbon. Regarding GHG emissions, the most widely used international carbon accounting tool for governments and businesses is the GHG protocol. This protocol serves as the foundation for almost every GHG standard in the world—notably, the International Organization for Standardization (ISO) and the Climate Registry. Corporate users include BP, Shell, General Motors, GE, AEG, Johnson & Johnson, Lafarge, and Tata Group. Non-corporate users include trading schemes (EU ETS, UK ETS, Chicago Climate Exchange); nongovernmental organizations (CDP, WWF, Global Reporting Initiative); and government agencies in China, the United States, US states, Canada, Australia, Mexico, and other jurisdictions.

According to the protocol, GHG emissions are divided into three scopes. Scope 1 relates to direct GHG emissions—that is, emissions that occur from sources owned or controlled by the company (e.g., emissions from fossil fuels burned on site or in leased vehicles). Scope 2 emissions are indirect GHG emissions resulting from the purchase of electricity, heating, cooling, or steam generated off-site but purchased by the entity. Scope 3 emissions encompass indirect emissions from sources not owned or directly controlled by the entity but related to its activities (e.g., employee travel and commuting, vendor supply chain). Obviously, Scope 3 emissions represent the largest GHG impact for many companies, whether in upstream activities (e.g., consumer electronics) or downstream activities (e.g., automotive industry). Scope 3 emissions reporting still lacks standardization, however, and the reporting level remains low; only 180 of the Fortune 500 companies reported on some portion of their supply chain in 2013.[45]

The estimation of the CO_2 equivalent of carbon reserves is a three-step process that involves the classification and estimation of hydrocarbon reserves that are then translated into CO_2 emissions. Most of the time, the data used for estimation of fossil fuel reserves and stranded assets concern proven reserves (a 90% probability that at least the actual reserves will exceed the estimated proven reserves). Those data are publicly available and must be disclosed in company reports. Once the proven reserves are estimated in volume or mass, two steps remain. First, the calorific value of total fossil fuel reserves must be estimated. Second, that calorific value must be translated into carbon reserves by using a carbon intensity table.

Carbon Data Providers

At the two ends of the spectrum of carbon data providers, we found entities that simply aggregate data either provided directly by companies or publicly available as well as those that use only their internal models to estimate carbon emissions and reserves.

Corporations themselves are the primary providers of carbon data via two main channels: (1) CSR (corporate social responsibility) reports from 37% of the world's largest companies (with a market capitalization exceeding $2 billion), which completely disclose their GHG emission information; (2) CDP provides the largest global carbon-related database, in partnership with Bloomberg, MSCI ESG, Trucost, and others. Companies respond to CDP's annual information request forms for the collection of climate change–related information; the number of respondents has increased from 235 in 2003 to 2,132 in 2011. Financial data vendors, such as Bloomberg, generally provide datasets sourced from CDP, CSR reports, and other relevant reports. The heterogeneity of sources explains the discrepancies that can sometimes be found in carbon footprint measurements.

Appendix D. TE Minimization with a Multifactor Risk Model

In this appendix, we describe the multifactor risk model that we used to determine the decarbonized portfolio with minimum tracking error. We reduce *ex ante* TE by first estimating factor returns, then estimating risk, and ultimately minimizing TE.

Ex Ante and *Ex Post* Tracking Error

Index managers usually seek a very low tracking error, but some may also seek higher returns by optimizing index replication (e.g., tax optimization, management of changes in index composition, management of takeover bids). For index managers, there is a trade-off between the goals of minimizing tracking error and maximizing return. Portfolio managers use two different measures of tracking error: (1) *Ex post* TE is the measure of the volatility of the realized active return deviations from the benchmark, and (2) *ex ante* TE is an estimation (or prediction) based on an estimated multifactor model.

Ex ante TE is a function of portfolio weights, benchmark weights, the volatility of stocks, and correlations across assets. Thus, to estimate portfolio risk once portfolio weights and benchmark weights are given, we need the covariance matrix of security returns. One can estimate such a covariance matrix by using historical data of security returns, but that method is burdensome and prone to estimation error (spurious correlations).

An alternative method is to use a multifactor model. We rely on the widely used Barra multiple-factor model (MFM),[46] which decomposes the return of an individual stock into the weighted sum of common factor returns and an idiosyncratic return as follows:

$$r_i = \beta_{country\ i} f_{country\ i} + \beta_{sector\ i} f_{sector\ i} + \beta_{size\ i} f_{size\ i} + \cdots + u_i$$

$$r_i = \sum_{j=1}^{j} \beta_{ji} \tilde{f}_j + u_i$$

$$\begin{bmatrix} r_1 \\ \vdots \\ r_n \end{bmatrix} = \begin{bmatrix} \beta_{11} & \cdots & \beta_{1k} \\ \vdots & \ddots & \vdots \\ \beta_{nk} & \cdots & \beta_{nn} \end{bmatrix} \begin{bmatrix} f_1 \\ \vdots \\ f_j \end{bmatrix} + \begin{bmatrix} u_1 \\ \vdots \\ u_n \end{bmatrix}$$

$$r = \beta f + u,$$

where

β_{ji} = the factor loading for security i on common factor j

f_j = the common factor return

u_i = the part of the return that cannot be explained by common factors

Estimating Factor Returns

Common factors used by Barra include industries, styles (size, value, momentum, and volatility), and currencies; 68 factors are used for the multiple-horizon US equity model.

Common factor returns are estimated using monthly stock returns. The time series of factor returns are then used to generate factor variances and covariances in the covariance matrix:

$$\begin{bmatrix} \mathrm{Var}(f_1) & \cdots & \mathrm{Cov}(f_1, f_k) \\ \vdots & \ddots & \vdots \\ \mathrm{Cov}(f_k, f_1) & \cdots & \mathrm{Var}(f_k) \end{bmatrix}.$$

To capture variance and covariance dynamics and improve the predictive power of the model, Barra uses an exponential weighting scheme that gives more weight to recent data, and so, on average, the last two to three years of data represent 50% of the available information ("half life").

From Factor Returns to Risk Estimation

Similar to components of returns, components of risks can be divided into common factor sources and security-specific risks:

$$\mathrm{Var}(\text{total risk}) = \mathrm{Var}(\text{common factor risk}) + \mathrm{Var}(\text{active specific risk}),$$

and the multifactor equation becomes

$$\mathrm{Var}(r) = \mathrm{Var}(\boldsymbol{\beta} f + u)$$

$$\mathrm{Var}(r) = \boldsymbol{\beta}\boldsymbol{\Omega}_f\boldsymbol{\beta}' + \boldsymbol{\Delta},$$

where

$\boldsymbol{\beta}$ = the matrix of factor exposures

$\boldsymbol{\beta}'$ = the transposed matrix

$\boldsymbol{\Omega}$ = the variance–covariance matrix for the k factors

$\boldsymbol{\Delta}$ = the diagonal matrix of specific risk variances

The volatility, σ_p, of any portfolio p, represented by a vector of portfolio weights $\mathbf{W}_p$, is thus

$$\sigma_p = \sqrt{\mathbf{W}_p\left(\boldsymbol{\beta}\boldsymbol{\Omega}_f\boldsymbol{\beta}' + \boldsymbol{\Delta}\right)\mathbf{W}_p'}.$$

TE Minimization

In the case of tracking error minimization, the objective function is the *ex ante* tracking error; constraints can range from turnover limits to reweighting rules with or without active weight constraints, among others.

Let us consider an example of a low-carbon, low-TE, multi-utilities fund. First, we have a reference universe of 10 constituents: the multi-utilities industry group in the utilities sector in a large economic zone. We assign to each constituent an index weight equal to $\left[\text{Mkt cap}(i)/\text{Total mkt cap}\right]$ in order to obtain a market cap–weighted index, and we let $\left(w_1^b,\cdots,w_{10}^b\right)$ be the constituent stocks' weights. We rank the constituents according to their carbon intensity (e.g., CO_2e/GWh) and then adopt the following constraint (rule):

$$\begin{pmatrix} w_1^b \\ w_2^b \\ \vdots \\ w_{10}^b \end{pmatrix} \Rightarrow \begin{pmatrix} 0 \\ w_2 \\ \vdots \\ w_{10} \end{pmatrix}.$$

In other words, the optimal portfolio $(0, w_2, \cdots, w_{10})$ will be the result of the minimization of the following objective function:

$$\text{Min}\left[\sqrt{\left(W^p - W^b\right)'\left(\boldsymbol{\beta}\boldsymbol{\Omega}_f\boldsymbol{\beta}' + \boldsymbol{\Delta}\right)\left(W^p - W^b\right)}\right],$$

where

$$\forall i = 1,\cdots,10;\ 0 \le w_i$$
$$i = 1;\ w_1 = 0,$$

and

$\left(W^p - W^b\right)$ = the active weights of the portfolio with regard to the benchmark
$\boldsymbol{\Omega}_f$ = the variance–covariance matrix of factors
$\boldsymbol{\beta}$ = the matrix of factor exposures
$\boldsymbol{\Delta}$ = the diagonal matrix of specific risk variances

Barra uses an optimization algorithm to minimize TE under the new constraint of excluding stock 1. It selects active weights depending on the factor loading of each security and the covariance between each factor in order to create a new portfolio that closely tracks the reference portfolio.

Appendix E. Performance Attribution in the MSCI Europe Low Carbon Leaders Index vs. the MSCI Europe Index

In this appendix, **Table E1**, **Table E2**, and **Table E3** give several measures of performance attribution for various sectors in the MSCI Europe Low Carbon Leaders Index versus the MSCI Europe Index.

Appendix F. Percentage Contributions to Specific Risks by Sector

In this appendix, **Figure F1** depicts the breakdown of the percentage contributions to specific risks by sector.

Figure F1. Percentage Contributions to Specific Risks by Sector

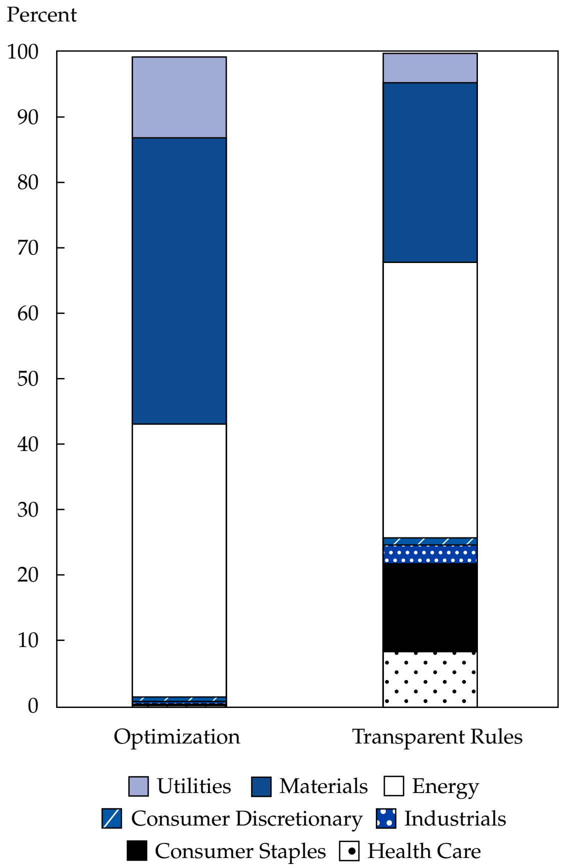

Table E1. MSCI Europe Low Carbon Leaders vs. MSCI Europe, 7 November 2014–31 January 2016

	MSCI Europe Low Carbon Leaders Index			MSCI Europe Index			Attribution Effect		
Sector	Weight	Total Return	Contribution to Return	Weight	Total Return	Contribution to Return	Allocation Effect	Selection Effect	Total Effect
Total	100.00	6.06	6.06	100.00	4.17	4.17	0.37	1.52	1.89
Materials	6.18	2.65	0.20	7.23	–17.72	–1.10	0.20	1.27	1.47
Utilities	3.87	7.55	0.30	4.00	0.83	0.04	0.02	0.25	0.27
Health care	13.48	11.16	1.29	13.84	9.28	1.12	0.00	0.21	0.21
Consumer discretionary	12.57	12.58	1.41	11.45	12.18	1.23	0.09	0.05	0.15
Industrials	12.93	7.74	0.98	11.04	7.11	0.74	0.06	0.07	0.14
Telecommunication services	5.61	17.44	0.89	4.95	16.58	0.70	0.08	0.05	0.13
Information technology	3.69	25.97	0.93	3.56	21.92	0.69	0.02	0.11	0.13
Financials	24.64	–4.18	–1.18	22.75	–4.55	–1.26	–0.15	0.11	–0.04
Energy	5.15	–26.05	–1.33	7.13	–16.82	–1.10	0.40	–0.52	–0.12
Consumer Staples	11.90	22.71	2.56	14.07	24.19	3.12	–0.37	–0.08	–0.45

Sources: Amundi; MSCI; FactSet.

Table E2. MSCI Europe Low Carbon Leaders vs. MSCI Europe—Materials Sector, 7 November 2014–31 January 2016

	MSCI Europe Low Carbon Leaders Index			MSCI Europe Index			Attribution Effect		
Sector	Weight	Total Return	Contribution to Return	Weight	Total Return	Contribution to Return	Allocation Effect	Selection Effect	Total Effect
Materials	6.18	2.65	0.20	7.23	–17.72	–1.10	0.20	1.27	1.47
Diversified metals and mining	0.75	–23.73	–0.36	1.84	–55.54	–1.15	0.68	0.36	1.04
Construction materials	0.47	28.56	0.10	0.75	–0.75	–0.01	0.01	0.11	0.12
Specialty chemicals	1.69	14.25	0.32	1.16	12.26	0.12	0.04	0.03	0.06
Steel	0.34	–23.61	–0.06	0.27	–43.40	–0.11	–0.04	0.09	0.06
Diversified chemicals	1.27	–7.61	–0.06	1.16	–9.39	–0.06	–0.02	0.02	0.00

Sources: Amundi; MSCI; FactSet.

Table E3. MSCI Europe Low Carbon Leaders vs. MSCI Europe—Utilities Sector, 7 November 2014–31 January 2016

	MSCI Europe Low Carbon Leaders Index			MSCI Europe Index			Attribution Effect		
Sector	Weight	Total Return	Contribution to Return	Weight	Total Return	Contribution to Return	Allocation Effect	Selection Effect	Total Effect
Utilities	3.87	7.55	0.30	4.00	0.83	0.04	0.02	0.25	0.27
Multi-utilities	1.43	–0.20	–0.01	1.82	–8.02	–0.13	0.08	0.11	0.19
Water utilities	0.38	21.29	0.09	0.21	21.24	0.04	0.03	0.00	0.03
Electric utilities	1.45	12.10	0.18	1.63	7.66	0.10	–0.03	0.05	0.03
Gas utilities	0.50	10.96	0.05	0.30	10.84	0.03	0.01	0.00	0.01
Renewable electricity	0.11	–3.12	0.00	0.04	–3.12	0.00	0.00	0.00	0.00

Sources: Amundi; MSCI; FactSet.

Notes

1. A recent study by a team from the National Oceanic and Atmospheric Administration found that this perceived slowdown was entirely the result of measurement errors in recorded ocean temperatures (Karl, Arguez, Huang, Lawrimore, McMahon, Menne, Peterson, Vose, and Zhang 2015).
2. For an analysis of the consequences of this deep uncertainty for the economics of carbon pricing, see Litterman (2012).
3. For a widely quoted speech on climate change and the "tragedy of horizon" and related "transition risks," see Carney (2015).
4. The United Nations Framework Convention on Climate Change (UNFCCC) coordinates global policy efforts toward the stabilization of greenhouse gas (GHG) concentrations in the atmosphere, with a widely accepted policy target for the coming decades of limiting GHG emissions to keep average temperatures from rising more than 2°C by 2050. However, no concrete policies limiting GHG emissions have yet been accepted that make this target a realistic prospect. Although the process led by the UNFCCC stalled following the adoption of the Kyoto Protocol, a number of countries have taken unilateral steps to limit GHG emissions in their own jurisdictions. The 21st Conference of the Parties to the UNFCCC, which was held in Paris in December 2015 (http://www.un.org/sustainabledevelopment/cop21/), is seen by many observers as a crucial milestone in the fight against climate change. For further details, see Appendix A.
5. A handful of organizations contribute to raising awareness of carbon risk among institutional investors. For example, the Portfolio Decarbonization Coalition (PDC)—co-founded by AP4, CDP, Amundi, and UNEP FI in September 2014—enables pioneers in the decarbonization of portfolios to share their knowledge and best practices. When it was founded, PDC set a target of $100 billion in institutional investment decarbonization to be reached by the time of the Paris conference in December 2015. It was able to significantly surpass this target, with its 25 members claiming $600 billion of decarbonized investments out of $3.2 trillion of assets under management. For more information, see http://unepfi.org/pdc/ and Top1000Funds (2015). Another example is the "Aiming for A" coalition—a group representing institutional investors—which engages carbon-intensive companies to "measure and manage their carbon emissions and move to a low-carbon economy."
6. For more information on stranded assets, see Appendix B.
7. The carbon footprint of a company refers to its annualized GHG emissions relative to a financial metric (e.g., revenue or sales) or a relevant activity metric (e.g., units produced). For further details, see the pertinent discussion later in the article as well as Appendix C.
8. See Gartner, Inc. (2016).
9. Later in the article, we report the performance results of the "decarbonized" S&P 500 and MSCI Europe indexes.
10. The mechanics that affect the relationship of carbon legislation, technological changes, and financial returns are obviously complex and not straightforward. But the purpose of decarbonized indexes is to circumvent these difficulties by focusing on an area with somewhat less uncertainty: the companies most exposed to carbon risk. Later in the article, we delve into further details.
11. To explore the links between portfolio decarbonization and the incentives it gives to companies to rechannel their investments and lower their carbon footprint, see http://unepfi.org/pdc/wp-content/.
12. Koch and Bassen (2013) estimated an "equity value at risk from carbon" for European electric utilities, which is driven by their fossil fuel mix, and showed that a filter on companies with a high carbon-specific risk reduces the exposure to global carbon risk without otherwise affecting the risk–return performance of an equity portfolio.
13. See "Energy and Carbon—Managing the Risks," ExxonMobil report (March 2014).
14. These are mostly environmental, social, and governance (ESG) analysts, who until recently were largely segregated from mainstream equity analyst teams and whose audience consists predominantly of ethical investors.
15. HSBC is a notable exception, with its early integrated analysis of the materiality of carbon risk in the oil and gas as well as coal industries (HSBC 2008). Since then, the Carbon Tracker Initiative has been instrumental in raising awareness of stranded asset issues, and energy-focused analysts are increasingly and consistently integrating carbon-related risk into their analyses (see, e.g., HSBC 2012; Lewis 2014).
16. A multisector generalization of this optimization problem can break down the first set of constraints into companies that are excluded on the basis of their poor ranking in carbon intensity across all sectors, as well as companies that are excluded within each sector on the basis of either their poor carbon intensity score or high stranded assets relative to other companies in their sector.
17. Unless noted otherwise, tracking error is calculated *ex ante*.
18. This level of outperformance over such a time frame is hypothetical and for illustrative purposes only. Although we hope that a scenario of radical climate risk mitigation policy measures is possible in the near future, global climate policy implementation and its potential impact on equity valuation understandably remain a very speculative exercise.
19. In this respect, it is worth mentioning that Veolia and Danone now include carbon footprint improvement targets in their executive compensation contracts.
20. An interesting example of such a mechanism is the JPX-Nikkei Index 400, a new index based on both standard quantitative criteria (e.g., return on equity, operating profit, and market value) and more innovative qualitative criteria (e.g., a governance requirement of at least two independent outside directors). Launched with the support of the giant Japanese pension fund GPIF (Government Pension Investment Fund) to foster better corporate performance, the JPX-Nikkei 400 was quickly dubbed the "shame index." It is now carefully scrutinized by analysts, and companies are taking inclusion in the index more and more seriously.
21. For a discussion of the relationship between sustainability investments and shareholder value creation, see Khan, Serafeim, and Yoon (2015).
22. For an attempt at comparing different providers' results within a given universe, see http://www.iigcc.org/events/event/50-shades-of-green-carbon-foot-print-workshop. The differences that emerged came from different estimation models. But professionals agree that the measures are globally converging toward a much-improved harmonization.
23. For 60% of the companies in the MSCI World Index, at least 75% of emissions are from supply chains (Trucost 2013).
24. Moreover, most modern optimization techniques use factor exposures and correlations to reduce tracking error risk from such known systematic factors as volatility, small cap, and beta; they would therefore increase the weights on high-volatility/low-carbon stocks to replace high-volatility/high-carbon stocks.
25. Index and ETF investments represent a growing share of total investment products, amounting to almost 14% of total assets under management, with a year-over-year growth rate of 10% from 2013 to 2014.
26. Beyond the $11 trillion in index funds, asset owners that are members of CDP represent an asset base as high as $95 trillion (see CDP.net).
27. When AP4 started investing in 2012, a 48% reduction in carbon footprint was achieved.

28. For an early analysis of carbon-efficient indexes in emerging markets, see Banerjee (2010).
29. The criteria for excluding a stock from the index are straightforward: First, companies with the highest emissions intensity (as measured by GHG emissions/sales) are excluded, with a limit on cumulative sector weight exclusion of no more than 30%. Second, the largest owners of carbon reserves per dollar of market capitalization are excluded until the carbon reserves intensity of the index is reduced by at least 50%.
30. Our performance attribution analysis was for the MSCI Europe Low Carbon Leaders Index from 7 November 2014 to 29 January 2016.
31. During the same period, the MSCI North America Low Carbon Leaders Index outperformed the MSCI North America Index by 121 bps.
32. The allocation effect measures whether the choice of sector allocation led to a positive or negative contribution. All else being equal, overweighting outperforming sectors leads to a positive allocation effect.
33. The selection effect measures within each sector whether the portfolio manager selected the outperforming or underperforming stocks.
34. The Global Industry Classification Standard is an industry taxonomy consisting of 10 sectors, 24 industry groups, 67 industries, and 156 sub-industries.
35. Notable exceptions include the French government, which took a lead role ahead of the Paris conference in mobilizing the financial sector by requiring institutional investors to report on their climate risk exposure. A handful of central banks have also been instrumental in raising awareness of the possible hazards of climate change regulations and the potential mobilization of financial institutions. Significant contributions include the People's Bank of China and UNEP Inquiry (2015) report "Establishing China's Green Financial System" and the Bank of England's ongoing prudential review of climate-related risks to the financial sector.
36. See Article 173 of *Projet de loi relative à la transition énergétique pour la croissance verte*: "La prise en compte de l'exposition aux risques climatiques, notamment la mesure des émissions de gaz à effet de serre associées aux actifs détenus, ainsi que la contribution au respect de l'objectif international de limitation du réchauffement climatique et à l'atteinte des objectifs de la transition énergétique et écologique, figurent parmi les informations relevant de la prise en compte d'objectifs environnementaux." // "The information relative to the consideration of environmental objectives includes: the exposure to climate-related risks, including the GHG emissions associated with assets owned, and the contribution to the international goal of limiting global warming and to the achievement of the objectives of the energy and ecological transition."
37. Prominent voices in the business community have expressed their concern that the debate over climate policy has become too politicized. Also, in June 2014, the US Environmental Protection Agency unveiled an ambitious program calling for deep cuts in carbon emissions from existing power plants, with a 30% national target by 2030—which is equivalent to 730 million tons of carbon emission reductions, or about two-thirds of the nation's passenger vehicle annual emissions.
38. See "The Paris Agreement Marks an Unprecedented Political Recognition of the Risks of Climate Change," *Economist* (12 December 2015).
39. See https://www.whitehouse.gov/the-press-office/2014/11/11/fact-sheet-us-china-joint-announcement-climate-change-and-clean-energy-c.
40. The interregional ETS covering the Beijing, Tianjin, and Hebei Provinces was under discussion in February 2016, at the time of writing. In addition, the National Development and Reform Committee issued a paper in February 2016 that set up an agenda to ensure the establishment of a national ETS in 2017. We note that following China's lead, a movement is underway to move away from existing oil and gas subsidies. According to a recent IMF study by Coady, Parry, Sears, and Shang (2015), global subsidies for fossil fuels were estimated to be $333 billion in 2015.
41. The current price level is far below $30, with average carbon prices ranging from the lowest at RMB9.00/tCO$_2$e in Shanghai to the highest at RMB44.4/tCO$_2$e in Shenzhen, with others traded at RMB35 in Beijing, RMB23 in Tianjin, RMB22 in Hubei, RMB13 in Chongqing, and RMB14 in Guangdong (as of 4 March 2016); around EUR4.96/CO$_2$e (as of 7 March 2016) in Europe; and $7.5/CO$_2$e under the Regional Greenhouse Gas Initiative in the United States (as of 2 February 2016).
42. Pope Francis's *Laudato Si'* encyclical (published in May 2015), Muslim scholars' *Islamic Declaration on Global Climate Change* (published in August 2015), and US rabbis' *Rabbinic Letter on the Climate Crisis* (released in May 2015) show that climate change has become a shared concern among religious authorities.
43. For a recent study on the risk of stranded assets, see Lewis (2014).
44. See ExxonMobil (2014); Shell followed with its "Open Letter on Stranded-Asset Risk" in May 2014.
45. See https://www.greenbiz.com/blog/2013/08/12/hybrid-lcas-help-companies-size-scope-3-emissions.
46. For a thorough review of Barra equity risk modeling, see MSCI Barra (2007).

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