EDHEC-RISK Climate Impact INSTITUTE

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EDHEC BUSINESS SCHOOL

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Introduction

I am delighted to present the inaugural EDHEC-Risk Climate Impact Institute issue of the EDHEC Research Insights supplement to Investment & Pensions Europe.

Since 2001, EDHEC Business School has pursued an ambitious research agenda, combining academic excellence with practical relevance. Our approach involves advancing scientific inquiry in areas in which the school has reached critical mass in terms of expertise and research results and highlighting practical implications and applications to decision-makers. Additionally, we foster strategic partnerships and business ventures supported by the EDHEC Endowment Fund to expedite the transfer of innovation to the industry.

This approach was initiated by risk and investment management research centre EDHEC-Risk Institute, which has now become EDHEC-Risk Climate Impact Institute, reflecting the school's commitment to advancing sustainability across economic activities and helping organisations to integrate sustainability risk and impact considerations into strategic and operational decision-making processes.

At the forefront of this inaugural issue is the groundbreaking research on climate risk modelling led by our Scientific Director, Professor Riccardo Rebonato, and his team. This research, supported by index provider Scientific Beta, aims to extend and repurpose climate scenario analysis and stress testing methodologies. The current scenario analysis framework originated from the need to inform public policy and has developed through a global collaboration between leading experts in climate science, economics, and related fields. This earlier work is of excellent scientific quality but is not meant to serve the needs of investors: no asset pricing implications can be drawn from reference scenarios that do not have probabilities associated with them. And selecting a reference scenario for stress testing without information about likelihood may lead to misallocation of resources and ineffective risk management. Reporting on the first breakthroughs from our climate risk modelling research, Professor Rebonato demonstrates how to identify strong relationships between economic, demographic, and technological variables to derive probability distributions of climate outcomes. These distributions enable investors to gauge the level of uncertainty they face, and discern which outcomes are more likely, thus warranting greater attention.

Drawing on these advances, Doctor Dherminder Kainth, Research Director, subjects the IPCC SSP/RCP framework to scrutiny using model risk management approaches. He underscores the importance of identifying and consistently modelling key risk drivers, particularly when extending the framework to areas such as asset pricing. He also highlights potential shortcomings in the framework's design, which may underestimate risk and foster a false sense of security regarding the impacts of climate change and the trajectory of the climate transition. In this latter respect, a second article by Professor Rebonato contends that the next phase of decarbonisation is likely to require major public involvement, which may be funded by either taxation or debt. He illustrates how debt financing could directly impact government bond prices and indirectly influence equity valuation through the discounting channel.

Two contributions in this issue examine the investor value and greenwashing risks associated with two key metrics identified by the Task Force on Climate-related Financial Disclosures. Professor Gianfranco Gianfrate discusses the lack of correlation between disclosure of internal carbon prices and carbon intensity reduction, emphasizing the need for evidence of integration into corporate decision-making. The other contribution delves into the risk and impact materiality of value chain emissions, identifies critical data deficiencies, and offers recommendations for investors and standard-setters.

The final contribution, authored by Professors Teodor Dyakov and Dominic O'Kane, looks at how the experience of extreme weather events across the world influences the investment choices of mutual fund managers. Their results suggest further greening of portfolios from more frequent climate events. This research benefits from the support of Amundi.

We hope that these articles will prove valuable, informative and insightful to our readers. We extend our sincere appreciation to IPE for their collaboration on this endeavour.

Frédéric Ducoulombier, Director, EDHEC-Risk Climate Impact Institute

How can strategic investors deal with climate uncertainty?

Riccardo Rebonato, Scientific Director, EDHEC-Risk Climate Impact Institute; Professor of Finance, EDHEC Business School

Climate scenarios are indispensable to investors because of the unprecedented nature of climate change. Since market 'expert knowledge' is not available, they must come equipped with probabilities.

Current scenarios were created with policy goals in mind. Despite their excellent quality, they do not serve the needs of investors well. In particular, they have no probabilities associated with them, and do not adequately convey the huge uncertainty in climate outcomes.

We show how it is possible to create probability *distributions* of climate outcomes, that allow investors to appreciate the degree of uncertainty they face, and to judge which realisations are more likely, and should therefore command greater attention.

The climate challenge for strategic investors

Climate risk is a new source of concern for strategic investors. There are many reasons why they should be worried. First of all, like market risk, it is a *systematic* risk, and, as such, cannot be eliminated by diversification. Second, exactly because it is systematic, it may in principle attract a risk premium: whether this should be positive or negative (or, zero) is, however, far from easy to ascertain.[1] Third, climate risk is by its very nature radically new, and investors cannot refer to an accepted 'playbook' of responses, as they would in the case of, say, market or credit risk – they are stepping into uncharted investment territory.

In order to tackle these sources of concern, investors must be able to form an idea of the most plausible climate outcomes, of what may 'lurk in tails', and of 'thickness' of the distribution between the central moment and the tails of the distribution – roughly speaking, of the degree of uncertainty. This explains why they have recently looked with renewed interest at climate scenario analysis and climate stress testing. We shall argue that this interest is well placed, but also that, in the climate risk domain, these analytical tools must be embedded in a probabilistic framework.

One often hears the objections that market scenarios are routinely used by practitioners without explicit probabilities attached to them. Why should climate scenarios be different? The reason is that, when it comes to market scenarios, investment professionals have (often painfully) built a precious body of expert knowledge based on 100 years-plus of financial data. This body of knowledge allows them to carry out 'informal' probability assessments of the likelihood of a market scenario – in practical terms, it allows them to tell whether and how much they should worry about the scenario in question. And, if one really wanted, a more formal probabilistic assessment of the likelihood of a market scenario could always be carried out based on the historical frequency of past market moves. Not so, however, in the case of climate outcomes, whose dynamic and unprecedented nature brings to the fore completely new challenges.

Unfortunately, the best-known and most widely used climate scenarios (which have been created under the auspices of the Intergovernmental Panel on Climate Change) do not have any probabilistic dimension, and this is one of the reasons why they do not serve the needs of investors well. This is not because the existing scenarios are of poor quality – far from it: they are of *excellent* quality, and teams of world-known experts have contributed to their formulation. However, these scenarios were not created with the need of investors in mind because they were built with a policy focus.

Shouldn't policy-useful scenarios also serve the needs of investors? Not necessarily. First of all, in the policy area, it is reasonable to err on the side of caution (a 'policy tilt' underpinned by the so-called 'precautionary principle'). When it comes to investing, however, there is no 'safe way to be wrong': for a long-term investor faced with climate risk, the consequences of an excessively prudent asset allocation can be every bit as severe as the results of an overly aggressive stance.

Second, as mentioned, the currently used IPCC-endorsed scenarios have completely eschewed *any* assessment of their relative likelihood. Because of their policy origin, this makes historical sense, but it is of no use to financial planners, who need an understanding of what the most plausible outcomes may be; of how uncertain we are about these estimates; and of what may happen if things go really wrong – in short, what they need is a *probability distribution* of climate outcomes.

From scenarios to probability distributions

For these reasons, we have already argued (Rebonato, Kainth and Melin [2024]) that the probability agnosticism of the IPCC scenarios makes them poorly suited to the needs of investors. Most contentiously, we intend to show here that the very language of scenarios is poorly suited to

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[1] In work forthcoming in *The Journal of Portfolio Management* (Rebonato [2024]), we explain why determining the sign, let alone the magnitude of the climate risk premium is particularly difficult, both from the empirical and the theoretical point of view.

dealing with climate uncertainty, and that investors must familiarise themselves with the related but distinct dialect of probability distributions. (The required step is not as big as it might seem: after all, investors routinely handle the concepts of expected returns and variance – and, when they do so, they often have in the back of their minds an underlying normal distribution with these parameters. The challenge is that, when it comes to climate outcomes, their distribution is going to be far more skewed and even more fat-tailed than the distribution of market outcomes.)

To understand why the language of scenarios is poorly suited to the climate domain, it pays to look in some detail at the IPCC-endorsed scenarios, which have become, or have inspired, the current benchmark scenario approach.[2] These are made up of a combination of socioeconomic narratives (SSPs) and representative pathways of carbon emissions (RCPs). The socioeconomic narratives cover such diverse aspects as demographic growth, technological progress and economic development – to say nothing of political and social features such as 'resurgent nationalism' or 'growth of inequality'. These narratives are compelling and, the more detailed they are, the more convincing they sound. The problem is that, with so many variables at play, there is a staggering number of possible ways to combine them. Since each combination is a possible narrative, there are far too many 'possible worlds' for the human mind to handle with any ease: if we allow for as few as three variables, each allowing a 'high', 'medium' and 'low' state, 162 scenarios result. And this is why the IPCC has created only six such narratives. Each one is both engaging and coherently structured. However, these six possible ways in which the world may evolve over the rest of the century certainly do not span the full range of possible outcomes, and, since they have not been associated with *any* probability, one cannot even argue that these are the most representative or likely narratives – the ones that should command investors' undivided attention. They are just six 'plausible' stories.

This matters. When one works out what, say, climate damages might be if the third narrative unfolded, one is in effect conditioning on the very specific realisation of all the socioeconomic variables in that narrative. This means that the calculated damages only apply if that particular narrative unfolds – an event about whose probability investors are given no indication. It comes to little surprise, then, that the Network for the Greening of the Financial System should have chosen the narrative with the monicker 'Middle of the Road' as the *only* narrative around which all its scenarios have been built. Given the name, it is understandable that it should have been interpreted as the most likely, and therefore singled out as the one worthy of most attention, but the name hides the fact that no such probabilistic statement is made in the SSP/RCP approach!

Since, in isolation, each narrative is plausible, an investor may well form her own opinion about its likelihood; however, she will immediately note that many possible combinations of the underlying variables are missing (for instance, the plausible 'Green Growth' scenario of high abatement obtained alongside high economic growth and declining population growth is not present). In technical terms, the six IPCC-chosen scenarios do not span the sample space, and therefore one cannot just associate them with probabilities adding up to 1.

The situation is even more complex. The multitude of pathways that lead to a given climate outcome still do not uniquely define what an investor is truly interested in, ie, the climate damages that may affect their portfolio: to link temperatures to damages one needs a damage function – and, as discussed in Rebonato, Kainth and Melin (2024) and Kainth (2023), this introduces additional uncertainty. And the temperature at the end of the century (or on any other date) will also depend on the abatement policies chosen along the path. Even if, again, we only allow these two variables (the severity of damages and the aggressiveness of the abatement policy) to assume a 'low', a 'medium' or a 'high' value, this still brings about a further multiplication of scenarios. Once we allow also for the damage exponent to assume a 'low', 'medium' or 'high' value,[3] the 162 scenarios mentioned above become 4,374. So, the damages associated with an investor's portfolio are conditional on a certain realisation of the demographics, of the economy, of the technology, of the abatement aggressiveness and of the damage exponent – and, even if we rely on bold assumptions, we have thousands of such combinations. Admittedly, some combinations may be highly unlikely, but the plausible combinations are far more than six! It is clear that, in the climate-risk context, a naïve scenario approach is fraught with huge problems. This way of presenting the problem, however, also points to its possible resolution.

Suppose for a moment that the scenario builder has chosen the low, medium or high values for each of the state variables to have the same probability. If this is the case, we can group the thousands of (now equiprobable) scenarios into subsets that produce approximately the same damages, and associate to these damages a probability. For instance, one may find that, out of the 4,374 overall scenarios, 87 produce portfolio damages between X and Y%: this means that probability of portfolio losses in that range is approximately 87/4,374 = 2%. The way we have presented the 'problem with scenarios' has naturally led to *probability distributions*, and these, we claim, are the correct tools for a problem as complex as climate risk.

The procedure we have sketched was of course predicated on the modeller's ability to choose 'low', 'medium' and 'high' values of *equal probability*.[4] This is clearly a challenge. For some variables, such as GDP growth, we may have a wealth of historical data spanning centuries that can be extrapolated into the future. For technological progress, we may also have empirical data about the pace of innovation observed in the recent past, and some grounds for projecting future levels of technological development and their dispersion. But quantities such as the 'aggressiveness' of an abatement policy pose a much greater challenge. Even in this case, however, *something* meaningful can be said.

Looking under the bonnet – what the SSP/RCP scenarios imply

To understand both how difficult it is to assign probabilities to quantities such as policy aggressiveness, and how one may try to solve the problem, let us go back to the SSP/RCP scenario framework. We

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[2] The 'hidden assumptions' in the IPCC scenarios are analysed in this issue in the companion paper, Assessing the SPP/RCP framework for financial decision-making, by Dherminder Kainth.

[3] The SSP/RCP approach attempts to reach a much finer granularity in the policy resolution, as it presents six (not three) different values for the horizon forcing (forcing represents the difference between energy in and energy out, and can be related to a temperature). Each forcing is therefore the result of a policy. Again, no probabilities are associated with these implicit policies, despite the fact that some appear implausibly aggressive, and others even more hesitant than the current pace of decarbonisation. In the SSP/RCP approach the implicit policy is translated in the social carbon tax (carbon tax) levied along the path. More about this in the text.

[4] The 'low', 'medium' and 'high' partition of the sample space for each variable is clearly introduced for illustrative purposes. In practice, one would use Monte Carlo sampling techniques, which allow one to handle multiple sources of uncertainty, and to obtain much finer spatial resolution.

have so far looked mainly at the narrative but, as mentioned, these are coupled to different degrees of abatement aggressiveness via the Representative-Carbon-Pathway variable – a quantity that can be intuitively understood as the temperature resulting from that policy.[5] The way the coupling is achieved is by tuning the degrees of freedom of the IPCC-approved models to reflect the chosen narrative. These fine-tuned ('calibrated') models then optimise a single variable, the *carbon tax*, in such a way as to obtain the desired horizon temperature with the minimum cost: the carbon tax is assumed to be spent in the most efficient way on the abatement and removal technologies necessary to limit the temperature increase to the desired value.

This seems a reasonable enough procedure. However, the users of the IPCC-endorsed probability-agnostic scenarios have no way of knowing (short of looking carefully under the bonnet of the SSP/RCP engine as we have done) whether the 'solution' (the carbon tax) found by the model makes economic sense. Very few users, for instance, are aware that a 2°C warming is just not possible for the Regional-Rivalry SSP3 – *which means that it has zero probability*. If we recall that, globally, we spend between 3% on education and defence, and about 8% on the biggest spend item of all, healthcare, surely these levels of taxation must be associated with very low probabilities – *probabilities that are inherited by the associated SSP/RCP combinations, ie, scenarios*. However, all the scenarios are presented on the same probabilistic footing.

One can also look at the problem from a technological, rather than fiscal, angle. Let us consider the combination of the Middle of the Road narrative with the goal of keeping the temperature increase under 1.5°C. Under this combined scenario, in 10 years' time (from 2020 to 2030) abatement expenditures would climb from 8% to almost 60% of GDP. Even assuming no real GDP growth, this would equate to approximately \$60trn devoted in 2030 to the installation of wind turbines and solar panels. Let us neglect for a moment the fiscal plausibility of such a level of taxation. We can still perform some quick back-of-the-envelope calculations to get a feel for the technological feasibility of this scenario. To keep the argument as simple as possible, let us neglect direct air capture and carbon sequestration and storage (which are in any case likely to play a minor role between now and 2030), and let us assume that the burden of decarbonisation of the whole economy (not just of the energy sector) is split 50-50 between solar installations and wind turbines.

Assuming a cost of \$2m-4m for a wind turbine, this equates to 10m turbines being installed every year (and the pace of turbine installation to be *increased* in the following decades). But, according to the Global Wind Energy Council, the total installation of wind turbines in the world to date (cumulative, not per annum) has been 341,000. Clearly, also simple technological considerations indicate that the probability of this scenario combination should be extremely low. But since the investors using the scenarios are nowhere told of the low likelihood of these, they are given no indication about where they should 'look for climate trouble'. As explained above, what investors require is a probability distribution of possible climate outcomes, but this is not part of the current scenario landscape. We therefore move to showing how it can be obtained.

Building probability distributions for climate outcomes

When it comes to probability distributions of climate outcomes, one must distinguish between baseline and policy distributions: the former apply to a world in which no abatement actions are taken; the latter consider the effect of abatement policies of different aggressiveness. Creating the policy distribution is clearly more challenging, as one must also take into account the effect on temperatures of different courses of climate action, which are highly uncertain. Policy distributions can therefore be either conditional, when one abatement path is assumed to prevail; or unconditional, when one averages over all the possible abatement policies, each weighted by its probability of occurrence. We shall see how this can be done.

For both types of distributions, a good starting point is the Kaya (1990) identity, which, for each region, expresses emissions as the product of the *population*, times how rich the region is (GDP/Population), times how much energy this region requires to produce one unit of GDP (Energy/GDP), times the amount of emissions required, given the technology of that region, to obtain one unit of energy (Emissions/Energy):

$$\begin{aligned}&Emissions = \\ &Population \times GDP / Population \times Energy / \\ &GDP \times Emissions / Energy\end{aligned} \qquad (1)$$

The blueprint for arriving at a distribution of climate outcomes from this relationship then unfolds as described below, first for the baseline case and then for the policy case.[6]

The baseline case

Let's consider the simpler baseline case first – the case, that is, of no policy action. Empirically, one finds that both the energy intensity of GDP and the emission intensity are a (noisy) function of GDP/person.[7] The rate of growth of the population is also found to display a statistically significant dependence on GDP/person. Therefore, all the terms on the right-hand side of equation (1) can be expressed as some function of GDP/person, plus residual noise. As an illustration, figure 1 shows the (noisy but clear) relationship between the rate of growth of the population and GDP/person (in thousands of dollars, on the x axis). One can obtain these relationships directly from empirical data, or one can reverse-engineer them from the output of the SSP/RCP models, as described in Rebonato, Kainth and Melin (2024).[8]

In either case, the key point is that there exist a number of well-established economic models that can produce distributions of GDP (and, as a byproduct, of GDP/person) at various horizons. Thanks to the noisy relationships between energy intensity, population growth and emission intensity on the one hand, and GDP/person on the other from a distribution of GDP/person via the Kaya identity, one can therefore obtain a distribution of emissions. From this, well-established climate models can produce a distribution of temperatures. When these are coupled with a chosen damage function, these temperature distributions can then be related to distributions of economic damages (ultimately, impairments to cashflows).

Each of these steps requires, of course, careful handling and adds significant uncertainty, but the conceptual path to arrive at a distribution of climate outcomes *in the baseline case* is clear enough.

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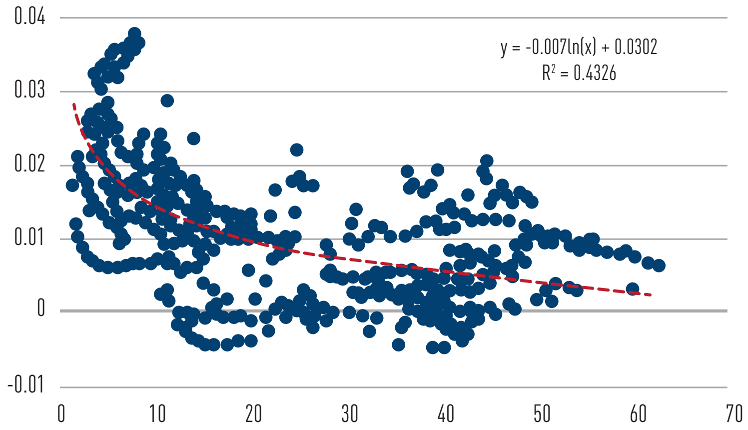
[5] The Representative Carbon Pathways are characterised by a forcing (difference in energy in and energy out per unit time) at a chosen horizon, expressed in W/m^2. As an approximation one can then translate the forcing into a temperature.

[6] We present in this paper only the main conceptual steps behind the procedure. More details can be found in Rebonato, Kainth and Melin (2024).

[7] The decreasing dependence of the energy intensity as a function of GDP/person as societies become richer is in large part due to the shift from manufacturing to services observed in rich economies. As societies become richer, technological progress tends to reduce the fossil-fuel intensity of energy production. The two effects together contribute to the so-called environmental Kuznets curve.

[8] The advantage of the latter procedure is that one remains as close as possible to the widely accepted SSP/RCP framework.

1. The rate of population growth as a function of GDP/person ($1,000) on x axis



One ‘simply’ has to map a distribution of future economic output (something that can be directly obtained as a by-product from any of the many Dynamic Stochastic General Equilibrium models in the literature) onto a distribution of future climate damages. The numerical challenges are non-indifferent, but the conceptual path is well trodden. To deal with the policy case, one must be more creative.

The policy case

The challenge ahead of us is how to create a distribution of climate outcomes in the presence of abatement policies. If the scenario user wanted to explore how a chosen abatement policy would change the baseline distribution, the only modification required would be to alter the term Emissions/GDP in the Kaya identity to reflect the effects of the chosen policy. All the plumbing already in existence to handle the baseline case would remain unchanged. This is simple enough, but of limited use.

What an investor would really like to have access to is not a distribution of damages dependent on a particular abatement path prevailing, but a damage distribution that reflects the unavoidable uncertainty about courses of abatement policy. This can be arrived at as follows.

First of all, as we explain in Rebonato, Kainth and Melin (2024), one can establish a close mapping between the optimal carbon tax and the aggressiveness of an abatement policy. The details are somewhat subtle, but the intuition is clear: since all the carbon tax is assumed to be spent on (efficient) abatement, knowing one quantity is almost tantamount to obtaining the other. And, once the abatement path corresponding to a certain carbon tax is given, well-established climate physics equations can translate this abatement into a temperature distribution. As we have seen, this is then the input to the damage function. So, in the policy case the huge complexity of the problem can be, effectively if not perfectly, reduced to a much simpler problem: determining the distribution of either the average aggressiveness of the abatement policy, or of today’s carbon tax.[9] This then raises the question: Can we say something about the likelihood of different levels of carbon taxation?

To some extent, we can. One may want to take an extremely non-committal approach, in which as little as possible is assumed about our state of knowledge of future abatement policies. Even in this case, fiscal, the monetary and technological ‘soft constraints’ can tell us something informative about the distribution of possible carbon tax levels. More precisely, one can still use the fiscal and technology considerations discussed above to limit the possible/plausible tax levels to a finite (and not too wide) range. In this non-committal approach (if, that is, one really believed that nothing more can be said than which values for the social cost of carbon are possible and impossible), one can then assign equal probability to each level of the carbon tax within the range. It is difficult to believe, however, that such a diffuse prior is the best description of our level of knowledge about what the possible carbon tax could be. There are several possible approaches to enrich our information set, and we briefly discuss one such possible avenue.[10]

There have been extensive surveys of what economists think the ‘correct’ carbon tax should be (Tol [2023]), with the polled estimates spanning a very wide range. The key observation is that this disparity of opinions generates in itself a distribution of carbon tax levels – and since, as we have seen, this quantity is very closely linked to the level of abatement, one can directly obtain a distribution for ‘abatement aggressiveness’. Admittedly, what one can obtain following this procedure is the distribution of opinions of economists (who, among other things, do not have to face re-election). For this and other reasons, the distribution of economists’ views therefore need not coincide with the distribution of politicians. One can, however, observe differences between economist-generated estimates of the carbon tax produced in the past, and the size of the contemporaneously enacted subsidies and taxes put in place by politicians. This observed variance can then be used to shift the distribution of carbon taxes recommended by economists so as to make it more representative of what politicians would actually do.

This transformation, while conceptually simple, is far from trivial, and it is a current topic of active research at EDHEC-Risk Climate Impact Institute. The overall underlying idea, however, is very intuitive: to move from the baseline case to the policy case, probability distributions must also take into account uncertainty about the abatement aggressiveness. As mentioned, this is closely related to the level of carbon taxation. About this we can estimate, first, what is possible; second, how this uniform distribution should be altered to account both for best expert opinion (the economists’ views) and for the inevitable wedge between what is considered theoretically optimal and what has been implemented. The engine to evolve in a consistent manner all the terms of the Kaya identity is then provided by an integrated assessment model (specifically, a much-extended and scenario-repurposed version of the Dynamic Integrated Climate-Economy model (Nordhaus and Sztorc [2013]).

Figure 2 shows an indicative graph of the temperature distribution obtained using this approach, and figure 3 displays a distribution of the possible damages

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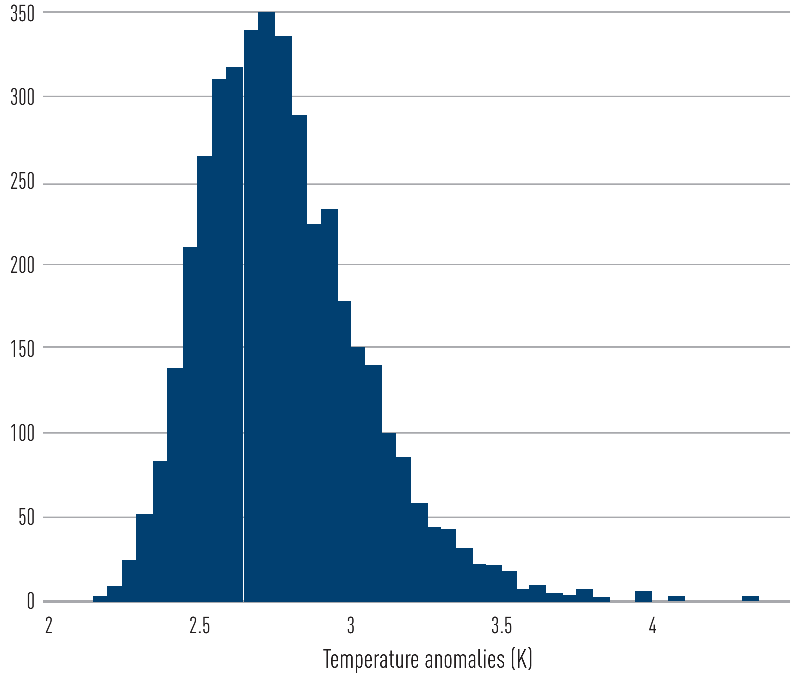
[9] While there are important differences between carbon taxation and subsidies, for the purpose of the present discussion all forms of government expenditure aimed at decarbonizing the economy (either by reducing the consumption of fossil fuels, by increasing the adoption of renewable technologies, or by carbon sequestration or removal) are referred to as a ‘carbon tax’.

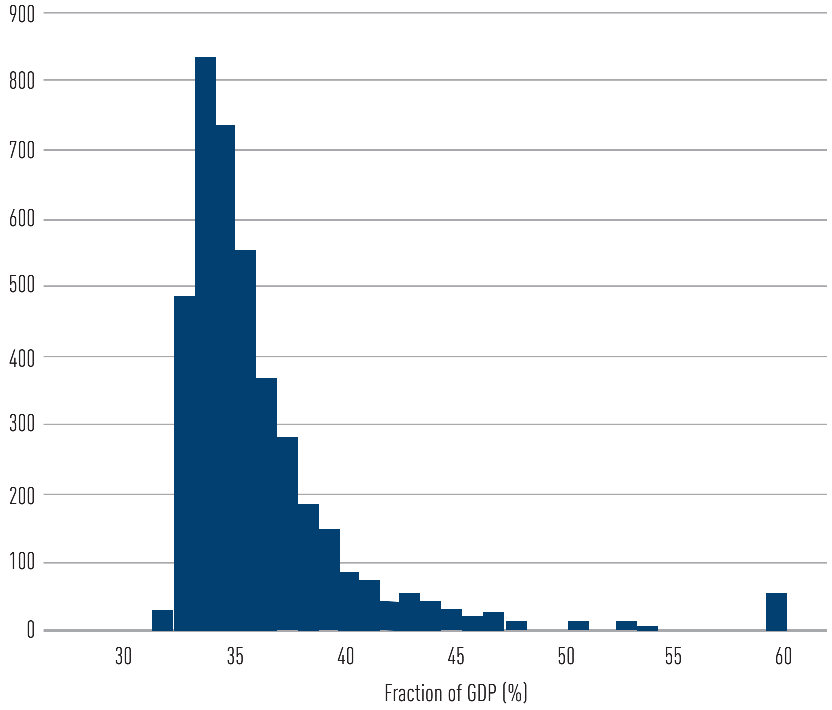
[10] For a fuller discussion, see Rebonato, Kainth and Melin (2024).

corresponding to a no-action policy, expressed as percentage losses of 2100 GDP. (We stress that these GDP losses were obtained with a particularly severe damage function, which allows for the presence of tipping points in the climate system. They do not necessarily represent our best estimate of damages for the assumed policy course and are only presented to show that a DICE-like engine *can* produce substantial losses to economic output. Whether the damage function used to obtain figure 2 is the most appropriate one is an empirical question, about which we are carrying out innovative research.)

2. An indicative realisation of the temperature distribution obtained using the approach discussed in the text



3. (Conditional) distribution of percentage GDP losses obtained in the no-abatement case for a severe damage function designed to reflect the possible existence of tipping points in the climate system



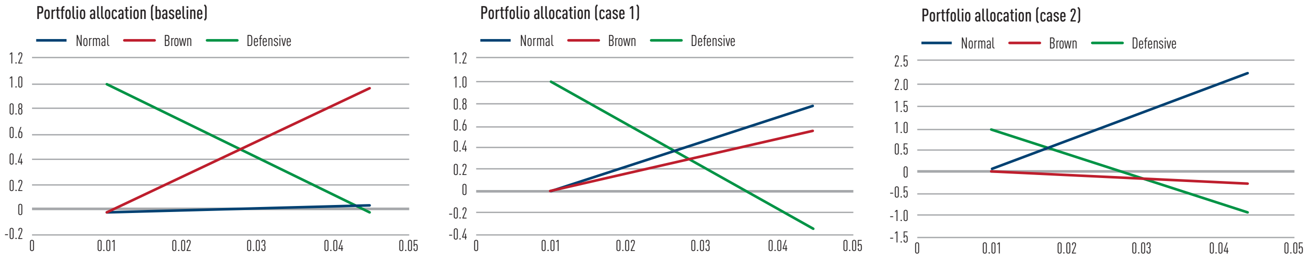
Conclusions: what can investors do with this information?

In this note we have advocated the use of probability distributions, rather than discrete scenarios, to investigate the effects of climate risk on an investor's portfolio allocation decisions. The procedure has been painted with a very broad brush, and the reader is referred to our technical publications for finer details, but the general idea should be sufficiently clear. What remains to be discussed is how investors can use this information is practice – also in this case, space constraints only allow us to do so from a 30,000-foot perspective.

The first observation is that information about *just the dispersion* of outcomes can significantly change the portfolio allocation. To illustrate the point, figure 4 shows an extremely simple allocation problem, where the portfolio manager had to decide how to split their wealth between a defensive, a 'green' and a 'brown' asset. The exercise is carried out first with no information about the climate risk-specific volatility of the brown asset (baseline case, left panel); next, with the volatility of the brown asset increased by 20% (middle panel); and finally with the volatility doubled (right panel). The target portfolio return is on the x axis. In all the cases considered, the expected returns from the different assets were not changed. Note how the allocation to the brown asset changes dramatically, from being the dominant asset in the left panel, to being *shorted* in the right panel – purely as a function of the uncertainty in its returns. The intuition is clear: even if the expected returns do not change, increasing the climate sensitivity increases the volatility, and decreases the Sharpe ratio. (For a fuller discussion, see Rebonato, Kainth and Melin [2024]).

This stylised example shows how important an appreciation of the relative uncertainty in outcomes can be when it comes to portfolio allocation. More

4: The allocation to a normal, brown and defensive asset with no information about the climate risk-specific volatility of the brown asset (baseline case, left panel), with the volatility of the brown asset increased by 20% (middle panel) and with the volatility doubled (right panel). The target portfolio return is on the x axis



realistic applications include approaches based on discounted-cashflow models. These can take a variety of forms, but in all cases the idea is to arrive at asset prices in the presence of climate risk by adjusting the index, sector or company-specific future expected cashflows for the damages obtained from a distribution such as the one in figure 2. The discounting of these cashflows is carried out by adjusting the risk-free rate by a risk premium term that, in principle, reflects both the general market risk and the specific market risk (if non-zero, this can be positive or negative, depending on whether the cashflows from a company add to or hedge away climate risk – see in this respect Rebonato [2024]).

For portfolio managers, making use of the information coming from a full distribution rather than a handful of hand-picked scenarios admittedly creates a departure from common practices. However, as mentioned, conceptually there is little new in this approach, since the time-honoured mean-variance approach (which, despite being dubbed 'modern', has been around since the late 1950s) assumes a distribution in the background. The only difference is that the mean-variance distribution of returns is *posited* to be normal, while the climate-aware distribution is *obtained* to display a heavy-tailed and skewed shape. Work is under way to generate some scenarios *starting from* distributions, but it is still not clear whether by themselves they can convey the richness of information financial planners need to invest wisely in times of climate risk.

Research is also under way to explore how reverse stress-testing can be obtained from the distributions of damages – as usual, for this problem the challenge is not to find how a certain loss can be incurred, but *the most likely way* in which this loss can materialise. The underlying idea is that, after partitioning the damages into a number of buckets, one can identify the socioeconomic paths converging into any given bucket and one automatically knows that, by construction, these paths all have the same probability. So, the outcome of a reverse-stress-testing exercise could be that, for a loss of X% to materialise, most paths show a particular combination of GDP growth, technological development, population growth, etc. The analysis could also be, however, that the same level of losses can be obtained for a bimodal (or multimodal) distribution of parent variables. Extensions of the work in Rebonato, Kainth and Melin (2024) are being considered in this context.

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Internal carbon pricing: impact or greenwashing?

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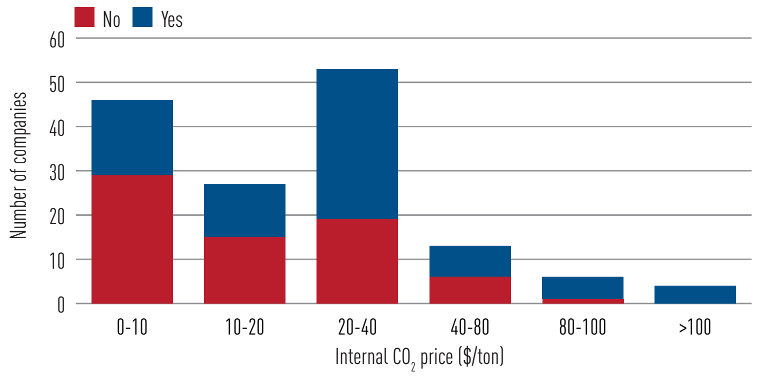
Internal carbon pricing (ICP) is a voluntary practice to manage firms' carbon footprints.

Understanding internal carbon pricing is thus becoming essential to corporates and investors alike.

Disclosing corporate ICP can result in a mere greenwashing exercise.

Only the actual integration of ICPs in firms' strategy is associated with a carbon footprint reduction.

1. Companies disclosing the internal carbon price



Notes: Number of companies disclosing the internal carbon price ($/ton), by interval of prices ('Yes' means there is a carbon price in the home country, 'No' otherwise).
Source: Bento and Gianfrate (2020).

Companies are increasingly called to collaborate in the fight against climate change in a context of rising public awareness of the need to accelerate decarbonisation and of an emerging global climate governance (Calvet, Gianfrate and Uppal [2022]). Their involvement is crucial as more than two thirds of the world's emissions since the beginning of the industrial revolution have been emitted by large companies. New tools for climate mitigation are emerging to assist with the delivery of corporate greenhouse gas (GHG) emissions objectives, with internal carbon pricing (ICP) becoming a widespread practice globally (Aldy and Gianfrate [2019]; Bento et al [2021]). ICP is a voluntary method for companies to internalise the social cost of their GHG emissions, even when all or part of their operations are out of the scope of external carbon regulations.

Companies adopt ICP in various settings and for many reasons. ICP can be used for risk management purposes, strategic planning activities and decisions about capital investments. Such voluntary practices are particularly important as mandatory emissions trading and carbon taxing schemes cover less than a quarter of global emissions and less than 5% of emissions are covered by a direct carbon price that is consistent with the goals of the Paris Agreement (World Bank [2023]). Disclosure of ICP usage may also help persuade investors to reduce the premium required to compensate for poor current performance in terms of GHG emissions. As for measuring the impact of such disclosure on climate performance, further investigation is required.

Understanding ICP becomes even more relevant for corporates and investors alike with the recent inclusion of ICP in the cross-industry metrics whose disclosure is required for compliance with the updated guidance of the Task Force on Climate-related Financial Disclosures (TCFD [2021]).[1]

Evidence about ICP around the world

Data about ICP adoption from companies comes from the Carbon Disclosure Project (CDP), which is a global initiative that surveys the carbon strategies of large global companies. The CDP started in 2002 at the request of 35 institutional investors managing more than $4.5trn of assets because of the growing need to obtain information about the financial impacts of climate change on firms' operations. The CDP requests information about the business threats and strategies related to climate change including internal carbon prices of the world's largest companies, organises the responses into a large dataset and publishes an annual report that presents the results of the inquiry. The CDP has been reported to be the largest effort to assemble standardised data on carbon emissions as well as information on companies' risks, opportunities and strategies to manage the effects of climate change.

Figure 1 presents the proportion of companies disclosing the internal carbon price from countries that have put in place a carbon policy, according to data from the World Bank (2016). This proportion tends to increase with the level of prices, suggesting a possible relationship between *local carbon policies* and the strategy of companies to price carbon internally.

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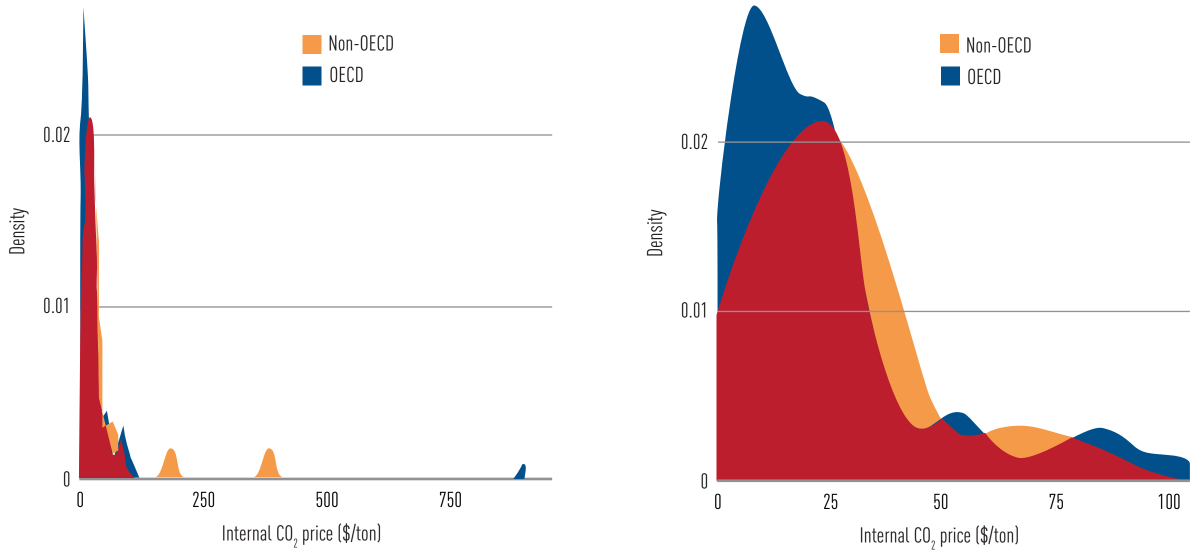
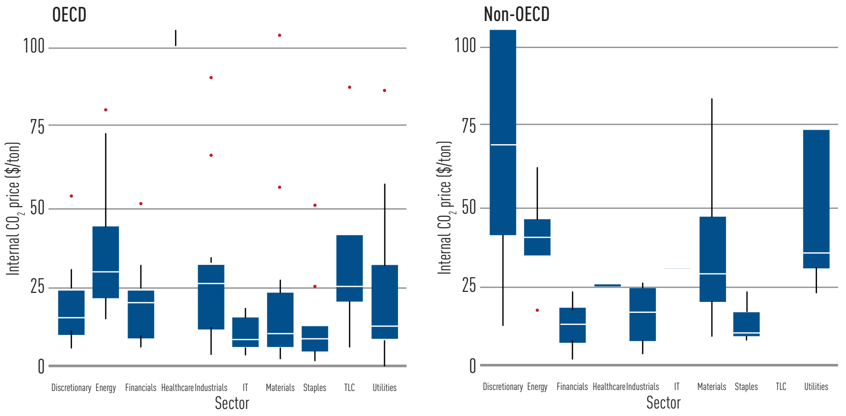
[1] The TCFD explains that: "Internal carbon prices provide users with an understanding of the reasonableness of an organisation's risk and opportunity assessment and strategy resilience. The disclosure of internal carbon prices can help users identify which organizations have business models that are vulnerable to future policy responses to climate change and which are adapting their business models to ensure resilience to transition risks." For futher information on the updated TCFD guidance, the reader is referred to Ducoulombier (2021).

2. Density distributions of internal carbon prices



Notes: Density distribution of internal carbon prices ($ per ton) of companies from OECD (n = 121) and non-OECD (n = 28) countries. Complete distribution (left) and prices up to €100 (right). Source: Bento and Gianfrate (2020).

3. Internal carbon prices by sector



Notes: Box plot of internal carbon prices by sector in OECD countries (n = 121, left-hand) and non-OECD countries (n = 28, right-hand). IT = information technology; TLC = telecommunication services. Source: Bento and Gianfrate (2020).

The firms' internal carbon prices are higher than explicit carbon prices (Bento and Gianfrate [2020]). This observation could reflect several situations:

- Firms price carbon at the level of effective carbon prices (command-and-control regulation, technology mandates and subsidies, etc) which are greater than prices in cap-and-trade markets or carbon taxes;
- Firms expect carbon prices to increase over the economic lifetime of the investments; and
- Firms do not implement the disclosed carbon prices in their investment decisions.

Figure 2 shows the distribution of internal carbon prices of companies in OECD and non-OECD countries. More than four-fifths of the internal carbon prices reported in the sample are from companies with headquarters in OECD countries. The companies in this area show a more fragmented distribution of prices with a concentration in low levels and in high levels (right-hand graph [?OK?]) compared to companies from non-OECD countries, even if the low number of observations in the latter tends to concentrate the values.

Figure 3 shows a breakdown of internal carbon prices by sectors grouped according to the Global Industry Classification Standard (GICS – Utilities, Energy, Financials, Telecommunication Services, Materials Sectors, Healthcare, Consumer Discretionary, Information Technology, Consumer Staples And Industrials). The shadow prices are more dispersed among the sectors in non-OECD countries (but a low number of observations). Energy, a traditionally highly emitting sector, has the highest prices in companies reporting from OECD countries (the second highest in companies from non-OECD). In addition, Energy and Utilities have the highest proportion of companies planning to price carbon or that currently price it (52% and 63%, respectively) among the disclosing companies (not shown, cf, CDP [2016]).

Despite the growing importance of internal carbon pricing, the consequences of such practice remain generally unexplored.

ICP adoption and carbon footprint

We study the relationship between internal carbon price reporting and carbon footprint, as a measure of the credibility of corporates' disclosures. Specifically, we study whether ICP adoption helps companies deliver on carbon footprint reduction or whether it is just a greenwashing exercise. In general, firms adopt and disclose ICP for several reasons:

- to gain social acceptance (Ghitti, Gianfrate and Palma [2023]);
- to improve the dissemination of shadow prices; and
- to gain a comparative advantage in the

future through an early adoption of carbon pricing.

On the other hand, companies may also disclose ICP as a communication strategy to improve reputation and/or to avoid more stringent climate policy, without integrating them in their operations – greenwashing (Ghitti, Gianfrate and Palma [2023]). This would improve the companies' reputation in the short run at the price of undermining the legitimacy around this environmental practice in the medium term and, worse, contributing to delaying the action against climate change. Despite the growing importance of ICP, the effectiveness of this practice remains mostly unexplored.

We explore the integration of these shadow prices in the firms' strategies. Empirically, we analyse the information about the ICP collected by the CDP. As mentioned, the Carbon Disclosure Project (CDP) surveys the business threats and strategies related to climate change to the world's largest companies, organises the responses into a large dataset and publishes an annual report that presents the results of the inquiry. We use the ICP collected in the 2016 CDP report (CDP [2016]). This is the only one published so far in which surveyed companies with an ICP were specifically asked:

- whether ICP had had an *impact* on business decisions, ie, has resulted in tangible changes in the operational activities and/or investments such as the development of low-carbon products or the investment in improving the energy efficiency in production; and
- whether ICP were expected to be embedded in corporate business *targets*, ie, they are part of a strategy to achieve a certain climate-related goal or target, such as being aligned with the needs of a 1.5°C scenario.

Because these items of the survey are only available for 2016, we restrict this analysis to companies reported as having an ICP price for that year.

To understand how the adoption of ICP impacts the carbon footprint of the companies, we test to what extent disclosure about ICP is associated with any actual reduction in emissions. We specifically investigate which ICP reporting behaviours are associated with a reduction of carbon intensity in 2019 versus the previous two years.

We use a logit model as follows:

$$\begin{aligned} Logit\left(RED_i\right) = \alpha + \beta_1 ICP_i + \beta_2 GDPP_i + \beta_3 NCP_i \\ + \beta_4 ENE_i + \beta_5 SIZE_i + \beta_6 ROIC_i \\ + \beta_7 BFEM_i \end{aligned}$$

where RED_i is an indicator equal to 1 if the carbon intensity (direct CO_2 emissions/revenues) in 2018 is lower than in 2016 for firm *i* and 0 otherwise, ICP_i is a dummy variable related to equal to 1 if companies have adopted a specific ICP-related reporting behaviour (alternatively, disclosing the level of ICP, actual use in the past of ICP for business decision making, or committed integration of ICP in corporate strategy targets) and 0 otherwise. The remaining independent variables are: $SIZE_i$ which is the natural logarithm of revenues for firm *i*, $ROIC_i$ which is the average return on invested capital, $BFEM_i$ which is the ratio of female board directors to total directors, $GDPP_i$ which is the logarithmic value of the GDP per capita of home country of firm *i*, NCP_i which is a dummy variable with value 1 if the home country of firm *i* has a national carbon pricing policy (climate tax or equivalent) and value 0 otherwise, and finally ENE_i is a dummy variable with value 1 if firm *i* is from the energy sector and 0 otherwise.

We analyse whether reporting behaviours related to ICP are associated with an actual reduction in standardised carbon reduction for companies reporting to the CDP in 2016 (see figure 4).

For the three models reported in figure 4, the dependent variable is a dummy equal to 1 if carbon intensity has decreased in 2019 versus 2016, and equal to 0 otherwise. Consistently across the models, while GDP per capita is not statistically significantly related to the likelihood of carbon intensity reduction, the existence of a national climate policy in the country of reference and the affiliation to the energy sector are positively associated to the likelihood of achieving a carbon intensity reduction. Size is also positively associated to a carbon intensity reduction likelihood (at 1%) as the ratio of female directors in the board (at 5%).

As for the reporting behaviours, model 1 in figure 4 shows that the disclosure of the ICPs does not appear to

4. Results of logit analysis of the reduction in carbon intensity for companies surveyed by CDP (2016)

	Dependent variable		
	Reduction in carbon intensity (dummy)		
	1	2	3
Reporting behaviours			
Disclosure	-.072		
	(.338)		
Impact		.606*	
		(.372)	
Target			.538***
			(.170)
Country and industry characteristics			
GDP per capita (log)	.110	.143	.125
	(.464)	(.471)	(468
National carbon price	1.460***	1.472***	1.458***
	(.321)	(.317)	(.310)
Energy (1 = yes; 0 = no)	.687***	.740***	.831***
	(.170)	(.211)	(.223)
Firm characteristics			
Size (revenues)	.247***	.230***	.237***
	(.083)	(.084)	(.085)
Profitability	-.024	-.025	-.030
	(.019)	(.020)	(.021)
% female directors	2.353**	2.228**	2.099**
	(1.034)	(1.047)	(1.026)
Constant	-7.445	-7.582	-7.590
	(5.363)	(5.437)	(5.452)
Observations	312	312	312
Pseudo R^2	.131	.135	.140
Log pseudolikelihood	-148.480	-147.782	-147.052

'Reduction in carbon intensity' is the dependent variable equal to 1 if 'carbon intensity' decreased in 2018 in comparison to 2016, equal to 0 otherwise; carbon intensity is a standardised measure of firms'direct carbon emissions computed as the ratio of annual direct CO_2 emissions (from Thomson Reuters Asset4) and the dollar revenues of the firm (from Datastream). Clustered standard errors in parentheses. Notation of the significance levels: *p<0.1; **p<0.05; ***p<0.01.

be associated with a carbon intensity reduction. In model 2, the reported impact of ICPs in decision-making is positively related to a carbon intensity reduction, with moderate statistical significance (10% level). On the contrary, model 3 shows that companies indicating in the 2016 CDP survey that they were integrating ICPs in the business operational targets are positively associated to the likelihood of delivering a reduction of carbon intensity.

Overall, these results help disentangle the role of greenwashing in the legitimacy creation for new climate accounting practices: for ICPs, it is not the price disclosure per se that predicts virtuous environmental behaviours, but rather the actual experience of ICPs in the past, and, more importantly, the declared commitment to use them in future strategy targets.

Conclusion

Action against climate change is urgent and requires the widespread participation of firms (Ducoulombier [2021]). Whether ICP adoption helps reduce firms' carbon intensity is an important question to answer given the rapid decarbonisation needed to deliver on the Paris Agreement targets, as global policymakers are converging on implementing carbon pricing across economies, starting with the larger firms. We show that the actual experience of ICP in the past, and the commitment to use it in future strategic targets, are more important when it comes to predicting virtuous environmental behaviours than the price disclosure *per se*.

This analysis has several limitations, including the reliance on a secondary data source. It focuses on reductions in carbon intensity, rather than total emissions. One could argue that only reductions in carbon intensity are feasible in the short term. Others may assert that some emission reductions could be 'low-hanging fruit' or even 'relabelling' of climate action for activities that companies were already planning to undertake anyway.

However, internal carbon prices are likely to enhance decision-making for internal projects with cash flows impacted by carbon risks and enable better interactions between companies and their stakeholders, especially investors, concerned with carbon risks. Carbon risks are impacting the cash flows of companies, especially the large emitters. Carbon-abatement efforts will put dramatically different levels of stress on the cash flows of different industries. The immediate impact on cash flows might be limited for now, but it will eventually be relevant in many industries. As carbon pricing influences current and future cash flows, firm valuations (McKinsey [2008]) are affected as well. Therefore, effectively accounting for carbon pricing risk when measuring corporate value becomes of paramount importance for both executives and investors.

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Assessing the SSP/RCP framework for financial decision-making

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The SSP/RCP framework is a powerful construct which has been central to how policymakers develop mitigation strategies and which has been embraced by financial community.

However, we believe that the scenarios which are developed using a series of models should be subject to scrutiny using well-established model risk management approaches.

Specifically, the framework is deliberately built as a set of scenarios with no associated probabilities, which is challenging for investors to use meaningfully with no view as to likelihood, dispersion and risks around the single paths.

We highlight areas where the design might lead to an underestimation of the risk, potentially giving rise to a false sense of security on the impacts of climate change and how transition might unfold.

Climate scenario analysis serves as a vital tool for financial institutions (eg, banks and asset managers) and central banks to assess the risks and opportunities presented by climate change. Typically, climate risk is classed as being either physical (eg, damage to infrastructure) or transitional (a greater likelihood of, for example, stranded assets or of sovereign defaults with potential financial contagion risk as we move to a low carbon economy). Financial institutions have begun to use scenario analyses to inform client pricing, business planning and internal risk management decisions; central banks have also used them to inform sector-level macro-prudential policies. To align their assessments of forward-looking climate-related financial risks, these actors seek standardised approaches. Traditional financial risk management hinges on making use of relatively rich pre-existing historical data (such as market prices and macroeconomic indicators) in designing tail-risk scenarios. Coupled with the use of appropriate sampling techniques, it is relatively straightforward to generate a large number of scenarios with an associated likelihood, enabling both risk-based asset pricing and estimating quantiles of potential losses to inform capital estimates. For stress tests, a stress situation is created as an exogenous shock to the system, with a given likelihood of occurrence which tests the resilience of a given business line or indeed the entire financial system.

Climate risks are, however, different to financial risks in several ways, and this introduces its own challenges. For physical risks, despite significant research efforts, there are still deep uncertainties associated with the effects of greenhouse gas (GHG) emissions on future economic output. The risks associated with the transition are far more complex than classical financial risk, as they apply not only to the financial system but potentially imply unprecedented structural changes across economies and also involve complex socio-economic feedbacks. It is also clear that markets are not yet able to efficiently process climate information and therefore don’t reflect risks in asset prices accurately. Developing, for example, a probability distribution from past shocks is very unlikely to yield meaningful estimates of future impacts.

Faced with such complexity, firms turn to scenario analysis. However, while financial institutions are uniquely placed to manage financial risks, understanding climate risks necessitates using pre-existing expertise spanning various non-financial disciplines. The Intergovernmental Panel on Climate Change (IPCC) stands as the foremost scientific authority on climate change, tasked with furnishing governments at all levels with scientific information that they can use to understand risks and formulate appropriate mitigatory policies. Unsurprisingly the financial sector has looked to use the high-quality IPCC output.

In the next section, we give an introduction to how the IPCC scenarios are constructed. We will see how this framework, developed over much of the previous decade, is designed specifically as a scenario planning tool, primarily for the benefit of policymakers. However, it has proven very successful and now ensures consistency across a large body of climate research. In the following section, we will explore some of the issues associated with this framework, particularly when applied to a financial context. We make some general recommendations as to how to address these risks in the fourth section.

The SSP/RCP framework

Background

Scenarios made their debut in climate research approximately 30 years ago with the first IPCC Assessment Reports (ARs). Their popularity partly stems from the multifaceted nature of climate risk, which means that research communities representing different disciplines often focus on particular pieces of the climate crisis aligning with their expertise. Scenarios then represent a means to meaningfully integrate these disparate facets enabling, for example, policy making. This mirrors the challenge faced by financial institutions, discussed earlier.

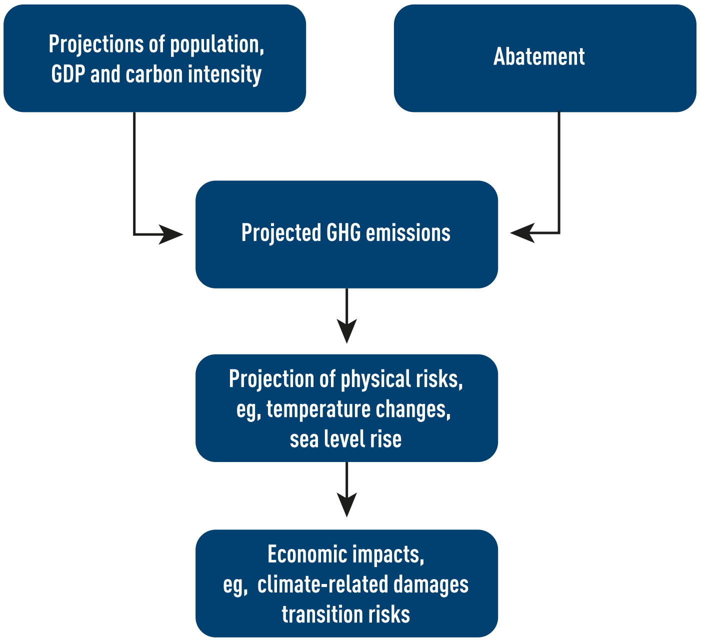
In order to develop climate scenarios, we might envisage a process similar to that illustrated on panel A of figure 1. Indeed, the initial IPCC ARs reflected this structure with the contributions of these research communities accorded to three different working groups (WGs):

- Physical climate analysis is performed by researchers in IPCC WGI. Using emission scenarios as inputs, large-scale models project climate (eg, temperature and precipitation) both regionally and worldwide.
- IPCC WGII assesses the potential impact of climate change on regional and global scales, with specific modelling of particular sectors or biomes. Climate model projections (as produced eg, by researchers in WGI) as well as the amount of GHG emissions (as produced eg, by researchers in WGIII) are inputs to this process.
- Emissions scenarios are the focus of researchers in WGIII and are generated using process-based integrated assessment models (IAMs). Process-based IAMs are sophisticated constructs that explicitly model the evolution of global energy supply and demand as well as land use over a long horizon (eg, until 2100). They have a high degree of detail, particularly for energy supply and demand; these are modelled as a function of underlying socio-economic processes (such as growth in population, development, urbanisation and technology).[1] In line with the IPCC's objectives, their principal use is to project cost-effective 'optimal' mitigation pathways conforming to stated policy outcomes (eg, limiting global warming to 2°C). This is achieved by firstly simulating energy demand (from eg, industry, buildings, agriculture etc). They also incorporate a granular and extensive range of supply options (eg, wind, solar, nuclear), their costs and how these costs evolve as a result of, for instance, feedback of current/future demand on supply, availability of reserves and learning-by-doing. The lowest-cost supply of energy, consistent with matching demand and complying with the stated policy objective, is then determined using an optimisation at each time. This then gives rise to a 'transition' pathway.

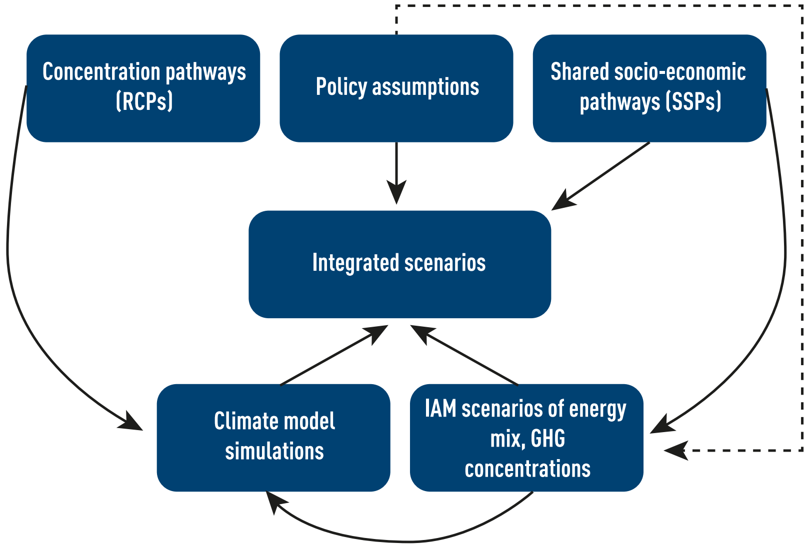
This suggests a sequential relationship between creating emission scenarios, climate projections, and impact studies (figure 1, panel A), and indeed this is how the IPCC used to operate. However, this led to a number of issues. The IPCC ARs are produced periodically, with the sixth round appearing in 2022. Coordination issues arose because, for example, while impact researchers were applying climate projections to update quantifications of future climate change impacts, physical climate researchers had already moved on to develop the next generation of modelling approaches. This led to a scenario misalignment in the research communities, which complicated the preparation of IPCC ARs. Concerns emerged about potential internal inconsistencies because there were multiple vintages of climate or damage models.

1. Schematic of scenario generation

Panel A: schematic of 'sequential' scenario generation



Panel B: schematic of scenario build in the RCP/SSP framework



Notes: Panel B is a replica of a figure in O'Neill et al (2020) and is reproduced in accordance with the Creative Commons Attribution 4.0 International License, https://creativecommons.org/licenses/by/4.0/legalcode). No changes were made to the figure.

Conceptually also a sequential model feels inappropriate. Future climate depends on energy usage, which in turn depends on socio-economic development and separately on the amount of mitigation (ie, the extent to which transition to a low carbon economy is expected to happen).

To resolve these issues, a number of

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[1] However, future impacts of climate change are generally excluded.

IPCC aligned academic research groups have developed the so-called Shared Socio-economic Pathway (SSP)/Representative Concentration Pathway (RCP) framework since 2010. In what follows, we discuss the two key constituents before describing how they are combined to give rise to the current IPCC scenario framework, schematically illustrated in figure 1, panel B.

The Shared Socio-economic Pathways (SSPs)

The SSPs are a small but diverse collection of five pathways designed to provide a common frame of reference across a large range of scenario-driven studies. Finalised versions were released in 2017. These pathways project a range of societal and economic factors, including, for example, population, development indicators such as health and education, economic growth, governance paradigms and technological progress. Most factors are given as broad-brush narratives describing changes for large world regions; a subset – population, GDP, urbanisation and educational attainment – is given as quantitative, country-specific projections. This is by design: quantitative estimates are important given their common use as inputs to emissions/climate damages models; furthermore, these variables are strongly inter-related and joint projection is important to ensure scenario consistency. Female education, for example, is seen as a key determinant in projecting both population and GDP. The SSPs do not, by design, include the impacts of climate change or indeed the mitigation and adaptation responses themselves.

The five storylines – SSP1 (sustainability), SSP2 (middle of the road), SSP3 (regional rivalry), SSP4 (inequality) and SSP5 (fossil-fuelled development) – span a spectrum of outcomes related to the ease with which we might manage future climate change. SSP1 and SSP5 envisage relatively optimistic trends for human development and economic growth, arising from investments in education and health, and the presence of well-functioning institutions. SSP5 assumes this arises from an energy-intensive, fossil-based economy, while in SSP1 there is an increasing shift toward sustainable practices. Conversely, SSP3 and SSP4 describe more pessimistic development trends, with less investment in education or health, rapidly growing populations, and increasing inequality. In SSP3 countries prioritise regional security, whereas in SSP4 large inequalities within and across countries dominate, in both cases leading to societies that are highly vulnerable to climate change. SSP2 envisions a central pathway in which trends continue their historical patterns without substantial deviations. In SSP1 investment in transition leads to positive economic growth, conversely along other pathways transitioning represents a drag on growth.

The Representative Concentration Pathway (RCP)

The RCP is a greenhouse gas concentration trajectory adopted by the IPCC. Four such pathways were initially used for climate modelling for the IPCC AR5 in 2014. The pathways describe different climate change scenarios, all of which are considered possible depending on the amount of GHGs emitted in the years to come. The RCPs – originally RCP2.6, RCP4.5, RCP6.0 and RCP8.5 – are labelled by the amount of radiative forcing in the year 2100 (2.6, 4.5, 6.0 and 8.5 W/m^2, respectively). Radiative forcing, in turn, is a measure of the combined effect of GHGs, aerosols and other factors that cause the trapping of additional heat. The higher values imply higher atmospheric GHG concentrations and hence higher global temperatures[2] as well as more pronounced climate change.

The RCPs were introduced primarily for the benefit of (physical) climate modellers, who have different requirements in future emission scenarios than, say, energy system modellers. They want outcomes that cover a wide range of potential future GHG concentrations, allowing the effective evaluation of model behaviour. Hence, while the pathways were developed as outputs of (pre-2010) IAMs, some are extreme and the possibility of such pathways depends strongly on future human development.

Combining SSPs and RCPs to generate scenarios

The SSP/RCP framework develops climate and societal futures in parallel, independently of one another and then combine them to create an integrated scenario. Both the SSPs and RCPs by themselves are therefore incomplete by design.

Integration to give a scenario is carried out using the process-based IAMs discussed above. IAMs expand the given SSP narrative by elaborating on implications for energy systems, land use changes and quantifying resulting greenhouse gas emissions and atmospheric concentrations. Typically, both ‘baseline’ scenarios (future developments assuming no further climate change impacts or new climate policies beyond those currently in place), and ‘mitigation’ scenarios (these explore the implications of climate change mitigation policies applied to the baseline scenarios) are developed. Mitigation scenarios are characterised by the level of actions required to reach a given RCP (ie, level of forcing) by 2100. Multiple different IAMs are used for the quantification of the SSP scenarios; again this is part of the approach by the IPCC recognising that modelling future energy costs is uncertain and subject to model risk.

This naturally leads to a matrix of scenarios as illustrated in figure 2. Each column corresponds to a given SSP, while each row contains climate model simulations based on a forcing pathway. While some combinations of social pathway and forcing are inconsistent with one another (eg, the narrative in SSP1 is inconsistent with the forcing of RCP8.5), different combinations of forcing and social narrative are consistent, dependent on levels of mitigation.[3]

As is standard within the scenario planning literature, there are no probabilities associated with any of the individual scenarios. They were specifically designed as a planning tool and therefore aim to expose a wide range of different ‘plausible’ outcomes; theoretically, all scenarios should be considered equally likely and appropriate actions taken. Probabilities were deliberately avoided as it was felt that they can distract from the story-telling qualities of scenarios, as well as leading to a presumption of predictive accuracy.

Success of SSP/RCP framework

This framework has proven to be incredibly successful in supporting consistent research across a wide range of topic areas. More than 1,400 analyses using the SSPs/RCPs have been published over the past seven or so years. These have covered climate change impacts on a range of sectors (including eg, air pollution, health, water, forest management, conflict, asset pricing) and future mitigation (eg, energy transition pathways) and adaptation (of buildings, health and water systems).

O’Neill et al (2020) have conducted a meta-analysis of these studies. They find that the full range of societal and forcing outcomes described in the SSP and RCP frameworks have been explored; we reproduce figure 3 from their work, which shows an extensive number of studies considering both the risks and the response options for each SSP/RCP combination.

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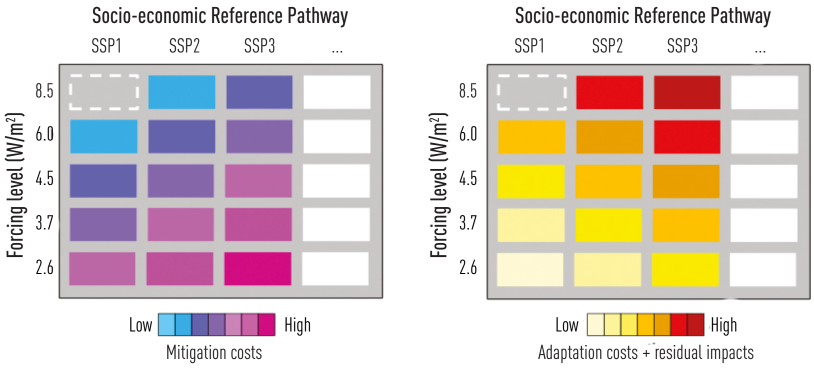
[2] Forcings of 2.6, 4.5, 6.0 and 8.5 W/m^2 correspond approximately to temperature anomalies of approximately 1.8, 2.6, 3.3, 4.6°C by 2100.

[3] These scenarios are commonly referred to as SSP*x*–*y*, where *x* is the specific SSP and *y* represents the forcing pathway, defined by its long-term global average radiative forcing level.

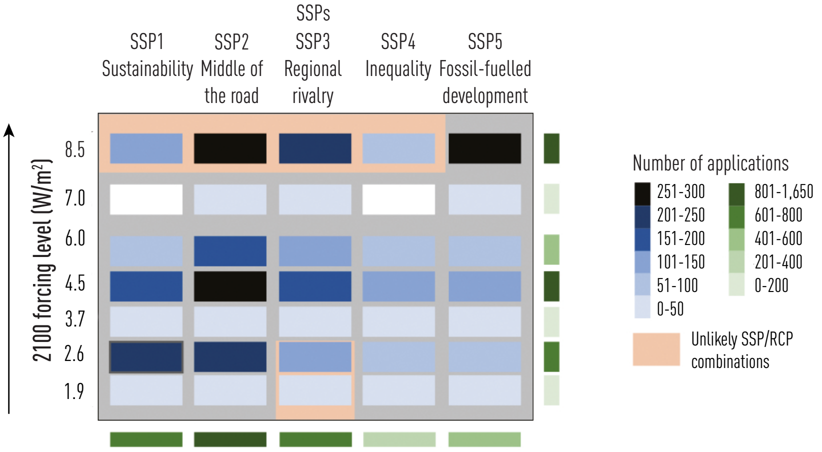
2. Conceptual illustration of how the integrated scenario framework can be used to assess the cost and benefits of climate policy



Notes: Different categories of climate-policy costs and residual impacts are expected to vary across the cells of the matrix. The empty cells (dashed lines) illustrate that not all combinations of forcing levels and SSPs are consistent. Colours in the left-hand matrix illustrate how achievement of lower forcing levels imposes a greater mitigation cost for any given SSP but that this cost also requires the SSP to be followed. Colours in the right-hand matrix suggest how the costs of avoiding a certain amount of impact (not specified here) through adaptation, combined with the impact costs that remain, are greater under some SSPs than others and under higher levels of forcing.

Source: Reproduced in accordance with the Creative Commons Attribution 4.0 International License (https://creativecommons.org/licenses/by/4.0/legalcode) from Vuuren et al (2013). No changes were made to the figure.

3. Application of SSP/RCP combinations



Notes: Numbers of applications of SSP/RCP combinations in 715 total studies applying integrated scenarios, published over the period 2014–19. Each cell represents an SSP/RCP combination, with colours indicating the number of applications. White cells indicate no applications. Green rectangles along the right side of the figure indicate totals for each RCP (rows); those along the bottom of the figure indicate totals for each SSP (columns). Unlikely SSP/RCP combinations indicate those in which integrated assessment models found the outcomes infeasible under the SSPs and SPAs assumed.

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The use of individual SSP/RCP scenarios, however, is somewhat uneven; for example, and there are more studies based on the 'middle of the road' development pathway (SSP2, 30%) than for the other SSPs. However, the focus on other SSPs and RCPs suggests that these futures are all seen to be worthy of concern. We also note a particular concentration of research associated with the highest forcing pathway, RCP8.5. Many have questioned the use of this forcing pathway (Hausfather [2019]), largely because it is unlikely unless we follow a socio-economic narrative analogous to fossil-fuelled development; its application in research associated with, eg, SSP2 represents a misapplication, with impacts which are perhaps more sensational than plausible.[4]

Issues

The widespread acceptance of the SSP/RCP scenario framework in the climate change literature has seen its adoption in finance. One of the most prominent examples is the NGFS scenarios (NGFS et al [2023]), for which all economic presumptions stem from the 'middle of the road' SSP2 development pathway. This paradigm significantly informs stress tests conducted by major banks. Anecdotally, we also understand the NGFS scenarios are being used to incorporate climate risks into the valuation of long-dated assets.

We argue, however, that while the SSP/RCP framework is well designed, it is important to recognise that the scenarios are outputs from a (relatively complex and somewhat opaque) model infrastructure. The extent to which they are applicable to a given use case (eg, asset pricing, stress testing) should be carefully validated, ideally using the well-established techniques associated with model risk management. In this section we will discuss some high-level areas where we believe that the use of the SSP/RCP framework should be treated with some caution.

Probabilistic scenarios and population growth

The guiding principle of the SSP/RCP scenarios is that there is no associated likelihood and all should be treated equally; the reality, however, is that some are more equal than others – for example, SSP2-4.5 is the base case favoured by the NGFS (NGFS et al [2023]); conversely with the exception perhaps of SSP5-8.5, most would argue that an RCP of 8.5Wm^{-2} is very unlikely and should not be considered (Hausfather [2019]). This implies a subjective association of probabilities.

We argue that using probabilistic methods (eg, by building benchmark models based on econometric methods) is a critical tool for challenging the plausibility of scenarios. Probabilistic approaches also enable the development of sensitivities and therefore facilitate decision making on the basis of risks. Separately, reviewing the models underlying the scenario stories – where, for example, common assumptions are used – is also critical, as it may highlight areas where the scenarios are less diverse than we

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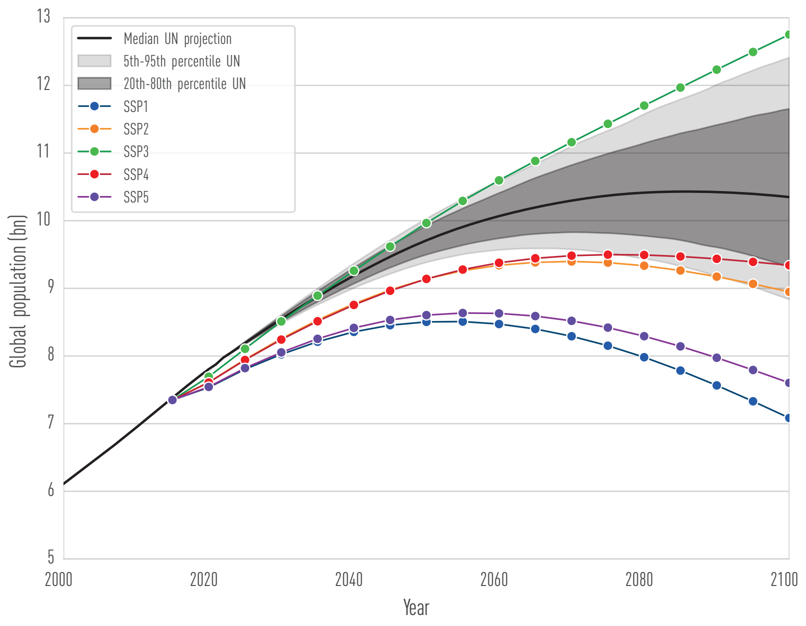
[4] This body of research can therefore be potentially misleading, as the likelihood of, eg, SSP2-8.5 is vanishingly small; however, probabilities are deliberately not part of the framework.

4. Global population projections embedded in the SSP scenarios and current median (and percentiles of) UN projections



might expect. We are not necessarily advocating the replacement of the SSP/RCP framework, rather that the use of probabilistic methods forms a complementary approach, critical for challenging scenario veracity, enabling greater precision in decision-making.

Future population trajectories are critical to the future development narrative underpinning the SSP/RCP framework; smaller populations (all else being equal) lead to reduced GHG emissions. In this section we explore how probabilistic analysis enables greater challenge of these projections; we will highlight that four of the five SSP projections have end-of-century populations below the 20th percentile of current UN projections.

Indeed, until 2010 most analysis of long-term population was conducted using scenario analysis or by expert judgement specifying future birth and death rates. It is only relatively recently that researchers have begun to apply probabilistic techniques. We reference the work of Raftery and Ševčíková (2023) for a review in particular; they have developed Bayesian models for statistically projecting the three components of population change: fertility, mortality and migration on a country-by-country basis. This approach – being probabilistic – enables the generation of country-level population projections, age structure, profiles by sex as well as confidence intervals and importantly sensitivities to underlying assumptions; it now underpins the UN's forecasts.

In figure 4, we compare the median as well as (5%, 20%, 80%, 95%) confidence intervals against the SSP forecasts for global population. We see that the SSPs encompass a greater range for end-of-century populations; furthermore, that population predictions are generally lower in the SSP, signifying a more rapid fertility transition and greater development than suggested by the work of Raftery and Ševčíková (2023). We do not opine on which is more correct; however, we note that the SSP/RCP analysis suggests a generally more positive outlook on development, which has implications for long-term economic progress and asset prices. Understanding these sensitivities should therefore form a key part of any assessment prior to adopting this framework.

GDP projections under SSP framework

Future GDP per capita is a very important indicator of human development and a key determinant of future ability to respond to climate change. GDP (both globally and on a regional/national basis) will also determine asset valuations. In this section, we discuss how GDP projections are developed and benchmark against historical time series. We find:

- Global growth rates are consistent with recent historical observations.
- The determinants of GDP growth are almost certainly more diverse than the 'human capital' mechanism which drives scenario growth.
- Empirical GDP growth rates of countries are far more volatile and less correlated than those developed in scenario; not capturing this could impact predictions of economic behaviours such as national savings rates and capital investment.

Background. Three alternative projections are available within the SSP framework; nonetheless, each adheres to a common framework, utilising the augmented Solow growth model[5] to project future economic growth. The principal idea behind the model is the so called 'convergence' mechanism, which posits that as economies advance, the incremental benefits derived from investments decrease. As a result, less developed societies discover it is economically advantageous to embrace innovations from the established technological frontier rather than spearhead new technology or methodologies. The enhanced model takes into account human capital, implying that the rate of convergence is influenced by factors such as education levels.

A useful approach to assess the SSP projections is to benchmark against history. Various global institutions (eg, the World Bank, the OECD and IMF) as well as research groups – the Penn World Tables (PWT) produced by the Potsdam Institute – have assembled time series of global GDP data sets (Feenstra, Inklaar and Timmer [2015]); most of these provide a comprehensive view across space but data quality is poor prior to the 1960s. We focus on the PWT data.

Growth rates. In figure 5, we have tabulated the average (across the three different models) of annualised growth rates of projected GDP implied by the various SSPs for the period from 2010 to 2050 and 2010 to 2100; we also show the normalised GDP at these two horizons for the five different pathways. We have compared these with the empirically observed growth in GDP obtained from the PWT purchasing power parity data. We find that the projected GDP growth until 2050 in SSP2 matches well what has been observed empirically. SSP1, SSP4 and SSP5 show higher growth, while SSP3 shows reduced growth. Hence to first order the scenarios and SSP2 in particular appear to be calibrated to historical expectations.

The modelled GDP growth rates are

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[5] This is a widely used economic development model and generally favoured because of its good empirical fit and connection with microeconomic theory.

5. Gross statistics related to GDP growth in SSP scenarios

Scenario	g^{2050}	g^{2100}	$\frac{GDP(2050)}{GDP(2010)}$	$\frac{GDP(2100)}{GDP(2010)}$
SSP1	2.814%	2.149%	3.095	6.986
SSP2	2.152%	1.579%	2.386	4.429
SSP3	1.891%	1.159%	2.169	3.030
SSP4	2.416%	1.790%	2.689	6.294
SSP5	4.430%	2.767%	3.989	12.217

Notes: All statistics relate to GDP per capita. We have computed annualised growth rate of GDP over the period 2010-50 (g^{2050}) and over 2010-2100 (g^{2100}). We also show the ratio of GDP per capita. By way of comparison, we note that global GDP has grown at 2.12 (±2.15)% since 1971. The comparative empirical ratio between GDP per capita in 2019 and 1979 is 2.3 ± 0.1.

found to be significantly higher initially (3.5-4%) and then decline smoothly: growth rates averaged between 2010 and 2100 are markedly lower than between 2010 and 2050. Even in the worst case, we are expected to be twice as rich in 2050 compared to 2010. This is a consequence of the Solow model, whereby the pace of 'technological' reform is believed to be decaying. By way of comparison the empirical GDP growth rate (2.12%) is far more noisy, with a standard deviation of ~2%. Empirically there is no obvious evidence of a secular decline.

VOLATILITY AND CORRELATION. In figure 6, we compare the GDP per capita growth rates for a set of developed, BRICS and emerging market economies using empirical data with the forecasts for the same countries assuming the SSP2 (middle of the road) scenario.

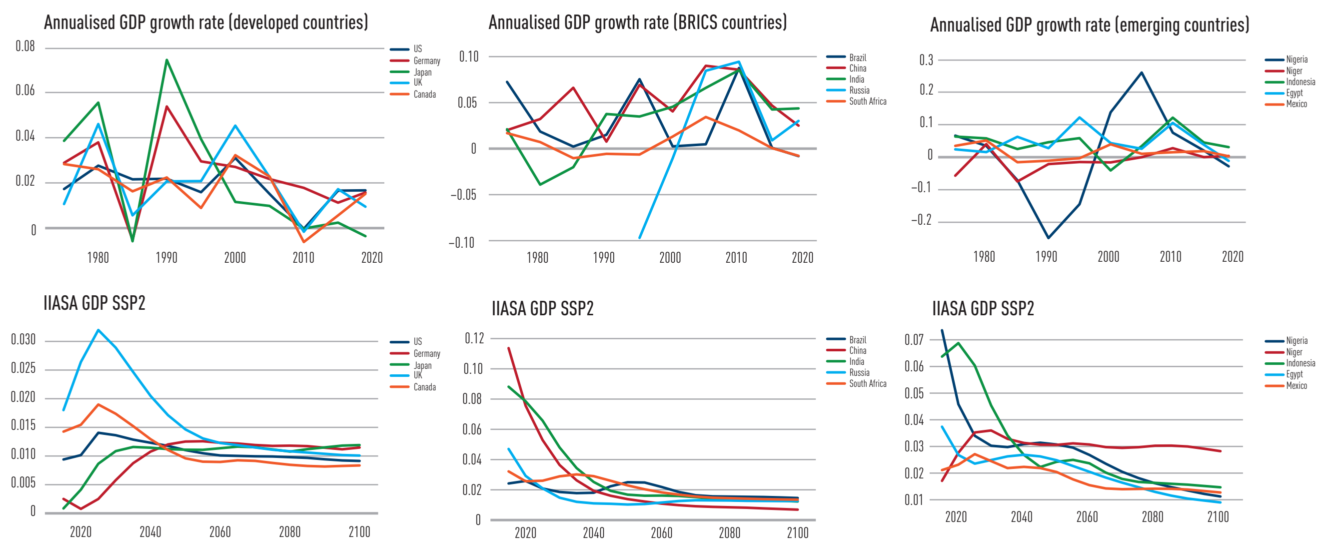
Two features are immediately apparent in the empirical data: annual growth rates for developed countries are generally smaller than for developing countries; secondly the volatility of growth rates is significant for all countries but is much larger for less developed countries. The projected growth rates are qualitatively different: there is no associated volatility and instead the growth rates show 'mean reversion', starting from comparatively high levels; again, the growth rates for poorer countries are much larger than for wealthy nations. The absence of volatility in the projected growth rates leads to them being highly co-integrated.

The absence of volatility reflects the fact that the SSP narratives do not model intermittent growth disruptions arising, for example, from political instability, conflict, commodity price shocks and distortionary fiscal policies. It is of course very challenging to do this. However, it is important to recognise the presence of such effects – because the volatility in growth will lead to (precautionary) savings and differing investment behaviour. Trade flows between countries will also be qualitatively different.

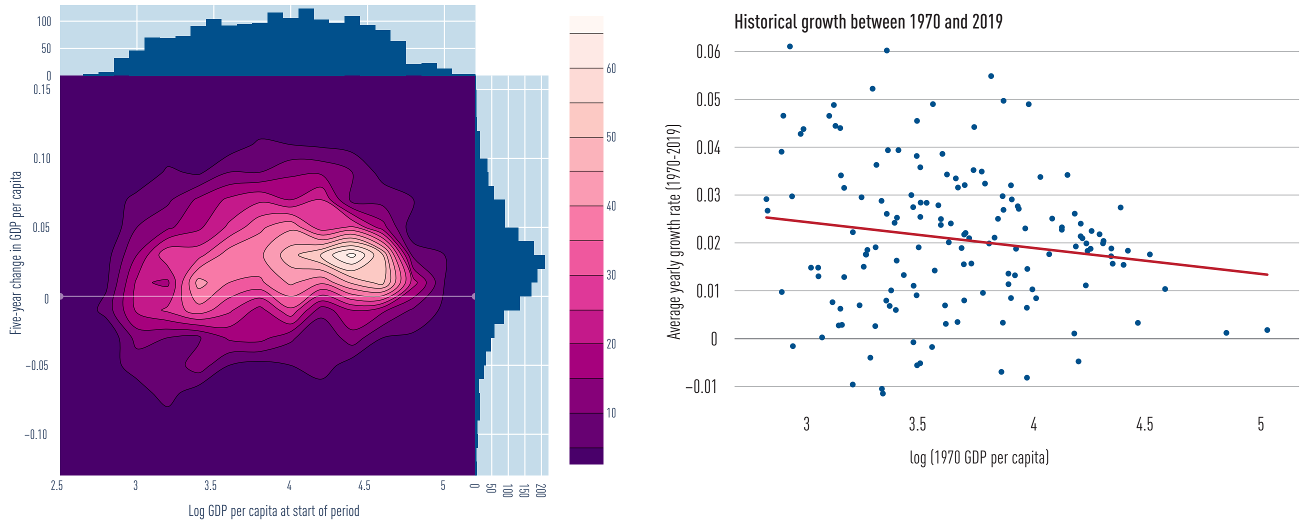
CONVERGENCE. If convergence significantly influences growth, we should see a consistent reduction in the income disparity between developed and developing nations over time, assuming an upward trend in education levels within developing countries' populations. Consequently, we should expect that poorer countries would grow far more quickly than developed countries, ie, if we plot the period changes in GDP as a function of GDP, one should expect to see a strong negative slope (Buhaug and Vestby [2019]).

In the left-hand panel of figure 7, we have plotted a histogram of five-year growth as a function of log GDP per capita for all countries using historical data from the PWT over the period 1970-2020. The right-hand panel shows a similar plot except now we plot changes over a 50-year horizon – we illustrate the average of the

6. Growth rate in GDP per capita over the period 1970-2020, for a selection of developed, developing and emerging market economies

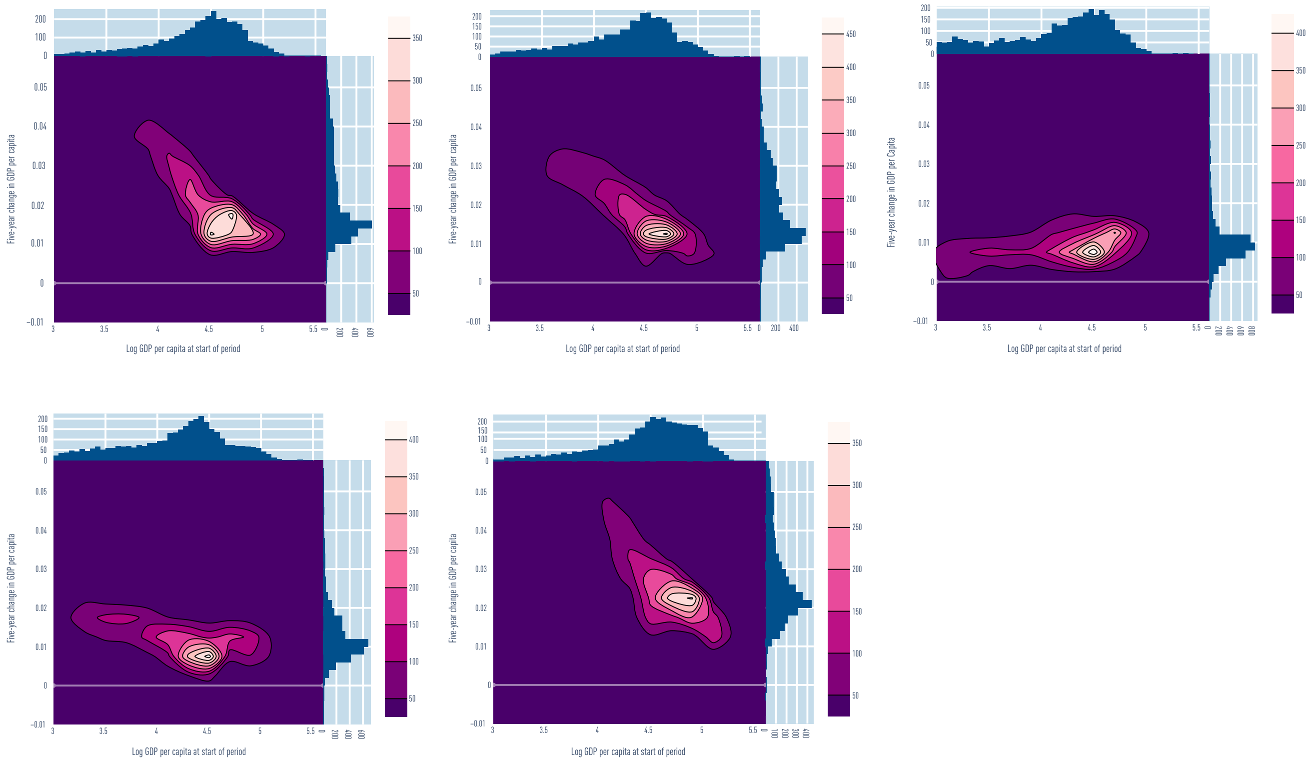


7. Average economic growth, 1970-2019, as a function of initial level of development in 1970



Notes: Left-hand panel: Density plot of growth rate in GDP over a five-year period against log (GDP) at the start of the period. Right-hand panel: Each plot represents an independent country; the solid line represents global linear trend.

8. Economic convergence rate in the SSP framework



Notes: We show the conditional change in GDP per capita (per country) as a function of (log) GDP per capita for SSP1-SSP5 as developed using the IIASA model. Note the strong trend for SSP1, SSP2 and SSP5 indicating the convergence narrative; it is weaker (but still present) in SSP3 and SSP4. Notice also how increments in growth are always greater than 0 – ie, growth is almost always positive.

yearly growth rates since 1970 against log GDP as of 1970 (following Buhaug and Vestby, 2019). In figure 8, we have plotted comparable data using the SSP projections supplied by the IIASA.

Hence, while there is little empirical evidence of convergence on short horizons, we identify some convergence in the data from the past 50 years; poor countries have grown (on average) (slightly) faster than richer countries.[6] Once again, we also see that growth rates for poorer countries are far more volatile. However, when we examine the SSP projections, the convergence narrative (see figure 8) is far more marked, and is observable even when we consider five-year changes for SSP1, SSP2, SSP4 and SSP5. Indeed it is only really SSP3 that behaves anything like what has been observed.

Convergence arises in the SSP scenarios because of increased human capital arising from better education. This is perhaps overly simplistic, and means the scenarios are perhaps less diverse than we might like.

The convergence/development narrative is central to the SSP framework. Low/lower-middle income countries accounted for 13% of global GDP in 2010 but are expected to account for 22-29% (32-49%) by 2050 (2100). Even ‘within model’, such growth may prove unrealistic, because the scenarios do not incorporate climate feedbacks. A number of authors have highlighted through econometric methods that climate change impacts the growth rate of GDP of poorer countries. Basic calculations suggest that climate damages could markedly reduce GDP growth in these countries leading to the persistence of global inequality.

Furthermore, there is a lag before improvements in human capital translate into higher economic growth; similarly, such changes must also be accompanied by other measures such as institutional reform, diversification away from reliance on extractive industries etc, all of which require time. This lag is not factored into the narratives.

Better education and higher GDP per capita are likely to lead to a more rapid fertility transition, which in turn implies a lower population, as seen in figure 4. Hence it seems that:

- The scenarios project significant reductions in inequality and growth in GDP in the first part of the century. This may bias towards a strategy of delaying climate action as we will be wealthier and therefore better placed to finance mitigation subsequently.
- The scenarios are not as pessimistic as one might generally consider when conducting stress testing.

Discounting

The discount factor chosen plays a critical role in shaping the course of action within models determining trade-offs between actions now and those in the future. In this section, we will discuss how the discount factor in the IPCC framework is related to the trade-off in timing of abating GHG emissions in process-based IAMs. This choice of a discount curve, however, has very wide-reaching implications on the transition pathway (and for subsequent scenario expansions such as for asset pricing); in what follows, we highlight some of these and how one might challenge the resulting narrative.

Discounting in process-based IAMs

Assuming there is no natural decay of CO_2 in the atmosphere[7], abating one ton of CO_2 today is equivalent to abating the same amount in the future. The growth of the (expected) carbon price should then be equal to the risk-adjusted discount rate; in the case where there is no uncertainty (eg, in economic output or future cost evolutions) then we would expect that the growth rate of carbon prices (g) should be equal to the risk-free interest rate (r_f) ie:

$$g = r_f \tag{1}$$

This result is easily generalised to the case where we allow for decay of greenhouse gases in the atmosphere and we allow for uncertainty (Gollier [2021]):

$$g = r_f + \delta + \phi\pi \tag{2}$$

where δ is the rate of natural decay of greenhouse gases in the atmosphere, and $\phi\pi$ represents the abatement risk premium and is the product of the income-elasticity (ϕ) of marginal abatement cost and the aggregate risk premium (π) in the economy. Following Gollier (2021), we have developed the annual discount rate (or equivalently the growth in carbon price) within the process-based IAMs, finding a median value of 5%, although in certain scenarios the growth rate can be as high as 15%. By way of comparison, Gollier has examined the rate of growth of the social cost of carbon in an extended cost benefit IAM[8] which incorporates uncertainties in economic progress and technological development, and following on from equation (2) obtains a value of 3.5%, with approximately half of this arising from the impact of uncertainty. Separately, Tol (2022) has surveyed the academic literature for the growth rate of the social cost of carbon in such models and highlights a range between 1.5% and 3%, assuming approximate calibration to market interest rates. These relatively small changes in discount factor lead to very significant differences in abatement expenditure in the future (a factor of two to three by 2050 and four to 10 by 2100).

INTERGENERATIONAL EQUITY AND ASSET PRICING. Discounting has direct consequences for intergenerational equity: high values of the discount rate reduce the mitigation effort of current generations deferring it to the future. This raises ethical issues, especially because future generations will also be the ones bearing the majority of the impacts of climate change. Indeed, a frequent criticism of the DICE model (Nordhaus [2017]) is that the chosen discount factor (at 1.5%!), calibrated to market discount factors, is too high and is ethically unfair.

Gollier argues on the basis of his results that the SSP/RCP framework of the IPCC inefficiently allocates abatement efforts over time. The same final concentration of GHG in the atmosphere could be obtained with a smaller impact on inter-generational welfare by abating more today (and hence a higher expenditure today) and abating less in the future.[9] The choice of discount factor assumed implicitly incentivises ‘waiting’. He points out that this is because process-based IAMs do not find, by design, the temporally optimal strategy.

IMPACT OF DISCOUNTING ON TECHNOLOGY. The choice of discount rate plays an important role in determining future technological pathways. As investment in abatement is, relatively speaking, delayed there is a greater probability that we will need to use carbon dioxide removal technologies to attain the end-of-century greenhouse gas concentrations, ie, we will overshoot the carbon budget. This is the principal reason why the optimisation approach within the IAMs leads to the extensive adoption of BECCS (Bioenergy with Carbon Capture and Storage); this is somewhat at odds with expert views. We also highlight the focus by a number of sources on removal technologies such as direct air capture, which may again be overly optimistic.

The use of an inappropriate discount rate may therefore bias policymakers and potentially investors.

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[6] We observe a difference of ~1% in annual growth rates on the basis of OLS across countries.

[7] This is not unreasonable for CO_2, but other GHGs such as methane are removed by biochemical processes more rapidly.

[8] These are models such as DICE, which explicitly determine the intertemporally optimal abatement strategy by maximising a social welfare function.

[9] To set against this, proposals for rate of growth of the social cost of carbon in, eg, France and the UK, have often exceeded 5% per annum; however, such headline rates disguise current low levels and the fact that schemes often apply only to a subset of emissions.

Future growth of expenditure on abatement (carbon tax). The SSP/RCP datasets detail future taxation on GHG emissions; we plot this for SSP2 in figure 9. As expected, we find that the carbon tax increases rapidly as we entertain more restrictive forcing scenarios, rising for example to 8% of global GDP for SSP2-26. The rapid increase is a direct consequence of the discount rate chosen in the IPCC scenarios. Indeed, for SSP3 taxation levels need to exceed total GDP to achieve low temperature anomalies.

As discussed above, the levels of taxation are assumed to be exogenous, determined by optimisation and hence enable the SSP/RCP matrix. To explore this further, we have analysed taxation as a function of GDP per capita, and, as per other studies in the literature (Le, Moreno-Dodson and Bayraktar [2012]), we find a strong relationship (see figure 10).

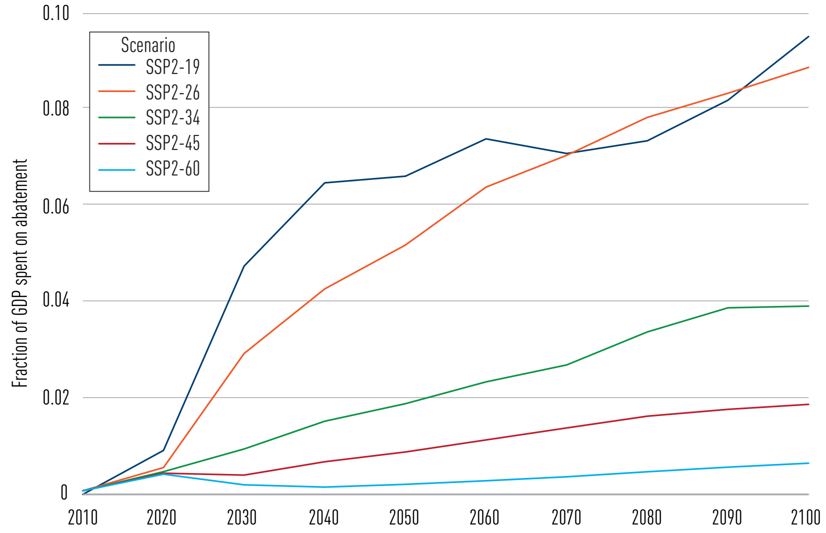
We characterise this behaviour using a logistic function assuming maximal taxation of 60%:

$$\frac{\text{Tax}}{\text{GDP}} = \frac{0.6}{1+e^{-\left(\beta_0 = \beta_1 \log\left(\text{GDP per capita}\right)\right)}} \tag{3}$$

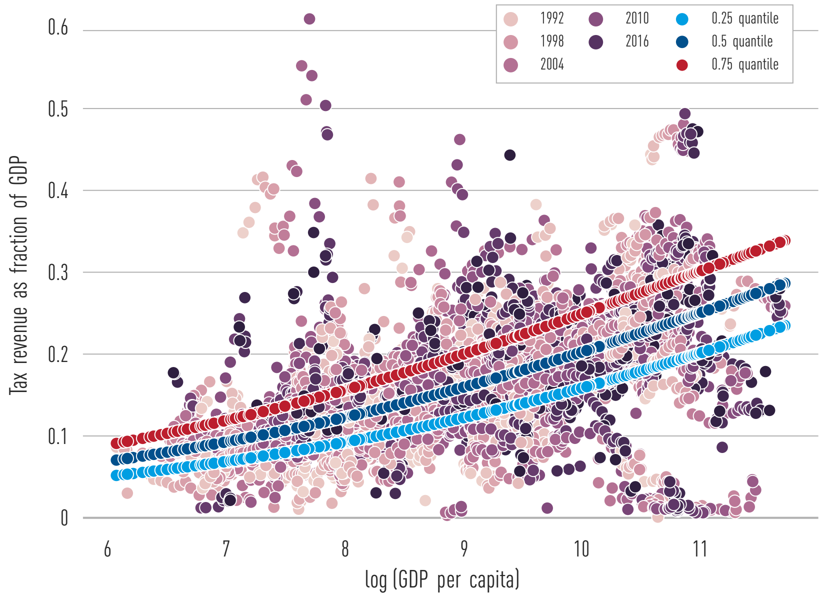
and have then parameterised on the basis of national GDP and taxation over the past 30 years (see figure 10).

This model assumes that the ability to increase taxation depends on increasing GDP per capita. For example, we find that the change in taxation assumed in SSP2 to achieve RCP1.9 requires spending an additional ~4% of global GDP on abating the effects of climate change. We estimate that this requires ~28% increase in GDP per capita, which is challenging to achieve from a growth perspective in SSP2 (see figure 5). This also assumes that all benefits of increased taxation would be diverted solely to fighting climate change, which is of course extremely unlikely. We argue that analysis of taxation patterns is a useful approach for benchmarking the likelihood of particular transition scenarios.

9. Fraction of total GDP spent on addressing greenhouse gas emissions in SSP2



10. Tax revenues as a fraction of GDP per country from 1990-2020



Notes: Typically tax revenues have risen as a fraction of per capita GDP; we have then fitted this using logistic quantile regression. We assume a maximum tax take of 60%.

Asset pricing

Lastly we consider the pricing of assets using the SSP/RCP scenarios.

The fundamental theorem of asset pricing states that the price of any asset is its expected discounted payoff. Suppose we have an asset, worth p_t at time t. Assume that the asset pays a dividend in the next period, d_{t+1}. Then the fundamental theorem states that:

$$p_t = \mathbf{E}_t\left[m_{t,t+1}\left(d_{t+1}+p_{t+1}\right)\right] \tag{4}$$

where $m_{t,t+1}$ is the so-called stochastic discount factor (sdf) over the period $(t, t+1)$. When computing the expectation in equation (4), we probability weight over all possible future states of the world. Furthermore how anticipated future payoffs are evaluated depends on statistical properties of the sdf and how it correlates with future cashflows (here the next period's value and dividend). Thus for example, assets that tend to have good payoffs in bad states of the world will be valued more highly than other assets which, for example, pay off well in good states of the world only. This is because such assets pay well when funds are more urgently wanted.

This means that computing expectations by naively conditioning on a particular SSP/RCP scenario could lead to inaccurate asset valuations, as it implicitly assumes that the likelihood of other states is very small (zero). It is likely that such approaches do not capture the diversification associated with green/brown assets accurately either. Asset pricing likely requires probabilistic scenarios.

Conclusions

The SSP/RCP framework is a powerful construct which has proven very useful both in harmonising research into climate change and enabling policymakers to develop mitigation strategies on both a global and national scale. Given the level of scientific consensus, it is unsurprising that this framework has been adopted within the financial community. We argue that while scenarios are useful, it is important that additional analysis is undertaken as part of adoption:

- The scenarios are developed using a modelling chain, and as such they should be subject to scrutiny using well established model risk management approaches.
- Specifically while the framework is deliberately built as a scenario matrix, with no associated probabilities, we argue that the use of econometric and probabilistic techniques provides valuable insight. Indeed, we would argue that it is challenging for investors to use the framework meaningfully without enhancements to incorporate a view as to likelihood, dispersion and risks around the single paths in the framework.
- The scenarios focus on transition and hence the social development/energy nexus; when extending to areas such as asset pricing, identifying and consistently modelling key risk drivers will be key.
- Many of the identified issues lead to an underestimation of the risk, potentially giving rise to a false sense of security on the impacts of climate change and how transition might unfold.

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Climate salience and the demand for green stocks by mutual funds around the world

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We conjecture that personal experiences associated with extreme weather events drive the perceptions about climate change among fund managers and get reflected in the stocks they trade.

To test this prediction, we study the effect of climate salience on the demand for green stocks among active mutual funds operating in 280 distinct global locations.

We find that climate salience is associated with an increased demand for stocks with lower emission levels and lower emission intensities.

Our findings suggest that as the frequency of extreme climate events increases, we may observe a further greening of funds' portfolios.

Institutional investors around the world are becoming increasingly concerned about their role in meeting global climate targets (eg, Krueger, Sautner and Starks [2020]; Stroebel and Wurgler [2021]). In addition, public expectations for a 'greener' fund industry have never been higher. The Paris Agreement, signed in 2015, calls for the global average temperature increase to remain below 2°C above pre-industrial levels. It specifically asks for us to make "finance flows consistent with a pathway towards low greenhouse gas emissions and climate-resilient development" (United Nations, 2015, page 3). Yet, the impact of climate change on the composition and trading decisions of fund managers remains unclear, with conflicting evidence.[1] Considering the urgency of climate change and the massive commitments of institutional investors around the world to sustainable investing, it is important to perform research to better understand the role of climate change on the mutual fund industry.

We study the role of salient climate events, such as the experience of extremely hot weather, in forming the beliefs and investment portfolios of professional asset managers. Our research is based on a large body of literature, showing that large climate events increase individual awareness about climate change and its consequences (eg, Akerlof et al [2013]; Myers et al [2013]; Zaval et al [2014]). Since investors are impacted by individual experiences (eg, Malmendier and Nagel [2011]; Luo, Yao and Zhu [2022]), salient climate events are likely to be important for their asset allocation decisions. Related work by Choi, Gao and Jiang (2020) documents that retail investors pay more attention to infrequent large climate events than to more frequent events that are smaller in importance.

Our analysis offers support for the importance of climate salience in forming managerial perceptions, using a sample of actively managed mutual funds from 34 domiciles situated in 280 distinct geographical locations. Specifically, we find that managers experiencing abnormally high temperatures during the previous 12 months are more likely to tilt their portfolios towards greener stocks (ie, stocks with lower levels of emissions and lower emission intensities). Abnormally high temperatures are less likely to change the perceptions of managers who already show awareness of climate change. Consistent with this prediction, green funds exhibit significant demand for green stocks, irrespective of recent temperatures. In contrast, managers of non-green funds are less likely to be aware of the effects of climate change. We show evidence that they exhibit a demand for green stocks only when climate is salient.

Our study is related to an emerging literature investigating the link between environmental concerns and the investment decisions of asset managers. The evidence is mixed. Some studies find a trend of decreasing exposure of institutional investors to companies with high emissions (eg, Choi, Gao and Jiang [2023]; Gibson Brandon et al [2022]). In addition, Starks, Venkat and Zhu (2023) show that institutions with long investment horizon hold stocks with higher ESG scores and Nofsinger, Sulaeman and Varma (2019) find that institutions underweight stocks with poor ESG profiles. Atta-Darkua et al (2023) document that asset managers who join climate-related investor initiatives tilt their portfolios towards stocks with lower emissions. Again, the effects are weak and conditional on the presence of carbon emission schemes within different jurisdictions. Within the US, Pástor,

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[1] See, for example, Choi, Gao and Jiang (2020); Bolton and Kacperczyk (2021); Gibson Brandon et al (2022); Atta-Darkua et al (2023); Choi, Gao and Jiang (2023); Starks, Venkat and Zhu (2023); Pástor, Stambaugh and Taylor (2023).

Stambaugh and Taylor (2023) also find weak evidence of the importance of climate for the asset allocation of fund managers. They document that the aggregate tilt of the mutual fund industry towards green stocks is a mere 4% of the assets under management. Bolton and Kacperczyk (2021) show that institutions underweight firms with high emissions, although the effect is limited to the most salient polluting industries, such as oil and gas. Lastly, Fernando, Sharfman and Uysal (2009) show that greener firms tend to have fewer institutional investors but more retail ones. Choi, Gao and Jiang (2020) find similar results.

We contribute to this literature by providing the first global study on the importance of climate salience to the allocating decisions of fund managers. In the aggregate, funds' investment decisions do not reflect concerns about the climate. However, personal experiences of abnormally high temperatures are reflected in the stocks that funds trade in the form of stronger demand for green stocks.

We further contribute to the literature on the importance of individual life experiences to financial decision making (eg, Malmendier and Nagel [2011]; Benmelech and Frydman [2015]; Bernile, Bhagwat and Rau [2017]; Cronqvist and Yu [2017]). For example, previous research documents the importance of macro-economic conditions when entering the workplace (Chen et al [2021]) and experience with bubbles (Luo, Yao and Zhu [2022]) to the portfolio choices of fund managers. We contribute by providing fresh evidence on the importance of experiencing salient events, such as the ones related to climate change, in forming the investment decisions of professional asset managers. Related work by Pástor, Stambaugh and Taylor (2021) argues that certain investors enjoy holding green assets as they are willing to sacrifice returns to hold their desired portfolios. In a follow-up paper, Pástor, Stambaugh and Taylor (2022) also argue that green stocks have outperformed in recent years due to previously unanticipated increases in environmental concerns. Our study suggests that personal experience with climate change may contribute to these effects.

Data and main variables

Our dataset spans the trading decisions of global actively managed equity mutual funds between 2009 and 2021, combining data from Factset, Morningstar Direct and Compustat. We restrict our analysis to funds' trading decisions among equities that are part of the MSCI World Index (consisting of 2,266 unique companies over our sample). There are three advantages to our approach.

- First, the index constituents are among the largest publicly traded companies in the world, for which there are relatively few concerns about data quality.
- Second, emissions data from Trucost do not cover most publicly traded companies. By choosing the equity part of the MSCI World Index, we limit the impact of any selection effects associated with the set of companies covered by Trucost.
- Third, since the MSCI World Index is a widely popular benchmark, the index constituents represent the most liquid stocks in the world. Thus, if managers update their beliefs about climate change, they are likely to trade in the stocks we focus on. The disadvantage of our approach is that we drop trades that are potentially informative about the perceptions of fund managers about climate change. However, the dollar positions among MSCI World stocks represent on average 66% of the total assets under management for the funds in our sample.

Our goal is to study the role of perceptions about climate change in the global asset management industry. Since we conjecture that managers update their beliefs about climate change at the same time as they are experiencing extreme temperature, they are going to contemporaneously enter and exit stocks with the same characteristics, ie, 'herd' into the same type of stocks. Thus, our empirical approach follows the earlier literature on mutual fund herding, which studies the determinants of the fraction of funds buying and selling stocks ('fund demand') at the same time. In addition, as the greenness of individual stocks is correlated with stock characteristics (Pástor, Stambaugh and Taylor [2021]), we test for the role of perceptions about climate change in driving fund demand for green stocks beyond what can be explained by stock characteristics.

Following Sias (2004), we compute the demand of mutual funds for stock i in quarter q as the raw fraction of funds buying a given stock:

$$Demand_{i,q} = \frac{No.\,of\ funds\ buying_{i,q}}{No.\,of\ funds\ buying_{i,q} + No.\,of\ funds\ selling_{i,q}}$$

One approach to measure company greenness would be to use the environmental 'Escores' provided by one or more of the ESG rating agencies. However, we opt out of this approach, for two reasons. First, previous research documents a substantial variation in scores across the different data providers (eg, Berg, Kolbel and Rigobon [2022]). The industry disagrees on the scope, measurement, and weight of the various indicators used to construct the scores. Second, Berg, Fabisik and Sautner (2023) point out that at least some of the rating agencies might be retroactively changing scores. This implies that we cannot be certain what exact ratings were available to investors at the time of their trading decisions. We opt to use the firm's emissions levels and intensities instead.[2] The focus on emissions is motivated by the measure's popularity among practitioners, the media, and academics. Emission intensities are also easy to interpret and understand. Our source of emissions data, Trucost, reports emissions under the greenhouse gas (GHG) protocol, measured in tonnes of CO_2 equivalent (tCO_2e) per year. We use the reported values of Scope 1 emissions, which reflect direct emissions produced by companies, as well as total emissions (Scope 1-3). Bolton and Kacperczyk (2021) use the log of reported emissions to uncover a relationship between emissions and returns, which suggests that investors pay attention to that measure. However, Aswani, Raghunandan and Rajgopal (2023) show that emission intensity (emissions scaled by sales) is a better measure of company greenness due to large correlations between emissions and company size. We use both levels and intensities in our analysis.

To capture climate salience, we measure abnormal temperature using historical weather data from the National Centers for Environmental Information (NCEI) in the US. This data consists of a daily record of temperatures from more than 9,000 worldwide stations. We extract a time series of daily mean temperatures from the weather station closest to the physical location of the fund's office for the period from 2000 to 2023. To compute our quarterly measure of abnormal temperature, we further require that the closest weather station has at least 10 years of historical data with at least 300 observations per year. Following Choi, Gao and Jiang (2020), we decompose observed temperatures into predictable, seasonal, and abnormal components. Specifically:

$$Abnormal\ Temp_{j,t} = Temp_{j,t} - Average\ Temp_{j,t} - Monthly\ Temp_{j,t}$$

where $Temp_{j,t}$ is the average daily temperature in month t for city j; $Average\ Temp_{j,t}$ is the average monthly local temperature for city j over the 120 months prior to month t; and *Monthly*

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[2] A company's CO_2 emission intensity is measured as the company's CO_2 equivalent annual output divided by its annual sales revenue.

$Temp_{j,t}$ is the average temperature for city j in the same calendar month over the last 10 years minus $Average\ Temp_{j,t}$. The remainder, $Abnormal\ Temp_{j,t}$, captures the abnormal temperature.

Following Di Giuli et al (2023), we identify fund managers as experiencing abnormally hot temperatures if $Abnormal\ Temp_{j,t}$ is on average higher than 2°F during the previous 12 months. The cutoff of 2°F roughly corresponds to one standard deviation in the distribution of the abnormal temperature and reflects our choice to focus on the most salient weather events.

Empirical tests

We estimate panel regressions of the demand of mutual funds for green stocks, controlling for stock and industry characteristics:

$$Demand_{i,q} = \alpha_q + \beta_q^G * Green_{i,q-1} + \gamma_q * \mathrm{X}_{i,q-1} + \psi_{i,q}$$

where $Green_{i,q-1}$ measures the 'greenness' of a stock using either company emissions levels or intensities computed at the end of the previous quarter. The vector of control variables $\mathrm{X}_{i,q-1}$ includes characteristics associated with funds' demand: size, book-to-market, profitability, investment, dividends-to-book, market beta, short-term reversal, momentum and lagged demand (Gompers and Metrick [2001]; Sias [2004]; Koijen and Yogo [2019]; Pástor, Stambaugh and Taylor [2023]). Our regressions include both time and industry-fixed effects.

The control variables and fixed effects are important for teasing out the relationship between fund demand and stock greenness. Pástor, Stambaugh and Taylor (2021) show that stock characteristics are correlated with ESG scores. Hence, mutual funds might appear to be trading on 'green' information while they actually change their portfolio exposure following, for instance, a style exposure. In addition, funds may be restricted in their investment opportunity set because of their mandated investment objectives. For example, value funds may appear to be less green than growth funds, simply because value stocks appear to have on average lower environmental scores than growth stocks. However, a climate-conscious value investor might still tilt their portfolio towards greener value stocks as part of their investment opportunity set, even though that set consists of stocks that have on average lower environmental ratings.

We report our main findings in figure 1. Overall, active funds do not trade in the direction of emissions (specifications 1-4). However, following abnormally high temperatures, funds tilt their portfolios towards greener stocks (specifications 5-8). The results hold when we proxy for green stocks using both the level or intensity of emissions, as well as when we use direct (Scope 1) and total emissions (Scope 1-3). Thus, increased awareness about climate change changes perceptions about the importance of climate in forming the investment decisions of professional asset managers.

Some investors may already be aware of the effects of climate change, even when climate is not salient. To test this prediction, we focus on a sub-sample of green funds only. These funds are most likely to incorporate beliefs about climate change in their trades, even when climate is not salient. A fund is classified as green if its name or reported strategy in Morningstar contains one of the strings: SRI, ESG, Social, Green, Environ, Responsible, Clean, Renewable, Sustain, or Impact. We study the demand of green funds for green stocks and report the results in figure 2. The demand of green funds is strongly related to all proxies of stock greenness, reflecting green funds' preference for green stocks. The findings support our intuition that in general, managers of green funds have stronger perceptions about the effects of climate change.

In contrast, abnormally high temperatures are likely to change the perceptions of investors who are less aware of the consequences of climate change. To test this, we first focus on a sub-sample of non-green funds. Overall, the demand of non-green funds is not driven by our proxies of stock greenness (specifications 1-4 in figure 3). However, following abnormally high temperatures, managers in non-green funds appear to buy stocks with relatively lower Scope 1-3 emission levels and intensities (specifications 7-8). We don't find statistically significant results when we proxy for greenness using only Scope 1 emissions, although the estimated coefficients point in the same direction (specifications 5-6).

One potential reason for this might be that Scope 1-3 emissions may be perceived to be more informative about the

1. The demand for green stocks among all funds

	All trades				Abnormally high temperature				Not abnormally high temperature			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
log (Scope 1)	−0.000				−0.002**				−0.000			
	(−0.10)				(−2.21)				(−0.11)			
Scope 1^{Int}		−0.001				−0.006**				−0.000		
		(−0.51)				(−2.15)				(−0.38)		
log (Scope 1–3)			−0.001				−0.003***				−0.001	
			(−1.33)				(−2.80)				(−1.08)	
Scope $1–3^{Int}$				−0.001				−0.006**				−0.001
				(−0.81)				(−2.43)				(−0.54)
Controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Time FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Industry FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	59,925	60,055	60,055	60,055	42,408	42,509	42,509	42,509	59,913	60,043	60,043	60,043
R-squared	0.121	0.121	0.121	0.121	0.053	0.053	0.053	0.053	0.119	0.119	0.119	0.119

This table presents the results of OLS regressions of trading demand on lagged characteristics, for the whole sample. Control variables include size, book-to-market, profitability, investment, dividends-to-book, market beta, short-term reversal, momentum and lagged demand. All variables are winsorised on the 1% level. All specifications include time (ie, quarter) and industry fixed effects. t-statistics are given in parentheses, based on standard errors clustered on the stock level. Statistical significance at the 10%, 5% and 1% level is indicated by *, ** and ***, respectively.

2. The demand for green stocks among green funds

	All trades				Abnormally high temperature				Not abnormally high temperature			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
log (Scope 1)	−0.002***				−0.004**				−0.003***			
	(−3.20)				(−2.15)				(−3.38)			
Scope 1^{Int}		−0.008***				−0.012**				−0.009***		
		(−3.47)				(−2.45)				(−3.38)		
log (Scope 1–3)			−0.004***				−0.004				−0.004***	
			(−3.13)				(−1.50)				(−3.17)	
Scope 1–3^{Int}				−0.008***				−0.012***				-0.010***
				(−4.16)				(−2.59)				(−4.44)
Controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Time FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Industry FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	56,070	56,193	56,193	56,193	20,095	20,129	20,129	20,129	55,261	55,380	55,380	55,380
R-squared	0.031	0.031	0.031	0.031	0.1	0.1	0.1	0.1	0.029	0.029	0.029	0.03

This table presents the results of OLS regressions of trading demand on lagged characteristics, for the sub-sample of green funds. Control variables include size, book-to-market, profitability, investment,dividends-to-book, market beta, short-term reversal, momentum and lagged demand. All variables are winsorised on the 1% level. All specifications include time (ie, quarter) and industry fixed effects. t-statistics are given in parentheses, based on standard errors clustered on the stock level. Statistical significance at the 10%, 5% and 1% level is indicated by *, ** and ***, respectively.

2. The demand for green stocks among non green funds

	All trades				Abnormally high temperature				Not abnormally high temperature			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
log (Scope 1)	−0.000				−0.001				−0.000			
	(0.66)				(−1.04)				(0.68)			
Scope 1^{Int}		0.000				−0.003				−0.001		
		(0.33)				(−1.29)				(0.55)		
log (Scope 1–3)			−0.000				−0.003**				−0.000	
			(−0.76)				(−2.31)				(−0.46)	
Scope 1–3^{Int}				0.000				−0.004*				0.000
				(0.05)				(−1.74)				(0.44)
Controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Time FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Industry FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	59,925	60,055	60,055	60,055	41,801	41,901	41,901	41,901	59,913	60,043	60,043	60,043
R-squared	0.12	0.12	0.12	0.12	0.045	0.045	0.045	0.045	0.118	0.118	0.118	0.118

This table presents the results of OLS regressions of trading demand on lagged characteristics, for the sample of non-green funds. Control variables include size, book-to-market, profitability, investment, dividends-to-book, market beta, short-term reversal, momentum and lagged demand. All variables are winsorised on the 1% level. All specifications include time (i.e. quarter) and industry fixed effects. t-statistics are given in parentheses, based on standard errors clustered on the stock level. Statistical significance at the 10%, 5% and 1% level is indicated by *, ** and ***, respectively.

stock greenness than the direct Scope 1 emissions. Last, there is no evidence that managers in non-green funds tilt their portfolios towards green stocks when climate is not salient, consistent with our intuition that they are in generally less perceptive about the impact of climate change (specifications 9-12).

Conclusion

We show that climate salience is important for the perceptions of mutual fund managers, as reflected in their trading decisions. Following abnormally high temperatures, the fund industry prefers to buy stocks with lower emission levels and emission intensities. We further show that the effect of abnormal temperatures on portfolio choices likely stems from fund managers who are most likely to update their perceptions about climate change. Our findings are informative about the formation of perceptions of climate change in the global fund industry, and the possible changes of these perceptions in the future. As the frequency of extreme climate events continues to increase, we are likely to see further greening of funds' portfolios.

We are currently conducting research, investigating the role of news mentions about climate change in the media as an additional driver of climate change salience. Our results also offer directions for future research. For example, the salience of climate change may have a more pronounced impact on the way investors allocate capital across fund managers rather than the way fund managers allocate across holdings. That is, climate salience may impact aggregate institutional holdings via a stronger demand for green funds among fund investors rather than a stronger demand for green stocks among fund managers. For policymakers interested in the greening of institutional portfolios, a fruitful direction of research would be the implementation of tools that increase awareness about the impact of climate change particularly among managers of funds without an explicit mandate of investing in green assets.

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Dealing with climate change: asset pricing implications of monetary and fiscal choices

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To fully decarbonise the economy by mid-century, abatement initiatives are required for which unsubsidised private intervention is less likely to provide financing than has been the case so far.

Public involvement will have to take the form of higher taxation or higher debt. In the present condition of unprecedentedly high public debt, and of reluctance to accept higher taxation, this creates a problem.

If the second phase of the green transition is mainly financed by debt, the global debt burden could rise by as much as 40%, putting pressure on interest rates. This would have direct repercussions on the price of government bonds, and an indirect effect on equity valuation via the discounting channel.

Setting the scene

In a recent article in *The Journal of Finance*, Bolton and Kacperczyk (2023) provided an analysis of the impact of climate transition risk on the pricing of global assets. Their excellent analysis is based on a key methodological assumption, ie, that by mid-century the decarbonisation of the economy will be achieved. Given this hard decarbonisation deadline, those companies or sectors that are currently delaying their transition towards decarbonisation will face a greater adjustment ('transition') risk, exactly because the 2050 deadline is assumed to be 'hard'.

Given the assumption, the analysis is logically impeccable. In this piece I intend to argue that investors should not take for granted that the 2050 decarbonisation goals will certainly be met. More precisely, I intend to explain that in the years to come financing the green transition will become increasingly difficult and politically painful. I will also argue that, if the decarbonisation targets are to be met, this will involve a much higher degree of publicly funded investment than has been the case so far. If, conversely, this public funding is not forthcoming, then temperature increases are likely to be much higher than currently hoped for, and physical damages will become more important (the analysis of Bolton and Kacperczyk [2023], by the way, concludes that the physical climate risk is currently not priced, a conclusion with which we concur – see Rebonato [2023] in this respect). I intend to show in this piece that, in either case, the prices of assets will be significantly affected.

Key to my argument is the magnitude and *source* of the financing required to achieve the decarbonisation of the economy. Let me start with the size. The estimates vary greatly, but the UN Intergovernmental Panel on Climate Change (IPCC) estimates that the financial investment necessary to meet the 1.5°C target should be between \$1.6trn and \$3.8trn per annum between 2020 and 2050 for the transformation of the energy systems alone.[1] Let's take the average and add the estimated costs for adaptation (about \$200bn per annum), and we reach a total of about \$3trn per annum. Along similar lines, the consultancy McKinsey[2] estimates that to meet the 1.5°C target "[c]apital spending on physical assets for energy and land-use systems will need to rise by \$3.5 trillion per year for the next 30 years, to an annual total of \$9.2 trillion per year for the next 30 years". To gauge how big these figures really are, one should remember that they are more than the world spends on the military (\$2trn); more than it spends on education (\$3.2trn) and about the same as the biggest spending item of all, healthcare (\$8.3trn).

This huge financing need can be provided in three ways: by private investment; by some form of taxation (generalised 'carbon taxes'), or by public debt. I intend to argue that the contribution from the private sector is going to be smaller for the phase of the decarbonisation process that we are entering. *If a near-complete decarbonisation of the economy by 2050 is to be achieved*, this will have significant either debt or fiscal implications. In turn, these dynamics will affect asset prices – directly, as far as fixed income assets are concerned, and via the discounting channel for equity assets. If, on the other hand, the financing is not forthcoming, we can expect significant climate damages, probably greater than the market is currently impounding. So, either via a transition-risk or a physical-risk channel, we can expect prices to be affected by how we handle the green transition. The rest of the paper makes this intuition more precise.

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[1] IPCC Report (2018); see Chapter 4, Strengthening and Implementing the Global Response, Section 4.2.1.1, page 321.

[2] McKinsey (2022)

The end of easy climate financing

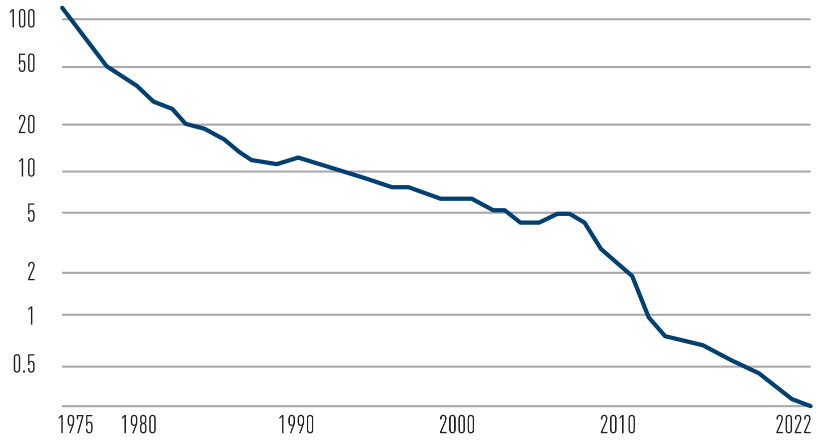
Despite a pace of decarbonisation which to date has been not nearly fast enough to keep us within the Paris Agreement 1.5-2°C target, there have been some notable successes in the abatement chronicles. The most impressive achievements have been in the progress made in making wind and solar energy competitive with fossil fuel-produced energy. When I was a physics student, my solid state physics professor taught us that, at the time, it took more energy to make a solar panel than it would make throughout its lifetime. Figure 1 shows how dramatically things have changed. A similar story can be told about the cost of electricity obtained from wind turbines.

How did solar power become so cheap? According to Perlin (2002), Bell Labs solar cell pioneer Daryll Chapin put the cost of one watt of solar photovoltaic capacity at $286 in 1956, which corresponds to well over $2,000 in current dollars. The cost of the electricity provided was staggering, but, for the application for which the panels were built, there were no alternatives, since the electricity was required to supply energy for the Vanguard I satellite in 1958. A textbook story from an (old) economics manual would then suggest that, as new solar panels for satellites were built, their prices began to come down, and they found some other not quite so marginal application (say, for lighthouses or mountain refuges), increasing demand, production and innovation – in short, setting in motion what economists call the 'learning by doing' process.

In reality, this is not what happened. The impressive price improvements shown in figure 1 have relied, especially in the early phases, on substantial subsidies.[3] In order to entice private investors, the size of the subsidy had to cover the difference in marginal cost between producing one watt of electricity with solar panels and with fossil fuels. As the cost of solar energy has been plummeting, this price difference has become smaller and smaller. So, the amount of solar energy produced (and subsidised) has increased, but the size of the 'unit subsidy' has been steadily declining: if the quantity of subsidised energy has grown exponentially, also exponentially have prices declined, and the total fiscal burden has not grown out of hand. The two blades of the cost scissors have now become so close, that it is beginning to be debatable whether subsidies are still needed for this form of energy production. This 'easy' first part of decarbonisation financing may, however, soon be over.

1. The cost of photovoltaic panels, 1975-2022

$/W (logarithmic scale)



Source: International Renewable Energy Agency (2023); Nemet (2009); Farmer and Lafond (2016); Our World in Data. This data is adjusted for inflation

Solar panels and wind turbines must, of course, play a key role in the decarbonisation of the economy, and their cost is likely to keep on falling. However, the application for which they are most suited, namely the production of electricity, is only a part – between 25% growing to 40% in the medium-term future (ie, circa 2050) – of the energy the world requires. In particular, what Smil (2021) calls the four pillars of the modern world, ie, cement, steel, fertilisers and plastics, all require high-intensity energy that is difficult to produce with renewables. Together these four pillars account for 20% of energy use, and for 25% of emissions. This means that just doing more of the same – only pursuing the renewable-driven abatement strategy, that is, that the private sector has so far found profitable to finance with ever smaller subsidies – will not keep us within the Paris targets.

What are the alternatives? Let's consider the first, carbon removal and storage. Along every single path in the IPCC models that limits warming to 1.5°C by the end of the century carbon removal, and carbon sequestration and storage, play an important role. The same can be said for most paths that avoid temperature increases greater than 2°C. And herein lies the rub. Consider carbon sequestration and storage (CSS), for instance, for which the technology has been well understood since the 1930s, and which can have effectiveness between 60% and 90%. We are not facing technological barriers to the implementation, but the cost of CSS is currently rather high. Admittedly, if more emitting companies were to embark on sustained programmes of CSS, the magic of learning by doing would certainly kick in, and the cost of capture and storage would probably follow a trajectory similar to the one shown in figure 1 for solar panels. The problem is that, no matter how cheap it can be made, CSS remains purely a cost.[4] This means that market mechanisms give private investors no incentive to apply CSS: the global warming externality remains unpriced. And as for direct carbon capture (DCC), it is even more expensive, and cannot be 'bolted on' to an existing power plant. So, a private investor in DCC would have to set up a company from scratch to extract at high cost from the air a substance (CO_2) that almost nobody wants to buy. Hardly a viable commercial proposition.

This is where fiscal measures of some form come again to the fore. (By fiscal measures I refer to the variety of initiatives that alter the fiscal budget of a country: these can take the form of the economists' favourite tax, the carbon tax; or of subsidies; or of tax credits for green energy producers.) The cost of CSS and DCC are indeed likely to fall significantly, but there is no cross-over point (as in the case of solar energy vis-à-vis fossil fuel

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[3] Incidentally, Pfund and Healey (2011) document that, in its early days, the fossil fuel industry also enjoyed substantial subsidies, and these were also very effective at lowering the cost of the energy produced. Of course, fossil fuels still enjoy substantial subsidies, but these have a different rationale.

[4] Sequestered carbon can have industrial applications (and therefore a market price), but the applications are either too small to make a difference, or are aimed at squeezing the last drop out of oil deposits – hardly an activity compatible with decarbonising the economy.

energy) beyond which the activity becomes self-sustaining through private investment with no or minimal government help: a cost remains a cost, no matter how small, and some form of inducement or penalty from the government will remain necessary essentially forever.

We have focused so far on the removal and sequestration part of the equation. But in the case of renewables the investment landscape may also be changing. Some of the more promising locations (in terms of insolation, average wind speed *and proximity to an existing grid*) have already been exploited. Middle East states that are trying to diversify their revenue stream currently eye with interest the vast desert areas where solar panels could have an energy yield only dreamt of in the cloudy north of Europe. The problem is, however, that solar energy produced in the Sahara cannot be quickly fed into an existing grid for distribution where the energy is needed. Electrons, unfortunately, cannot be transported down pipelines like oil or gas, and transmission over large distances entails substantial losses – the greater the distance, the greater the loss. China has pioneered thousand-kilometre transmission lines, but these have received huge public-finance support.[5] For private investors the infrastructure expenditure of a very long-distance transmission line on top of the high initial capital costs of renewable installations is likely to be an investment bridge too far.

Similar considerations apply to wind turbine farms, especially those of the deep offshore variety. A recent article in *The Economist* (2024) points out that, even for the distribution of electricity from renewables *within* a medium-size country like the UK (where wind turbines provide the lion's share of renewable energy), seven times more grid building will be required every year than it is currently installing. This extra grid capacity is not needed to transport energy over intercontinental distances. More prosaically, currently "Scottish wind-farm operators are paid to switch off their turbines when the wind blows strongly because the grid does not have the capacity to send all the electricity they produce to consumers".[6] Of course, "building seven times more grid every year requires a commensurate increase in investment". Predictably, private investors have only shown interest in building "the lower-risk bits of the grid".[7] This is why a *state-owned* new entity, GB Energy, is being set up to provide the rest of the required financing. This is a clear indication that, even for the more mundane electrification tasks in what I have called the second phase of decarbonisation, public intervention (either in the form of taxes or subsidies,[8] or of higher consumer costs[9]) is needed to entice investors to participate in these initiatives.

The problems with second-generation exploitation of renewable energy are not limited to the absence of existing nearby power network into which the electricity can be fed. Consider, for instance, the case of hydrogen. Hydrogen is frequently touted as a climate solution and could indeed be used to store surplus renewable power when it cannot be fed to the grid,[10] as feedstock or fuel for at least three of Smil's four recalcitrant pillars of modern society, and as an energy carrier for hard-to-electrify industrial processes and transport.[11] However, hydrogen is still a climate challenge, as it is currently produced from fossil fuels, primarily by steam methane reforming. There are alternatives, such as electrolysis (which involves splitting water into hydrogen and oxygen), but they also require a lot of energy. If this energy comes from burning fossil fuels, the gain in terms of greenhouse gas emissions is not obvious.[12] To provide the energy for its production with renewables, hydrogen should be produced in areas with great insolation and strong winds. Unfortunately, these areas are rarely co-located with the point of energy use and repurposing the existing energy storage and transportation infrastructure to support centralised hydrogen production (which need not make economic or environmental sense) would be very costly, when at all possible. For illustration, existing gas pipelines cannot be repurposed to the transportation of pure hydrogen because of the embrittlement of the pipeline caused by hydrogen ('pipeline-safe' blending of hydrogen with gas points to a concentration of hydrogen of at best 15%, and often of only a third of this value).[13]

The engineering details can become very complex, very soon. However, the message also in this case is that, if hydrogen is indeed to play the important role in the economy decarbonisation that many commentators expect it can fulfill,[14] substantial infrastructure support must be provided before private actors can be enticed to take up the infrastructure baton. As a consequence, one can see that the joint demands of CSS, DCC and infrastructure creation or repurposing will give rise to a substantial call for public funding. Where is this going to come from?

Financing the transition

There are mainly two government levers to finance the transition: via increased taxation (either of producers or of consumers)[15], and/or via increased issuance of public debt. Let's start with the latter. Unfortunately, after years of financial crises, after the COVID epi-

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[5] A 1,100kV link in China was completed in 2019 over a distance of 3,300km with a power capacity of 12GW. With these voltages and distances, intercontinental connections become possible. (The high voltage is needed to reduce losses in transmission: power is equal to current times voltage, and the heath 'friction' is proportional to the *square* of current.)

[6] The Economist (2024), page 17.

[7] Ibid, page 18.

[8] In microeconomics textbooks subsidies are often described as 'negative taxes'. This is correct from the point of view of the recipient of the subsidy. The subsidy is however paid by the government out of the available fiscal pot. So, if the same transfers and social benefits are to be kept, additional taxes or debt will have to be raised.

[9] Currently, the costs for grid upgrades are paid for by the consumers of electricity via their bills.

[10] There are several ways to store hydrogen, eg, in salt caves, in porous rock, in lined rock caverns, or in liquid form. See Londe (2023).

[11] For steel making, the direct reduction of iron ore in blast furnaces could be based on hydrogen rather than coke. The efficiency of electric arc furnaces, which can use up to 100% of scrap steel, could also be improved by using hydrogen as a reducing agent and energy vector. Ammonia production relies on hydrogen and could use green hydrogen in lieu of hydrogen derived from fossil fuels; the same is true of plastic production requiring hydrogenation, but this does not offer the same decarbonisation potential. Finally, cement production could use hydrogen as fuel in lieu of fossil fuels and to reduce the amount of clinker needed.

[12] In the US, the Inflation Reduction Act has given support to the production of hydrogen from fossil fuel, as long as coupled with carbon sequestration and storage – processes that are currently also expensive.

[13] In regulatory terms, France has the highest hydrogen blending figure at 6% (see https://www.iea.org/data-and-statistics/charts/current-limits-on-hydrogen-blending-in-natural-gas-networks-and-gas-demand-per-capita-in-selected-locations), and research commissioned by California suggests that safety concerns appear from blending above 5% (see https://docs.cpuc.ca.gov/PublishedDocs/Efile/G000/M493/K760/493760600.PDF).

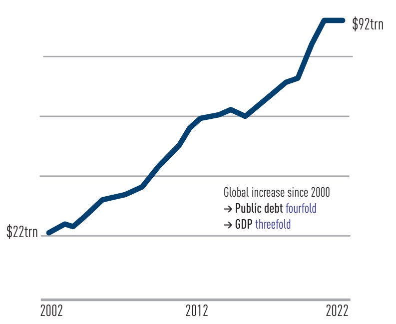
[14] See Tarvydas (2022).

[15] Taxation of consumers or producers has different economic and redistributive consequences. Producer taxation, in particular, can result either in increased consumer prices (if the producers have enough 'pricing power'), or in reduced dividends. Quanity controls have the effect of a tax on consumers (if, because of scarcity, they bring about an increase in price), and/or on dividends (because of reduced profits). Only in a world with perfect knowledge of production costs are quantity controls equivalent to taxation.

2. The level of global debt as a fraction of GDP, 2002-22

Public debt has increased more than fourfold since 2000

Global public debt, $trn



demic, and after the on-going war in Ukraine, levels of public debt are at an all-time high. US dollar debt has climbed by a factor of four from 2000 to 2022, while GDP has 'only' grown by a factor of three (see figure 2). Nobody knows what the sustainable the debt/GDP ratio can be (and this level is clearly strongly country-specific, depending as it does on whether the country can print money in the currency in which the debt is denominated – euro-zone countries do not have this privilege – and on the fraction of domestic versus foreign investors). However, it is clear that public debt cannot indefinitely grow faster than GDP. The reactions of the UK Gilt market to the unfunded debt implications of the short-lived Truss government suggest that, in a no longer close to zero-rate environment, markets are becoming less forgiving of unbridled borrowing.

In addition, most developed countries are facing a disadvantageous demographic evolution in the coming decades (the 'climate change decades'): as populations grow older, the largest component of public spending in every major industrialised country, ie, public pensions and social security, will come under greater and greater pressure. If the 2023 reluctance of the French electorate to countenance a modest increase in pension age is representative of a broader reluctance to reduce pension benefits, public expenditure faces strong headwinds in the decades to come. The ageing of the populations of developed countries only reinforces these headwinds when the second largest item of public expenditure is taken into account: healthcare.

What about taxation? Here there is a stark dissonance. In many countries, most voters agree that more should be done to curb climate change. This fails to translate, however, into support of actual taxation. A study by the University of Chicago[16] has found that, at least in 2018, only 42% of US voters believed that climate change is anthropogenic (a necessary condition for any form of taxation to be accepted).[17] As usual, those "Americans who accept that climate change is happening want the government to address it". However, even among this group, "forty-four percent support and 29 percent oppose a policy to reduce greenhouse gas emissions by taxing the use of carbon-based fuels". And as for willingness to pay, "57 percent of Americans are willing to pay a $1 monthly fee; 23 percent are willing to pay a monthly fee of $40". In the most optimistic projection, this would amount to less than $6bn per year, orders of magnitude less than what is required.

Admittedly Americans are somewhat of an outlier in the Western world in their degree of climate scepticism, and Europeans are more inclined to believe in the reality of the problem, in its anthropogenicity, and in the belief that 'something must be done' to curb it. And the desires of Europeans for better services (and pensions) are at least as strong as those of Americans. The voters' willingness to back these beliefs and desires with actual willingness to pay higher taxes remains, however, elusive. Figure 3 shows the level of taxation as a share of GDP versus GDP/person in 1986 and 35 years later, in 2021: the slope of the relationship has barely changed, and when large emitter countries have moved up the taxation slope (as in the case of India), this has only been because the country has become richer. The US has bucked the trend, but, as the same figure shows, 'in the wrong direction': the average level of taxation has remained virtually

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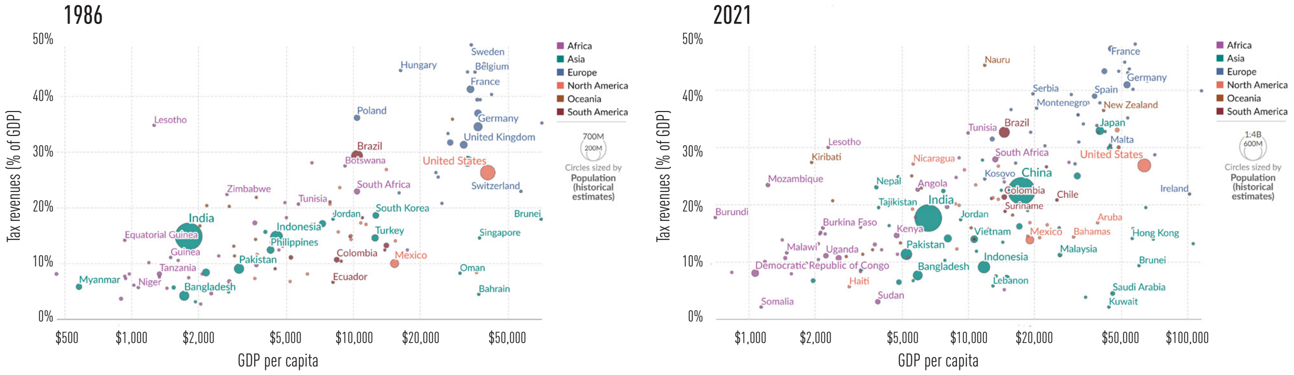
[16] NORC (2018).

[17] These findings are not unique. A recent survey by the Yale University Program on Climate Change Communication shows that only 32% of Conservative Republicans believe that climate change will harm the US. Even adding Liberal/Moderate Republicans and Independents, this fraction only increases to 58% and 64%, respectively.

3. Tax revenues as a share of GDP vs GDP per capita in 1986 and 2021

Taxes include direct and indirect taxes as well as social contributions. GDP per capita is adjusted for inflation and differences in the cost of living between countries



Source: UNU-WIDER Government Revenue Dataset (2023); World Bank; Our World in Data.

Note: Tax revenue includes social contributions. GDP per capita is expressed in international $[1] at 2017 prices.

1. International dollars: International dollars are a hypothetical currency that is used to make meaningful comparisons of monetary indicators of living standards. Figures expressed in international dollars are adjusted for inflation within countries over time, and for differences in the cost of living between countries. The goal of such adjustments is to provide a unit whose purchasing power is held fixed over time and across countries, such that one international dollar can buy the same quantity and quality of goods and services no matter where or when it is spent. Read more in our article: What are Purchasing Power Parity adjustments and why do we need them?

unchanged, despite its income (in constant dollars) having almost doubled.

Overall, while tax revenue as a percentage of GDP climbed strongly in the G7 countries from the 1960s to the 1990s, the upward trend has ground down towards zero for almost every country.[18] The world over, very few, if any, political parties have recently been elected on a platform of higher taxation for higher services. Overall, it seems fair to say that the willingness of the electorate to accept higher taxation levels currently seems extremely limited.

Quantification of the debt burden

In a recent document, the IMF[19] has made an estimate of how much extra debt could be raised in different decarbonisation scenarios. Its analysis makes use of a neo-Keynesian dynamic general equilibrium model with an energy input and a number of different fiscal policies, as in Traum and Yang (2015). The fiscal policies considered are "carbon pricing, green subsidies, public investment, and targeted transfers, as well as standard taxes on consumption, labour, and capital income".[20] Two decarbonisation paths are considered: "a substantial scaling up of green investment and subsidies to reach the net zero goal [by 2050] [..], and a moderate increase in such spending to contain the rise in debt".[21] In the moderate-increase scenario the emission would only be reduced by 40% by 2050, falling well short, therefore, of the expected emission decrease necessary to stay within the 2°C target by 2100.

The results are sobering. If the amount of investment necessary to reach the net-zero goal is undertaken via public-debt financing, the result would be an increase in GDP/debt ratio by 45% by 2050, an increase in the debt/GDP ratio that the IMF report describes as "likely unsustainable". Needless to say, this increase in borrowing would entail higher borrowing costs.

At the opposite end of the spectrum, if the decarbonisation were fully financed via taxation in the form of a carbon tax (the form that, as far as emission reduction is concerned, is the most effective and least distortionary[22]) the IMF estimates that a levy of $280/ton would be needed – a level of taxation that, the report understatedly reports "might be politically unpalatable in many countries". Combining this value with previous estimates[23] of the corresponding tax burden, a carbon tax of this magnitude would equate to an increase in taxation of approximately 6% of GDP. Estimates of the optimal social cost of carbon are notoriously sensitive to model assumptions, but, to give a yardstick for comparison, and leaving aside that overall fossil fuel emissions are currently *subsidised*, carbon trading schemes currently put the cost of 1 ton of carbon emissions at around $30.

The implications for asset pricing

The 'trilemma' this state of affairs poses (between public debt, level of taxation, and level of abatement) has awkward policy consequences.[24] Important as these are, we mainly look in this study at the implication for asset prices. If our analysis about the substantial role that public financing must play in what I have called the second phase of decarbonisation, the effects of the transition on asset prices are likely to be significant, and negative.

Much as the electorate may dislike higher taxes or higher debt/GDP ratios, we have argued that, if the second phase of the decarbonisation process is to take place, a higher reliance will have to be placed on either the fiscal or the debt tool (or both). Can one quantify the effects on asset prices of increased taxation or increased debt on economic growth, the level of rates? In the case of taxation, the outcome strongly depends on how the tax revenues is levied (eg, via a carbon tax, by increasing the general level of taxation, via subsidies, etc).[25] In the case of public debt, the analysis is considerably cleaner, and we therefore look at this aspect in some detail.

The first-order effects of increased debt issuance, of course, are going to be on the prices of government debt. Here one must clarify an important point. There have been several studies, reviewed in the excellent paper by Mongelli, Pointner and van den End (2022), aimed at assessing on theoretical grounds how the so-called 'natural rate of interest' should be affected by climate change. The natural rate of interest is an important unobservable quantity that serves as benchmark for central bank policy decisions. It can be defined as the real (as opposed to nominal) rate of interest which allows the economy to operate at its full potential without creating unwanted inflationary pressures. Arguably, the Fed funds rate minus spot inflation can be considered a reasonable proxy for the US natural rate of interest. The majority of the theoretical studies reviewed in Mongelli, Pointner and van den End (2022) predict that climate risk is likely to *decrease* the natural rate of interest. From this, one may be tempted to conclude that bond yields (or at least *real* bond yields) should also decline as a result of climate risk. This conclusion is however unwarranted. The first reason why o ne cannot directly translate changes in the natural rate of interest into changes in yields is that there is no concept of credit (default) risk in the definition of the natural rate of interest. In reality, as a government issues more and more debt, investors become more worried about its ability to service the debt, to repay the principal, and to refinance, and demand a yield compensation that increases with the debt maturity. The effect is very strong for emerging-market debt, but also G7 countries can display a similar dynamics: as an example, when in 2008 the UK government had to spend £50bn to rescue Royal Bank of Scotland, the CDS spread for the same bank and for the UK government only differed by less than 20bp (at one point the spreads were 250bp and 270bp, respectively).

In addition, as Mongelli, Pointner and van den End (2022) point out, "[h]igher public spending could also be related to social security expenditure to cover health, emergency housing, relief efforts and other costs stemming from natural disasters. The commensurate increase of fiscal deficits will likely lead to an increase of government debt and the associated higher demand for savings *will exert an upward pressure on r**" [emphasis added].

For our purposes, we will therefore assume in what follows that higher debt issuance will be associated with higher interest rates, through the channel of increased credit risk, and because of higher demand for savings (the investment needed for the 'second phase' of the decarbonisation). In making this assumption we are in line with the IMF approach to modelling the macro-fiscal implications of climate policies.[26]

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[18] In most developed countries, taxation is progressive, and therefore when income falls during a recession, tax revenues decline more strongly than GDP. This effect has been particularly pronounced during the 2008-09 financial crisis, and makes the detection of the underlying trend difficult.

[19] IMF (2023).

[20] Ibid, page 4.

[21] Ibid, page 4.

[22] There are, of course, redistributional issues associated with a carbon tax. These are in practice very important (witness the popular gilet jaunes reaction to a modest carbon tax in France in 2018), but they are not considered in this study.

[23] IMF (2019).

[24] "[C]arbon pricing is often unpopular, thus transforming the trade-off into a trilemma between achieving climate goals, fiscal sustainability, and political feasibility.", ibid, page ix-x.

[25] For detailed discussion, see, eg, IMF (2019).

[26] See Garcia and Nguyen (2022). See, in particular, "Sovereign interest rates are increasing in the debt-to-GDP ratio to capture the downward-sloping demand for safe assets, which is particularly relevant for countries with less fiscal space", pages 2-3.

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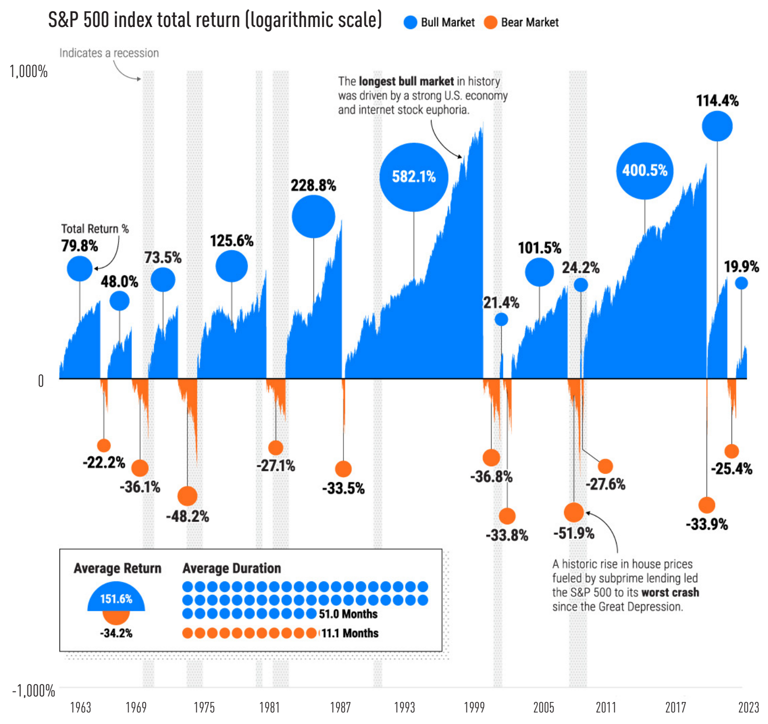
An increase in the debt/GDP ratio will cause a decline in price for existing debt, and a higher borrowing cost for new issuance. As corporate debt almost invariably trades at a *positive* spread to government debt, the impact is expected to be negative also for this asset class. The effect is likely to be more pronounced for countries with more limited debt headroom, ie, for emerging markets that have issued debt in denominated in US dollars or in other strong currencies, or for countries that have relinquished the power to print money in the currency of denomination of the debt (euro block). For all countries, as rates rise, the servicing burden will increase.

Higher rates will have important repercussions on equity prices as well, via the discounting channel and the related 'substitution' effect. A sustained increase in rates would see the dynamics observed during the rate-repression period after the 2008-09 crisis play out in reverse: while during this period an extremely accommodative monetary policy by central banks worldwide caused a series of 'controlled mini-asset bubbles' in virtually every asset class, an increase in rates would be likely to be associated with downward pressure on equity valuations. Figure 4 shows the duration and magnitude of equity bear markets from 1962 to date. Periods of recessions are marked by grey bars, and are almost invariably associated with bear market periods. Since recessions are often ushered in by an increase in rates to curb inflationary pressures, this brings about a negative association between equity valuations and the level of rates. And as the equity-market response to the latest bout of inflationary pressure (and increased rates) testifies, the link between lower equity valuation and higher rates remains active even if an outright recession is avoided.

If the 'green transition' is achieved mainly via taxation instead of debt, either consumers' spending power or dividends to equity holders (or both) will be affected. As mentioned, different forms of taxation have different levels of efficiency, and different macroeconomic impacts. This makes the quantification of the impact on asset prices difficult, but given the estimated magnitude of the fiscal effort, the effect can be expected to be significant.[27]

4. Periods of bear and bull markets for the S&P500 index from 1962-2023, and the location of recession periods (grey bars)



The **longest bull market** in history was driven by a strong U.S. economy and internet stock euphoria.

A historic rise in house prices fueled by subprime lending led the S&P 500 to its **worst crash** since the Great Depression.

Source: Visual Capitalist (Neufeld and Lam [2023]).

Both these scenarios are predicated on the decarbonisation of the economy taking place at a pace roughly consistent with a 2°C target. It is far from certain, of course, whether this will be the case. However, with any reduction in transition risk (as would happen, that is, if this decisive abatement action is not taken) *physical* climate risk correspondingly increases. Estimates of the economic impact of higher temperatures vary greatly (see the discussion in Rebonato [2023] and Kainth [2023]), but, under plausible scenarios, they could be very significant – the more so, the greater the margin by which the 2°C warming is exceeded. Since, for a fixed labour-capital split, equity prices reflect changes in economic output with a leverage effect (see, eg, Bansal, Kiku and Ochoa [2019]), the effect on equity valuation can be large also for physical climate risk.

Conclusions

Climate transition risk is understood in two different ways: either the risk of carrying out the required decarbonization of the economy in a disorderly manner (this is the perspective in Bolton and Kacperczyk [2023]); or the risk arising from abating too little or too much. The former interpretation points to the correct and efficient timing of the intervention; the latter, to the overall intensity of intervention. In its second interpretation, transition risk is inversely related to physical risk.

In this note the case has been made that the current global level of debt and willingness to accept higher taxation make type-II transition risk to be strongly skewed in the direction of an insufficient degree of abatement being undertaken. If this is the case, we can expect significant physical risk, with negative repercussions on economic output, consumption and ultimately, equity valuation.

If, instead, the required transition *is* carried out in a timely manner, we have argued that private financing will be less forthcoming (with limited subsidies) than it has been so far. This will entail either a higher level of national debt, or of taxation, or of both. If the debt level were to increase as much as the IMF (2023) projections suggest, the impact would be strong not only on the price of traded debt, but, via the discounting channel, also on equity valuations. So, either because of physical risk (if the transition takes place too slowly), or because of transition risk (if robust abatement does take place), one should expect a downward pressure on asset pricing. The

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[27] Of course, equity holders are consumers themselves, so that reduced dividends will also impact purchasing power. More broadly on debt vs tax, one key question is the textbook Ricardian equivalence: David Ricardo's point was that government debt will need to be repaid (via increased tax at some point) leading to an equivalent impact on households of the two funding choices. Empirically, it has been recorded that agents are imperfectly Ricardian and anticipate only partially the need to fund government spending (and curtail their spending in anticipation).

quantification of this effect is a topic of active research at the EDHEC-Risk Climate Impact Institute.

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Scope for divergence

The status of value chain emissions accounting, reporting and estimation and implications for investors and standard-setters

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The consideration of value chain emissions is crucial as they represent a material source of emissions that companies can mitigate, whether to address impact or transition risks.

Reporting of these indirect emissions has been voluntary; it remains sparse and is often guided by corporate convenience rather than emissions materiality. While data availability and quality are expected to improve in the medium term, reporting standards are not intended to support cross-company comparisons.

While data providers model value chain emissions, estimates are divergent and pay insufficient regard to firm specificities to support intra-sector comparisons.

Investors should treat the integration of value chain considerations into asset selection and reporting cautiously to avoid greenwashing. Value chain emissions may be used to guide overall policy, implement sector allocation, or initiate engagement with companies. Value chain considerations may still be included into asset selection via specific, security-level performance metrics and/or indicators of credible decarbonisation commitments and action.

Standard-setters must avoid requiring, condoning or encouraging uses of value emissions that are unfit for purpose, notably portfolio construction; they should support disclosure of value chain emissions, targets and plans, along with their standardisation, including through promotion of sectoral and value chain collaborations.

The number of companies disclosing estimates of greenhouse gas emissions in their value chains is set to increase rapidly in the second half of the decade as mandatory climate reporting ramps up in key jurisdictions and more companies are enticed or pressured by capital providers, business partners and customers to produce such estimates.

While value chain emissions are widely regarded as critical to understanding an organisation's climate-related impact and transition risks and opportunities, the perspective of their inclusion in the scope of a US Securities and Exchange Commission (SEC) climate disclosure rule has led to unprecedented backlash against the integration of sustainability issues into financial management. Acknowledgement of concerns by the chair of the SEC has fuelled speculations that the disclosure of value chain emissions may be curtailed or made voluntary, despite very broad investor support. Such an outcome would signify a departure from the strengthening global consensus among standard-setters and regulators regarding the importance of value chain emissions to investors. Indeed, disclosures on value chain emissions are not only mandated by European Union law but also integrated into the first set of sustainability-related financial disclosure standards endorsed by the International Organisation of Securities Commissions (IOSCO).

In this piece, we explain why value chain emissions matter; describe the state and future of corporate value chain emissions disclosure; discuss estimation and modelling challenges; and conclude with recommendations for investors and standard-setters.

Understanding the dual materiality of value chain emissions

Originally published in 2001 by the World Resources Institute (WRI) and the World Business Council for Sustainable Development (WBCSD), the Greenhouse Gas (GHG) Protocol Corporate Standard is strongly established as the world's most widely used GHG accounting and reporting framework.

The corporate standard requires that reporting entities first delineate their organisational boundaries, specifying the operations they own or control. The framework then mandates the establishment of operational boundaries, wherein emissions from operations are categorised as either direct or indirect, depending on the consolidation approach (equity share or control) applied to organisational boundaries. Direct emissions, referred to as Scope 1 emissions, emanate from sources owned or controlled by the company. Indirect emissions, on the other hand, are attributable to the entity's activities but arise from sources it does not own or control.

The standard further subdivides these into: (i) Scope 2 emissions, stemming from purchased energy (eg, electricity, steam, heating or cooling) consumed in equipment or operations owned or controlled by the entity; and (ii) Scope 3 emissions, encompassing other indirect emissions

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from upstream and downstream activities within the value chain, including the product-use and product end-of-life stages.

Compliance with the corporate standard (WRI and WBCSD [2004]) requires reporting entities to measure both Scope 1 and Scope 2 emissions. The reporting of emissions beyond those from sources 'owned or controlled' by the company has been justified on impact grounds by the fact that power generation is the largest source of CO_2 emissions globally and the assumption that industrial or commercial entities – which consume more than half of the electricity produced – may exert significant influence on these emissions through energy conservation and efficiency efforts, as well as engagement or replacement of energy suppliers.

Similar logic has been applied to justify the consideration of Scope 3 emissions, whose accounting and reporting are detailed in the 2011 Corporate Value Chain Standard (WRI and WBCSD [2011]). In most sectors, value chain emissions dwarf direct and purchased energy emissions combined and reporting entities often have considerable influence on these emissions through upstream ('cradle-to-gate') and downstream (post-sale) supply chain decisions, including product design.

Taking stock of indirect emissions has also been justified on business grounds as it allows entities to identify opportunities for cost savings and management of climate-related transition risks, ie, the risks associated with transitioning to a lower-emitting economy, including notably policy/regulatory risks (such as the reduction of fossil fuel subsidies or the introduction of caps on or pricing of GHG emissions); and market and reputation risks.

Limiting analysis to Scope 1 and 2 emissions can lead to incorrect inferences about an entity's absolute or relative impact and the risks and opportunities it faces. An investor comparing companies that have comparable businesses but different degrees of outsourcing of energy-intensive activities may well draw the wrong conclusions on their environmental footprints or transition risks. Ducoulombier (2021) observes that Apple's carbon intensity, measured as the ratio of Scope 1 and 2 emissions to revenues, is about 200 times lower than that of rival Samsung Electronics. This does not indicate better efficiency, however, as at the time of observation Apple was fully outsourcing manufacturing whereas Samsung had not yet embarked on large-scale outsourcing. When Scope 3 emissions were included, the difference in carbon intensities fell to a low two-digit percentage.

The consideration of indirect emissions however considerably increases the risk that emissions will be accounted for multiple times. The Scope 2 emissions of an entity are the Scope 1 emissions of energy generating entities. In a portfolio context, aggregating Scope 1 and Scope 2 emissions across entities results in double counting when the same emissions are accounted by electricity consumers and their suppliers. Guidance is available to avoid double counting. The problem is greatly compounded with Scope 3 as the same emissions may be accounted for multiple times in any value chain, and the problem cannot be neatly unpacked by considering scopes in isolation. How problematic this is depends on how the data are used – from an impact standpoint, it is generally considered that multiple counting indicates the existence of co-responsibility for emissions and/or of multiple levers to tackle them.

This notwithstanding, the consideration of value chain emissions is crucial for reporting entities and investors alike as they represent a material source of emissions to manage from the dual point of view of climate impact and transition risk and opportunities. Recent analysis of disclosures by companies from high-impact sectors found that value chain emissions accounted for three-quarters of their total emissions on average (CDP [2023]).

The state and future of Scope 3 emissions reporting

Voluntary reporting: quantitative strides against deep-seated qualitative shortcomings

Mandatory GHG reporting programmes have long been effective in countries responsible for the bulk of global emissions but were focused on direct emissions in heavy industry and the energy sector. The scope of mandatory reporting has expanded over time to listed and large companies and Scope 1 and 2 in multiple jurisdictions and voluntary reporting against the corporate standard has also progressed markedly in recent years.

However, value chain emissions reporting up to fiscal year 2023 was voluntary (except for certain large and listed companies in France), and reporting companies lagged in terms of Scope 3 emissions disclosure. Two thirds of the 23,000-plus entities contributing data to global environmental disclosure aggregator CDP in 2023 reported direct emissions but only 37% disclosed emissions across all three scopes (CDP [2024]).

Progress in the number of companies voluntarily reporting value chain emissions, however, has not been paralleled by an improvement in the quality of the data provided. For illustration, a major data provider applying basic plausibility checks rejected nearly three-quarters of the corporate reports it had collected for its 2023 dataset (Singh, Vyawahare and Schrager [2023]).

The Corporate Value Chain Standard breaks down Scope 3 emissions into eight upstream and seven downstream categories. Disclosure is on a comply or explain basis and companies can exclude activities or even whole categories of emissions provided this does not compromise the relevance of the reported emissions inventory.

In practice, however, the average reporting company only discloses data for just over a third of the categories, and the majority of reporting entities omit the most material categories.

Typically, a single category accounts for the majority of emissions, another category has very high significance and it takes at most three categories to capture the bulk of emissions (CDP [2023]). Overall, the most important upstream category is Purchased Goods and Services (Cat. 1) and the most important downstream category is Use of Sold Products (Cat. 11) for non-financial companies. The footprint of the financial sector corresponds to Investments (Cat. 15), which is also the dominant downstream category for listed real estate.

However, value chain emissions disclosure appears to prioritise 'convenience' over materiality. As an illustration, easy-to-track Business Travel (Cat. 6) is the most frequently disclosed category, although its contribution to inventories is anecdotal, while material categories are under-reported.

The reporting of value chain emissions has thus far been sparse, incomplete and insufficiently focused on material sources. This not only limits the relevance of these data and metrics naively derived from these data for decision-making but also constrains the quality of any estimation or modelling that can be derived from these disclosures.

Mandatory reporting to the rescue?

The number of companies disclosing value chain emissions is set to increase dramatically between now and 2030 as mandatory reporting is now effective in the European Union and was signed into law in California in October 2023.

Other jurisdictions have started to align with the recommendations of the Taskforce on Climate-related Financial Disclosures (TCFD), whose 2017 version calls for disclosure of value chain emissions "if appropriate" and 2021 update requires it when material. Further impetus has been provided by the June 2023 release of financial disclosures standards by the International Sustainability Standards Board (ISSB). The first topical ISSB standard pertaining to climate-related disclosures, it incorporates TCFD recommendations and requires disclosure of material emissions, including within the value chain. In July 2023, the International Organisation of Securities Commissions called on its 130 member jurisdictions to "adopt, apply or otherwise be informed by the ISSB Standards" to promote consistent and comparable disclosures for investors (IOSCO [2023]).

With the introduction of mandated reporting and assurance, the availability and reliability of reported data will improve markedly. However, due to specificities of value chain accounting and reporting, the data will remain irrelevant for certain usages and should be handled with extreme caution by investors.

Indeed, while the value chain standard is intended to promote consistency in accounting and reporting, it affords companies significant leeway in the selection of the inventory methodologies that are appropriate to their circumstances (options are available across the fifteen categories). Likewise, while minimum boundaries are identified for each category, the reporting of certain emissions is flagged as optional.

By way of illustration, companies may use either primary data, ie, data from specific activities within a company's value chain, eg, as provided by suppliers or employees, or secondary data, which may include industry average data, financial data, proxy data and other generic data. While calculations should rely on high quality and highly specific data, such data may be difficult to avail. It is understood that the accuracy and completeness of the inventory will improve over time as more and better data become available and the reporting entity transitions towards more specific calculation methods. Investment in internal resources and processes and long-term engagement of stakeholders across the value chain should improve the quantity, quality and specificity of data as well as their usage.

The leeway afforded to reporting entities derives from the primary purpose of the value chain standard, which is to help companies track and reduce their emissions over time. This of course may be an issue for parties that approach the data with different objectives and notably cross-corporate comparisons. For such usages, the flexibility of the standard is particularly problematic when it is applied to activities or categories that have material importance. CDP (2017) gives a stark illustration of the problem by comparing the reporting of Johnson Controls and United Technologies Corporation (UTC), two manufacturers of electrical equipment and engines. While Johnson Controls collects the emissions data from its direct suppliers to compute Scope 3 emissions from the goods and services procured, UTC uses an Economic Input-Output Life Cycle Assessment (EIO-LCA) model to estimate the cradle-to-gate emissions of all products purchased. This results in Scope 3 emissions for Purchased Goods and Services being seven times greater for UTC than for Johnson Controls (after rescaling to control for differences in revenues).

Lack of comparability is not limited to the cross section: change of accounting choices over time, in respect of boundaries or methodology inter alia, may generate considerable volatility in the data reported by the same company. While such changes may correspond to progress towards more comprehensive and accurate reporting, they contribute to very high volatility of reported data.

As things stand, the respect afforded currently to reported emissions by certain regulators and standard setters, eg, the Partnership for Carbon Accounting Financials puts corporate-reported emissions at the top of its data hierarchy (PCAF [2022]).

Estimation of value chain emissions

The consideration of value chain emissions is key to understanding the climate impact of economic activities and to assessing climate-related transition risk and opportunities. However, corporate disclosures are sparse, incomplete, volatile across time and essentially unfit for cross-sectional comparisons. It is thus natural to explore the potential of emissions modelling to produce more comprehensive, representative and standardised data to support a wide range of uses.

Corporate-level value chain emissions are available from multiple data providers. Commercial datasets may be comprised of reported data and/or modelled data. Providers including reported emissions in their datasets may choose to redistribute the numbers as sourced; include only those reported figures that pass their quality checks; or adjust reported numbers where needed to increase plausibility or comparability (capping and flooring based on peer group is standard practice). Providers may opt to include only modelled emissions in their datasets and either disregard reported emissions (eg, by generated estimates from business or financial data) or use these to calibrate and run their estimation models. Differences in data sources and processing (eg, update cycle, quality controls) will lead to different redistributed values across providers (Nguyen et al [2023], find identical values for only 68% of reporting firms across two major datasets that use reported values without adjustments; divergence is above 20% for 16% of the data). Differences in estimation approaches, assumptions and model calibration, and input data produce highly divergent values and low correlations across modelled datasets (Busch, Johnson and Pioch [2022]). Studies comparing reported and modelled datasets document low correlations and wide divergence. The degree of divergence is high enough to dramatically alter sorts: comparing a modelled dataset to reported datasets, Nguyen et al (2023) find that little over one of five observations fall in the same ranking decile and less than a third fall in adjacent deciles (and most of the divergence happens with firms in top or bottom decile by emissions and revenues).

Figure 1 gives a high-level view of value emissions modelling approaches. The simplest approaches multiply the non-reporting company's revenues by the representative carbon intensity (measured as the ratio of emissions to revenues) of a reference group; they ignore differences in business models, and how they may impact total emissions and their breakdown into scopes. Sector-specific multivariate models follow the same logic but allow for consideration of corporate fundamentals beyond revenues. The practicality and the output of such approaches is constrained by the availability, granularity, and quality of reported emissions. Various approaches may be combined to improve estimation by using more specific data when available (including simply extrapolating from past reported data). Multiple models may be run in parallel and combined to produce more stable output. Modelling categories separately should be expected to improve accuracy, but this remains difficult given current limitations of reported data.

Environmental Extended Input-Output (EEIO) modelling sidesteps the issue of sparse corporate emissions reporting as it relies on country/industry-level emissions – however, the granularity and precision of EEIO estimates is limited by the availability of corporate revenues breakdown and the definition of the basic modelling unit, and by nature they do not incorporate corporate specificities beyond revenues breakdown.

1. Approaches used for the modelling of Scope 3 emissions

Approach	Description
Application of sector statistic	A statistic of normalised emissions is computed from reported data at the industry group/sub-sector/sector level and used to estimate emissions for non-reporting companies
Sector-specific regression analyses	Non-reported emissions are estimated as output of sector-specific multilinear models using key financial metrics and possibly other fundamentals (eg, number of employees).
Bottom-up modelling	Life Cycle Analysis (LCA)-type methodologies are used to estimate emissions from the bottom-up, as much as possible by combining corporate-specific physical information with the appropriate emissions factors. Granularity, specificity and quality of data may vary
Top-down EEIO modelling	Emissions are produced by application of EEIO models, which requires mapping of company revenues to EEIO structure
Top-down EEIO modelling and LCA	EEIO approach is hybridised with generic product-based (LCA) data (typically for product-use phase emissions)

Source: Ducoulombier (2021)

Life-cycle analysis (LCA) extensions of EEIO models typically rely on representative products per industry and as such cannot incorporate corporate specificities beyond product portfolio composition. Furthermore, certain data provider implementations fail to recognise product differences that have been shown to materially impact value chain emissions. For illustration, up to a recent methodology update, a major data provider was estimating the value chain emissions of automotive manufacturers without considering the shares of electric, conventional and hybrid vehicles in their outputs.

Bottom-up modelling using LCA principles theoretically has the potential to produce highly corporate-specific emissions, but the dearth of standardised corporate reporting of physical information on outputs and processes makes the approach particularly research intensive, promotes reliance on high-level indicators and sector figures, and introduces subjectivity owing to the need for expert judgment.

Nevertheless, providers that have traditionally relied primarily on regression- or EEIO-based estimation models are increasingly using bottom-up modelling for high-stake sectors for which some physical data can be collected, eg, the energy and automotive sectors. Bottom-up modelling offers promise but realising its true potential requires meeting the challenges of acquiring reasonably objective, corporate-specific data on both activities and processes, at reasonable cost.

Progress in artificial intelligence seems to pave the way for improving the specificity of emissions estimation at reasonable cost, eg, by complementing EEIO with machine learning approaches trained to capture the impact on emissions (categories) of differences in business activities, geographies, or financials and fundamentals. This is a relatively new avenue for research and early results do not deliver dramatic changes. Nguyen et al (2023) find that the use of 'out of the box' machine learning models trained on aggregate and category level emissions only produces small improvements in prediction relative to straightforward and traditional approaches (computing emissions from peer-group emissions intensity and revenues, or using a linear model combining revenues, number of employees, and dummy industry indicators).

Altogether, there is insufficient consideration of corporate circumstances, including of business model considerations, in the modelling of value chain emissions. Hence modelled Scope 3 emissions, while preferrable to reported emissions in many ways, are also unfit for the purpose of intra-sector comparisons.

Implications for investors and standard-setters

Investors: ensure value chain data and usages are fit for purpose; explore alternatives to value chain emissions

Ensuring fit-for-purpose uses of value chain emissions. Investors need to accept that while the consideration of value chain issues is key from both impact and financial perspectives, the limitations of reported and modelled value chain emissions put severe restrictions on usage.

The quantity and quality of reported data should be expected to make great progress in the second half of this decade; this will pave the way for improvements in the quality and convergence of modelled data. However, in the current state of value chain emissions reporting and modelling, integration of Scope 3 emissions into investment management decisions must proceed with extreme care (as is understood, inter alia, by asset owner-led net-zero coalitions; see Ducoulombier [2022]).

Fiduciary duties (and professional standards) call for taking reasonable steps to:

- diligently assess the quality of data and ensure that it is fit for the intended purpose; and
- transparently disclose the limitations, risks, or uncertainties associated with its use or production.

Fiduciaries should detail the steps taken to mitigate these concerns, where relevant.

Similarly, fiduciaries allocating to strategies that incorporate value chain emissions data should take reasonable steps to assess whether the quality of the data and the way they are used are adapted to the strategy's objectives and constraints and ensure the strategy is managed in accordance with the investor's financial and non-financial objectives.

Raw value chain emissions data are typically not fit for the purpose of asset selection. Scope 3 emissions being larger than cumulated Scope 1 and 2 emissions by an order of magnitude in most sectors, basing intra-sector stock-selection decisions on total emissions would drown any corporate-level signals present in reported Scope 1 and 2 emissions in a sea of product and activity-based Scope 3 noise. Doing so would lead to disregarding the efforts made by companies in the mitigation of their greenhouse gas emissions and must be forcefully opposed (Ducoulombier [2020, 2021]). Scope 3 emissions data need to be considered separately, if at all.

Metrics and indicators derived from value chain emissions without proper considerations of data limitations should be assumed to have inherited these limitations until established otherwise. Scaling emissions by revenues or enterprise value to produce intensity metrics leaves the problem unaddressed. Portfolio alignment metrics may also be tainted by naïve use of Scope 3 data.

Scope 3 emissions modelling should aim for the highest level of granularity for which sufficient corporate data can be availed or reliably estimated. For more than a decade already, properly modelled value chain emissions have been providing relevant order of magnitude information at the levels of sectors or segments to:

- Assist in defining priority areas for action;
- Implement sector allocation;
- Initiate engagement with companies; and
- Meet investors' reporting needs (Raynaud et al [2015]).

When disclosing the emissions of their portfolios and derivative metrics, investors should report the Scope 1 and 2 emissions and metrics linked to their investments separately from their Scope 3 counterparts where information about the latter is required (as mandated by PCAF, [2022]). The disclosure of datapoints incorporating the Scope 3 emissions of underlying investments should be accompanied by mentions of data limitations.

BEYOND AND BESIDES VALUE CHAIN EMISSIONS. Value chain considerations still may be included indirectly into portfolio construction and stewardship to incentivise companies to decarbonise throughout their value chains and/or to manage exposure to associated transition risks. This may rely on value chain emissions-related metrics that can support security-level analysis such as:

- financial and/or physical measures of involvement in targeted high impact activities, eg, fossil fuel involvement or, at the other end of the spectrum, involvement in climate change solutions as identified in sustainable finance taxonomies;
- sector-specific key climate performance indicators, eg, energy efficiency of products; and
- metrics of upstream and downstream value chain climate-risk exposure, eg, in the spirit of Hall et al (2023), etc.

This integration may be pursued through the identification of issuers that take credible steps to address value chain emissions challenges, eg, produce high-quality inventories, set credible emissions reductions targets and transition action plans, deliver according to targets and plans. Assessment of issuers against such criteria could inform capital allocation and stewardship actions. Such approaches are mandated under voluntary net-zero investment frameworks (Ducoulombier [2022]).

Finally, concerned investors also should include Scope 3 considerations in their policy and issuer engagements, directly and/or through their participation in industry initiatives, to advocate for:

- Scope 3 accounting and reporting to ensure the challenges and opportunities of value chain decarbonisation are fully appreciated by companies, notably those in high impact sectors;
- Standardisation of Scope 3 accounting at sector level and support of supply chain initiatives to further contribute to data improvement; and
- Adoption of value chain decarbonisation targets by issuers.

STANDARD-SETTERS: AVOID ABETTING GREENWASHING, SUPPORT DISCLOSURE AND STANDARDISATION. Standard setters should heed Hippocrates' advice and first do no harm by ensuring they neither require nor encourage unsuitable usages of value chain emissions. This means ensuring that they:

- avoid mandating portfolio construction on the basis of targets or metrics significantly influenced by the value chain emissions of underlying investments;
- avoid implicitly endorsing the steering of capital allocation by such targets and metrics through mandated disclosures; and
- ensure that voluntary disclosures of such targets and metrics be accompanied by appropriate caveats about data limitations.

Standard-setters should be aware of the risks of heightened adverse selection and moral hazard inherent in explicit and implicit endorsement of unsuitable usages of data.

In this regard, the European Commission's decision to steer the construction of its Paris-aligned and Climate Transition Benchmarks by scaled total emissions was particularly detrimental. The choice of metric for what has since become a highly successful investment label contradicts the bloc's ambitions to redirect capital flows toward the transition to a low-carbon economy and institutionalises illegitimate claims about the impact of these benchmarks. Four years later, with a better understanding of the challenges of value chain reporting and the risks posed by greenwashing, it would be appropriate to realign the regulation with its stated objectives.

Policy makers committed to the transition should introduce and enforce regulation supporting decarbonisation across the economy. As part of this effort, they should require administrations and firms, starting with large entities, to produce standardised disclosures of emissions and, where relevant, set emissions reductions targets and produce ongoing reports on progress achieved and actions taken to remain on track.

To enhance the effectiveness of these measures, governments should support the production and adoption of sector-specific guidance for emissions accounting, reporting, target setting, and transition plans. Furthermore, they should promote initiatives aimed at fostering cooperation across supply chains and proactively share information and tools to accelerate the adoption of best practices.

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