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Asleep at the Wheel? The Risk of Sudden Price Adjustments for Climate Risk

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Abstract

A large number of studies has failed to date to identify a robust and economically significant climate risk premium or climate beta, either at the aggregate or at the sectoral level. The author examines several explanations of why this may be the case, and finds that a mispricing of climate risk is the most likely explanation. If this is true, price adjustments will eventually occur, either in a gradual or in an abrupt way. This is a novel source of risk, which should be on the radar screen of long-term investors.

Three key takeaways:
1. The author considers the possibility that climate risk may not be fully reflected in asset prices.
2. He finds that the price adjustment for climate risk should be large both in the case of successful tackling of the climate change problem, and in the case of delayed action – yet statistical studies show very little responsiveness of prices to climate news.
3. The possibility of a late recognition of the necessary price adjustment is considered, and it is argued that the severity of the adjustment could be enhanced if the readjustment is sudden.

Asleep at the Wheel?
The Risk of Sudden Price Adjustments for Climate Risk

As a relatively new risk factor, climate risk can in itself provide a new source of shocks (additional volatility) to climate-sensitive asset prices. This is *not* the kind of risk we are examining in this paper. Instead, we focus on the possibility that market prices may be underestimating or neglecting the (transitional and physical) effects of climate risk on the cashflows of companies and the revenues of governments.[1] If this is the case, a price readjustment, especially if sudden, of equities, corporate bonds, loans and government bonds could cause widespread losses (and increased volatility). *This* is the novel risk we focus on in this paper.

The possibility that climate risk may be imperfectly reflected in current prices has only recently been given the attention it deserves. For instance, in a recent review paper on climate stress testing Acharya, Berner, Engle, Jung, Stroebel, Zeng, and Zhao (2023) argue that "[w]hile [the] literature has convincingly documented that climate risks are currently priced across a range of asset classes, *much less is known about whether they are adequately priced*. The adequacy of current risk pricing is, however, an important question for assessing the likelihood of potentially substantial short-run asset revaluations as there might be strong learning effects and revisions in the price of risk associated with the inherently evolving nature of climate risk realizations. [...] If investors fail to accurately update beliefs in response to information about future climate risk realizations, this might reduce the average present-day effects of long-run physical climate risks across the different scenarios; on the other hand, it could also lead to more substantial revaluation risk in case beliefs eventually move by a substantial amount".[2]

Against this background, most authors who have looked at the impact of climate outcomes on asset prices (such as Dietz, Bowen, Dixon, and Gradwell (2016)), have simply *posited* that current prices totally fail to reflect climate-damage information. While analytically convenient, this assumption is clearly too strong to remain unchallenged, as it implies a total lack of informational efficiency for one of the most discussed risk factors under the gaze of investors. We therefore start by examining the validity of (at least a weak form of) this assumption in the next section.

Why do we think that this novel source of risk could be important? Two observations suggest that this may be the case. The first is that, as we discuss in what follows, attempts to detect a 'climate beta' (the sensitivity of different asset classes – infrastructure projects *in primis* – to climate shocks) have so far been met with mixed success at best: there is no universal agreement as to which asset classes have a positive or a negative climate beta, and the price sensitivity has always been found to be at the limit of detectability (of statistical significance). Economic significance, as we discuss, is even more dubious than statistical significance. The most flattering characterization of the climate-beta studies to date is that they lack robustness: small changes in the design of the analysis can make the effect disappear, or change its sign. We discuss below why this may the case, but this suggests that, if prices have so far reflected climate information, they must have done so to a very limited extent.

1 - Prices combine both 'actuarial' expectations of cashflows and a discounting rate for these cashflows. We look separately at the effects of climate damages on the discount rate.
2 - Emphasis added

The second observation is that this muted sensitivity of prices to climate news is difficult to reconcile with the expected economic outcome of *any* climate policy: as we shall discuss, if we deal with climate change seriously, the transformation of the whole economy will have to be substantial (with adaptation and abatement costs of the same order of magnitude as what we currently spend on education or defence); if, on the other hand, the climate change problem is left untackled, temperatures on the planet are likely to reach levels never experienced by the human species. It is against the backdrop of these huge changes that the muted sensitivity of asset prices to climate innovations constitutes a puzzle.

Since during the last decade the risks associated with global warming have been among the most salient and widely discussed,[3] what could be the reason for this elusive sensitivity of the prices of different asset classes to climate risk? Logically, one can advance five explanations:[4]
1. the market is informationally efficient and has already impounded all the relevant information;[5]
2. the market is informationally efficient, but it expects the climate-related cashflow impairment to be small for all sectors, even if no significant climate action is taken;[6]
3. the market the market is informationally efficient, but it expects the climate-related cashflow impairment to be small because it believes that climate risk will be effectively managed – eg, that the temperature increase will remain within the Paris Agreement 1.5-2 C target;
4. the market the market is informationally efficient, and believes that climate damages will be significant, but these damages occur so far in the future that they are effectively discounted down to almost zero in arriving at today's prices.
5. the market is 'asleep at the wheel', by which we mean that the prices do not correctly reflect expectations and uncertainty about climate outcomes.

In a way the fourth explanation – that future damages are so remote that, after discounting, they have little effect on today's prices – appear so simple that it presents itself as the most likely one. We discuss in what follows that the argument is actually more complex, and that, in the presence of impairments to aggregate consumption, it is not obvious at all that current prices should be unaffected by distant damages to the whole economy. Instead, we intend to argue in this paper that the third and fifth explanations are the most likely.

If we are correct, in both cases, substantial repricing of assets can be expected. This can happen via two channels. If the market is asleep at the wheel (explanation 5), this slumber cannot continue indefinitely: after all, corporate cashflows and government revenues over time turn from 'discounted expected' to 'realized'. It is this revision in expectations that can give rise to a significant price-adjustment risk (the 'novel risk' this study focusses on).

3 -At the latest World Economic Forum, climate risk topped the 10-year-risk survey among 14,000 CEOs and practitioners. See https://www.weforum.org/reports/global-risks-report-2023/digest
4 - We should also point out that, when it comes to climate change, we are much closer to a situation of Knightian (Knight (1921)) uncertainty than of risk with statistically-determinable probabilities. This makes the evaluation of probability-weighted outcomes that is at the heart of asset pricing particularly arduous. We simply mention in this respect the results by Coles, Loewenstein, and Suay (1995) who find that, when parameters are uncertain, "estimation risk affects equilibrium portfolio weights, asset betas, asset expected returns, and market expected return".
5 - If markets are informationally efficient, asset prices would, of course, still respond to unexpected climate shocks, but the (possibly time-dependent) expectation part would be fully reflected in the prices. There would be no non-unexpected-climate-shock-driven price changes.
6 - Saying that 'the market expects' is obviously very crude. There is heterogeneity of expectation held by market participants. The wealth-weighted average of these discounted expectations produce the price. The expression 'the market expects' should be read as an abbreviation for a preponderance of wealth-weighted views in a particular direction.

If, instead, asset prices show little dependence on climate risk because the market is pricing in a 'soft landing' scenario (explanation 3), we argue that this outcome should not be taken as a central expectation, and that, in any case, it would have very strong sectoral effects (which instead appear to be muted at best). To buttress our case that the 'soft-landing' scenario may be unwarrantedly optimistic, we argue below that the 1.5 C target is in practice virtually unachievable, and that even limiting temperature increases to 2 C implies changing emission policies at a rate that is historically unprecedented, technologically very challenging, and extremely unlikely for the vast regions of the world that are expected to grow in the twenty-first century. So, irrespective of whether explanation 3 or 5 is correct, we show that the risk of large and widespread price adjustments is large.

Do Prices Respond to Climate Shocks?

In the introductory section we have suggested that studies that have tried to detect a 'climate beta' has so far been met with limited success.[7] Other studies, reviewed in what follows, have been less ambitious in scope, and have just tried to measure whether asset prices move in response to climate innovations. As we discuss, the effect has been muted at best. Lack of responsiveness to climate shocks could be prima facie evidence that prices do not impound climate risk information. Since, however, this observation is an important part of our argument, we discuss this point in some detail in this section.

The most direct way to estimate a climate beta is to carry out a regression of observed asset returns against a suitable climate index (after controlling for the other known factors).[8] The problem is that, unlike the case of factors such as inflation or unemployment which are almost directly observable, there is no obvious observable proxy for climate risk. Different approaches have therefore been followed to create an index (a time series) representative of climate risk.

In one popular approach, following the pioneering work by Engle, Giglio, Kelly, Lee, and Stroebel (2019), several attempts have been made to create this climate index from textual analysis. Unfortunately, the out-of-sample explanatory power of these early indices has been disappointingly low: after controlling for the loading of the climate risk factors on established factors, such as momentum or value, the incremental R^2 statistics afforded by the 'pure' climate factor is of the order of a few percentage points. Using an advanced version of this approach, Maeso and O'Kane (2023) obtain statistically more significant result, but, then again, only for one special combination of the several indices they build.

Given these problems, Chini and Rubin (2022) (and from a different angle Lindsey, Pruitt, and Shiller (2022)) have adapted to the climate-change problem the general approach by Kelly, Pruitt, and Su (2019). The idea here is to capture latent factors and time-varying loadings by introducing observable characteristics that instrument for the unobservable dynamic loadings. Chini and Rubin (2022) extend the approach by using these latent climate characteristics to construct a climate proxy that is also orthogonal to the traditional financial risk factors. The approach is very appealing, but, when they use it to to explain the returns of corporate bonds, Chini and Rubin (2022) find that a '[s]ystemic environmental factor does not help to explain bond returns on top of financial standard factors'. In the case of equities, only for the most obvious sectors, Oil and Utilities, is the increase in the R^2 of the returns regression statistically significant, and even in this case by very modest amounts (a few percentage points).

A separate strand of research (see, eg, the work by Pastor, Staumbaugh, and Taylor (2022), In, Park, and Monk (2019), Alessi, Ossola, and Panzaca (2020), Cheema-Fox, Perla, Serafeim, Turkington, and Wang (2021), Hsu, Li, and Tsou (2022)) has therefore taken a different approach, via the construction of long-short (factor-mimicking) portfolios, whose returns should be proportional to the latent climate factor. This approach has one significant advantage over the index route: perhaps there *has* been a readjustment of prices, but this has occurred as a gradual process of growing climate awareness,

7 - These studies are sometimes cast in terms of detecting a green premium ('greenium'). Any risk premium is given by the market price of the associated risk factor times the sensitivity ('beta') to that factor. Failure to detect a greenium is in theory compatible with a high climate beta, if the attending market price of risk were close to zero. In this case, prices would reflect actuarial expectations of climate outcomes, and this could only happen because of a lack of covariance between consumption and climate-related payoffs. Another (and arguably simpler) explanation for a failure to detect a greenium is that the climate beta for a security is low or zero.
8 - This type of regression could find a statistically and economically significant response of prices to climate surprises even if markets were informationally efficient. Issues of correlation between a climate index and established factors are routinely dealt with by orthogonalization – see, eg, Chini and Rubin (2022).

not directly linked to specific 'climate news'. Tracking the performance over time of a long-short portfolio could reveal this effect.

There is a problem, however, with this approach: it is not obvious which securities should go in the long and short portfolios (indeed, the approach is somewhat circular, because, to do the sorting, it assumes that at least the sign of the climate-beta should be self-evident). The sorting is often based on ESG ratings, but it is well-known how the correlation between ratings from different providers can be very low. See, in this respect, the comprehensive analysis in Avramov, Cheng, Liuoi, and Tarelli (2022) that documents and discusses the implications of the lack of consistency of ESG information provided by different agencies. Whatever the sorting method, the results are far from clear, with the field evenly but unhelpfully split: Pastor, Staumbaugh, and Taylor (2022), In, Park, and Monk (2019), Cheema-Fox, Perla, Serafeim, Turkington, andWang (2021) find that only the returns of green assets are affected by climate risk, while Bolton and Kacperczyk (2021),[9] Hsu, Li, and Tsou (2022) and Alessi, Ossola, and Panzaca (2020) draw the same conclusion but for brown assets. As Chini and Rubin (2022) conclude, "By choosing different measures [one obtains] different results: [the] sign of the 'greenium' [and hence of the climate beta] is not clear."

This state of affairs is far from ideal. Admittedly, since the 'climate index' obtained by all these studies is rather opaque and can be difficult to interpret and validate, it is possible that the prices of securities do respond to climate shocks, but these are not properly captured by the index itself. Or, perhaps, prices have adjusted gradually over time, but we have failed to measure the effect because we have misclassified green and brown securities. More work in this direction is clearly necessary. However, given the variety and ingenuity of the approaches employed, it is fair to say that, if the climate impact on prices were loud and clear, in one way or another it would have been unambiguously detected. In reality, the weak and often conflicting results suggest that prices are at most weakly affected by climate information. How can this be the case?

9 - To be precise, Bolton and Kacperczyk (2021) do not create a long-short portfolio, but run a regression of returns on ESG metrics.

Are Climate Outcomes Price-Relevant?

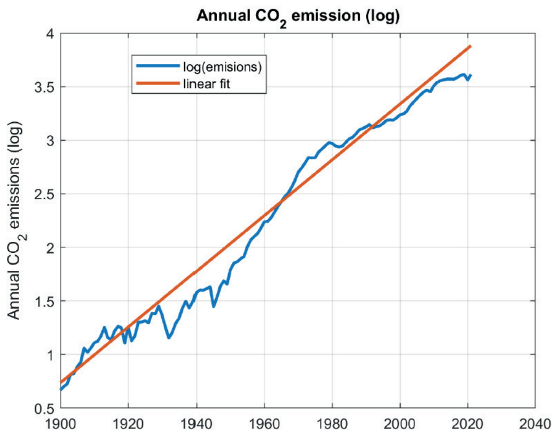
A possible explanation of why prices appear to respond so little to climate information is that perhaps climate outcomes have little relevance for the expected cashflows, and for the riskiness of these cashflows. As mentioned in the introductory section this could be either because climate damages are expected to be small even if climate risk is left unmanaged; or because the market expects that efficient mitigation actions (emission abatement, carbon removal, adaptation) will limit climate change or make its effects 'innocuous'. Distinguishing between the two possible explanations is important: if 'climate change does not matter', then no big readjustments of the economy will be required, and no significant sectoral effects are to be expected. If, on the other hand, it is mitigation and adaptation that will mute the effect of climate change, then there is almost universal agreement that this will require a major re-wiring of the whole economy, and sectoral effects should be strong. We therefore look at these two possibilities separately.

Does Unmanaged Climate Risk Matter for Asset Prices?

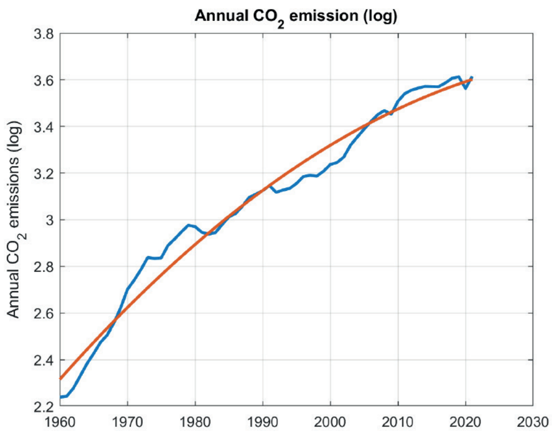
The first possibility (that unmanaged climate risk will have little effect on cashflows) is difficult to justify. Under a business-as-usual scenario, the concentration of CO_2 in the atmosphere would most likely continue at its current rate, which, it should be remembered, is still almost exponential, as shown in Exhibit 1a. (Exhibit 1b shows the modest decrease in the exponential growth rate experienced since the 1960s.)

Exhibit 1: The natural logarithm of the CO_2 annual emissions from 1900 (land use change not included) and a linear fit ($-48.663 + 0.026 \times t$) (left panel); same quantity for the years 1960 to date and their quadratic fit. Source: Our World in Data.

(a) Emission paths consistent with 1.5 C warming by 2100



(b) Emission paths consistent with 2 C warming by 2100



Now, as we shall soon discuss, there may be more uncertainty about the relationship between emissions, concentrations and temperature than usually acknowledged, but the directional link between the level of atmospheric CO_2 and global temperature is one of the most firmly established relationships in climate science. And if concentrations continue along the current business-as-usual trajectory, temperature increases around 3 C, and possibly more, by the end of the century are very likely. (See Climate-Action-Tracker (2022) and footnote 21.) What the economic damages could be in this temperature range (a temperature range that the human species has never experienced, as we have to go back to the Pliocene, some three million years ago, to find similar global temperatures) is very imperfectly know. However, a number of serious studies project very severe consequences. (See Lynas (2020) for a useful and detailed degree-by-degree review of expected climate effects).[10] And even if there is disagreement about the magnitude of the climate effects and of the attending economic damages, the sheer magnitude of the uncertainty about what could happen should be reflected in prices – after all, as we hear after every inconclusive election, 'markets hate uncertainty'. Yet, as we have seen, the explanatory power of a climate factor is small in magnitude, and ambiguous in sign.

It could be argued that, while the *human* costs of climate change could be very high, the aggregate *economic* costs may be much more muted. The most affected populations, the argument goes, are in the poorest parts of the world, and these contribute very little to economic output, and hence to asset prices. So, according to this line of reasoning, while the climate changes in vulnerable but poor areas could be large, the effects in the rich, Northern part of the world could be limited, or even beneficial (say, for countries such as Russia or Canada). Now, it could be debated at length whether, due to partial cancellations, the aggregate effect on global economic output is really as small as some models suggest.[11] Discussing the appropriate exponent of the damage function (the function, that is, that links damages to temperature) would entail too long and contentious a detour. We only make two observations: first, the often-quoted DICE damage function is at the very low end of damage estimates, and virtually all its enhancements (eg, by including the possibility of tipping points) increase the level of aggregate damages; second, even if these low damage estimates are correct, by the way they have been obtained,[12] they only refer to aggregate output, and sectoral effects could still be very large. However, has we have seen, the climate betas are small and ambiguous also at sectoral level.

Will Climate Risk Be Successfully Mitigated?

Here we come to the heart of the paper. Could it be that the market correctly expects the effect of climate change to be successfully managed? We intend to show

1. that we should be very uncertain, not just about damages for a given temperature outcome (as it is broadly acknowledged), but also about temperature outcomes given CO_2 concentrations – this matters, because, if the link between concentrations and temperature is as imprecisely known as we show it is, a strong confidence in our ability to engineer a 'soft climate landing' is misplaced;

10 - This reference offers a useful and balanced compilation of the estimates from peer-reviewed scientific studies of the climate consequences of different degrees of global warming.
11 - Famously, the benchmark DICE model (see, eg, Nordhaus (2017)) has been roundly criticized for assuming an excessively 'bland' quadratic dependence of damages on the temperature anomaly.
12 - Typically by regression of aggregate economic output against temperature anomaly.

2. that, even if our climate models were much more precise than they actually are, the policy changes required for the soft landing are unprecedented, both quantitatively and qualitatively;
3. that these policy changes are difficult to reconcile with the plausible (and much-to-behoped-for) development trajectories of those parts of the world (such as sub-Saharan Africa) that have not experienced sustained economic growth to date.

Let's consider these points in turn.

The sharpness of the target of 1.5 to 2 C of warming by 2100 suggests that we can steer our emissions to achieve a desired temperature with tenth-of-degree precision. Indeed, this is the impression conveyed by graphs such as those shown in Exhibit 3 (which actually display the average obtained using multi-model means), to which we return in what follows. The reality is very different. One of the key inputs to the climate models used to link emissions to temperature is the Equilibrium Climate Sensitivity.[13] Exhibit 2 shows a fit to the dispersion of estimates of this quantity found in the literature for this key variable. As the exhibit shows, there is a 10% chance that the true sensitivity may be below 1.7 or above 4.7. And the right panel of Exhibit 4 shows the dispersion of temperature outcomes associated with 2-C-on-average-consistent emission schedule. The curves were obtained by reproducing independently[14] the results produced by the majority of the climate models that translate CO2 concentrations into temperature anomalies discussed in the latest Intergovernmental Panel on Climate Change (IPCC) report. The set of climate models that are strongly caveated in the IPCC report have been excluded. If they were included, the dispersion we report would be significantly wider. Furthermore, we have not included in our calculations the uncertainty in the models that translate emissions into concentrations. Our conclusion are therefore, if anything, conservative.

This is poorly appreciated, but very important: even if we follow an emission trajectory that on average should land us inside the 1.5-2 C target, the error in our 'landing spot' can be very substantial. Since the current warming is already around 1.2 C, and given the inevitable thermal inertia,[15] the landing error is far more likely to be on the upside than on the downside. If these considerations were properly taken into account, the confidence in our ability to achieve a 'soft climate landing' should be low, and the temperature outcome very uncertain *even if we committed without hesitation to a 'virtuous' abatement programme*. This high degree of uncertainty should by now have been impounded in asset prices. Yet, as we have seen, prices barely seem to reflect climate information, suggesting overconfidence, and likely underestimation of the magnitude of climate risk: what we have described above as 'the market being asleep at the wheel'.

The (model) uncertainty analyzed above would be present even if could be 100 percent confident that an emission path compatible *in expectation* with the 1.5-2 C target will be followed. But let's assume for a moment that we are absolutely sure about the temperature outcome for a given emission schedule. How likely it is that the aggressive abatement / removal schedule necessary to hit the target (a schedule whose speed macroeconomist

13 - The Equilibrium Climate Sensitivity is the rise in global temperature in response to a doubling of CO_2 concentration with respect to pre-industrial levels. It is a key input to all climate models.
14 - Author's calculations based on the model reparametrization carried out by Dherminder Kainth.
15 - See Hansen, Sato, Simons, Nazarenko, von Schuckmann, Loeb, Osman, Kharecha, Jin, Tselioudis, Lacis, Ruedy, Russell, Cao, and Li (2022) for a sobering perspective on the extent of the degree of warming already 'in the pipeline'.

calls 'precipitous') will indeed be followed? Exhibit 3 shows the abatement paths needed to keep the temperature with 1.5 and 2 C by 2100, and paints a worrying picture. The left panel shows that the 1.5 target is in practice almost unattainable. As for the optically more achievable 2 C target, it is important to compare the trajectories consistent with the achievement of this target[16] with the real global-emission trend up to today, as shown in the left panel of Exhibit 4. And, as a reminder of the degree of uncertainty in our estimates, the right panel of the same Exhibit 4 shows the spread of temperature outcomes consistent even with this extremely ambitious emission trajectory, as produced by the 17 models that we have parametrized and implemented and which are considered equally plausible by the 2021 IPCC report.

Exhibit 2: Fit to the dispersion of estimates found in the literature for the climate sensitivity, one of the key climate model inputs.

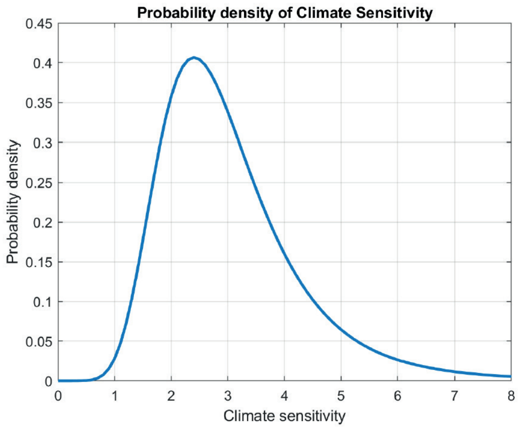
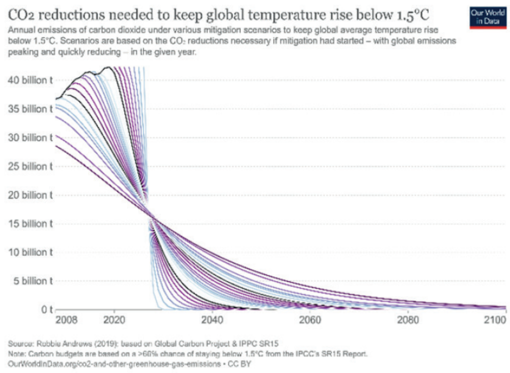
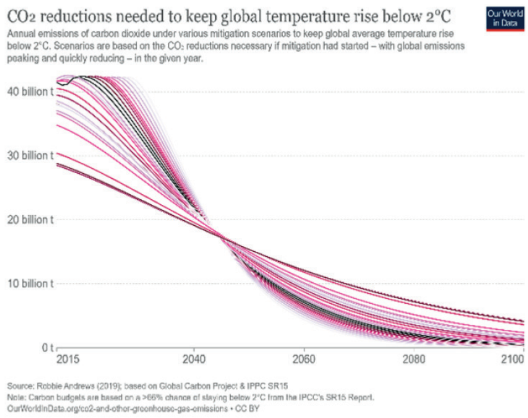


Exhibit 3: The smoothest emission paths consistent with 1.5 C and 2 C warming (left and right panel, resp.) by 2100. The first part of the sharp black line shows the historical emissions; the sharp black line then continues following the smoothest emission path compatible with the stated target. Source: Our World in Data.

(a) Emission paths consistent with 1.5 C warming by 2100



(b) Emission paths consistent with 2 C warming by 2100



16 - Admittedly, there are many such trajectories. The 'window of opportunity', however, is so narrow, that they are all extremely similar.

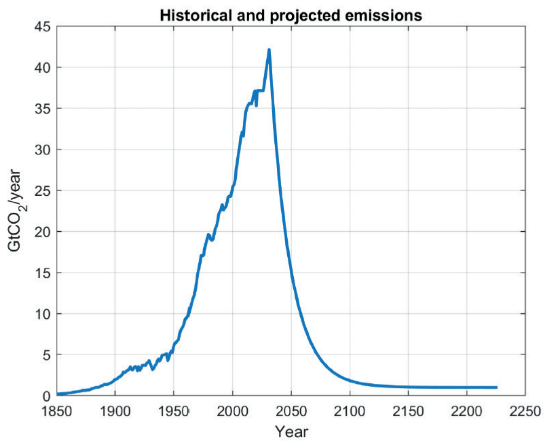
Clearly, the inversion of the historical emission trend required to stay, on average, below 2 C must be sudden and extremely steep. If not at a global level, has a similar rate of decline been observed at least for some countries? What were the policy choices of these fast abaters? Could, in short, the experience of these countries become a template for successful decarbonization?

To answer these questions we have made use of the classification of countries suggested by McKinsey (see Tai, Samandari, Patchod, and et al (2022)):
1. affluent, energy-secure countries (eg, Australia, Saudi Arabia, United States);
2. affluent, energy-exposed (eg, Germany, Italy, Japan);
3. large, emission-intensive economies (eg, China, India, South Africa)
4. developing, naturally endowed economies (eg, Brazil, Mexico, Indonesia)
5. developing, at-risk economies (eg, Nigeria, Colombia)

and we have chosen the highest-emitting countries in each group. For each country we have gathered data not only about their historical total emissions, buy also about emissions linked to the production of cement. We have chosen cement as a representative of the four 'pillars of material consumption' (see Smil (2021), Smil (2022)) which are currently difficult if not impossible to produce at reasonable cost with renewable energy (the others are blast-furnace steel, ammonia and plastic). At the moment, these four forms of utilization of fossil fuel energy globally account for 20% of energy usage and 25% of emissions, but this is only valid at the aggregate level: countries that are classified as 'large, emission-intensive' (group 3) devote a much larger share of their energy usage to steel and cement, and their production is still sharply growing. China, in particular, produced more cement (4.4 bn tonnes) in the two years before the COVID crisis than the United States in the whole of the twentieth century.17 This is very important for the global abatement prospects, because the four 'material pillars' currently require the high energy density offered by fossil fuels (and hence they are still not easily replaceable with renewables), and are going to be a growing percentage of energy utilization as group 3, 4 and (eventually) 5 countries continue or start their development trajectory.

Exhibit 4: Left panel: the historical emissions from 1850 to today (jagged part of the curve) and a smooth path of required emissions compatible with an expected warming of 2 C by 2100. Right panel: the dispersion of temperatures corresponding the same emission schedule obtained using 17 different models considered equally reliable by the 2021 IPCC report.

(a) Historical and projected emission path consistent with 2C warming by 2100



17 - Smil (2022), page 96.

(b) Temperature outcomes consistent with the same emission path for different climate models.

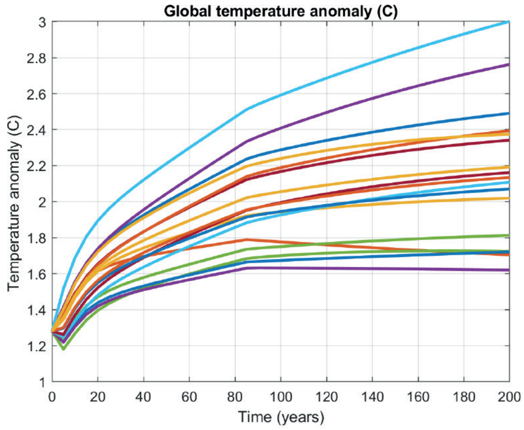
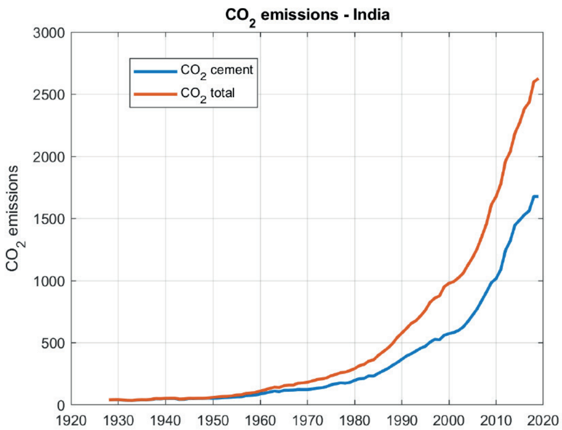
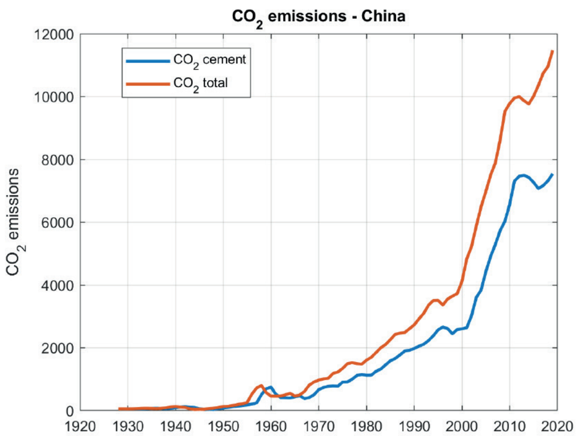


Exhibit 5: The total CO2 emissions and the cement-production-related CO2 emissions for India and China as representative of group-3 countries.

(a) Emissions (India)



(b) Emissions (China)

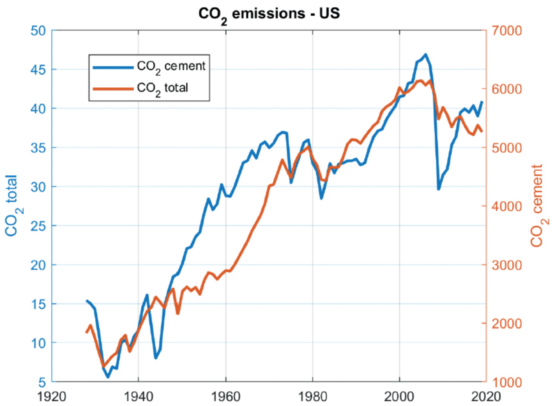


We can clearly see the difference in energy mix between group-1 and group-2 or group-3 countries by comparing Exhibits 5 and 6. For China and India (Exhibit 5), the emissions from the cement sector are not only extremely strongly correlated with, but also very similar in magnitude to, total emissions. Exhibits 6a and 6b then show that for group-2 and group-3 countries the correlation can be high (as in the case of the US), or low (as in the case of Germany), but in all cases cement-related emissions are today a small and falling fraction of total emissions.

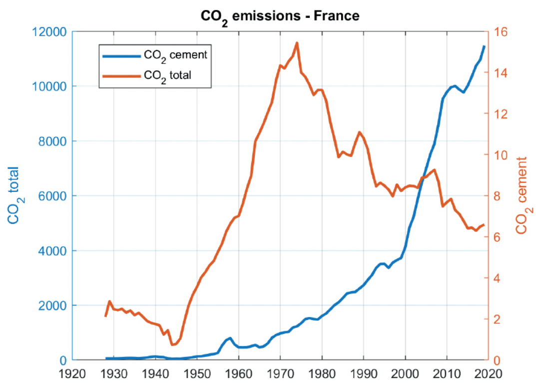
The situation is very different for group-4 countries. Exhibit 8 shows total emissions and carbon-related emission for two group-4 countries (Nigeria and Kenya) that are just beginning to embark on a development path: the striking feature is not only that the cement-related emissions are a much higher fraction of total emissions than it is the case for group-1 or group-2 countries (the countries that have already made significant decarbonization strides), but also that cement-related emissions are very strongly increasing. In the case of Nigeria, the ratio of cement-related emissions to total emissions has risen from less than 1% at the start of the century to almost 7% – close, that is, to the same ratio for China (the country in groups 1 to 3 with the highest ratio). As for Kenya, the ratio has risen over the same period from around 5% in 2000 to a staggering 18% in 2021 (there has been no COVID-related dip in the case of Kenya). This is an indication that, if group-4 and group-5 countries are to embark on a sustained development path, we can expect a surge in cement production, and, as long as cement can only be obtained with fossil fuels, in cement-related emissions. Similar considerations apply to steel and to nitrogen compounds such as ammonia (two of the remaining three 'material pillars' for which renewable means of production are difficult or currently non-economic).

Exhibit 6: The total CO_2 emissions and the cement-production-related CO_2 emissions for the US and France as representative of group-2 countries.

(a) Emissions (US)



(b) Emissions (France)

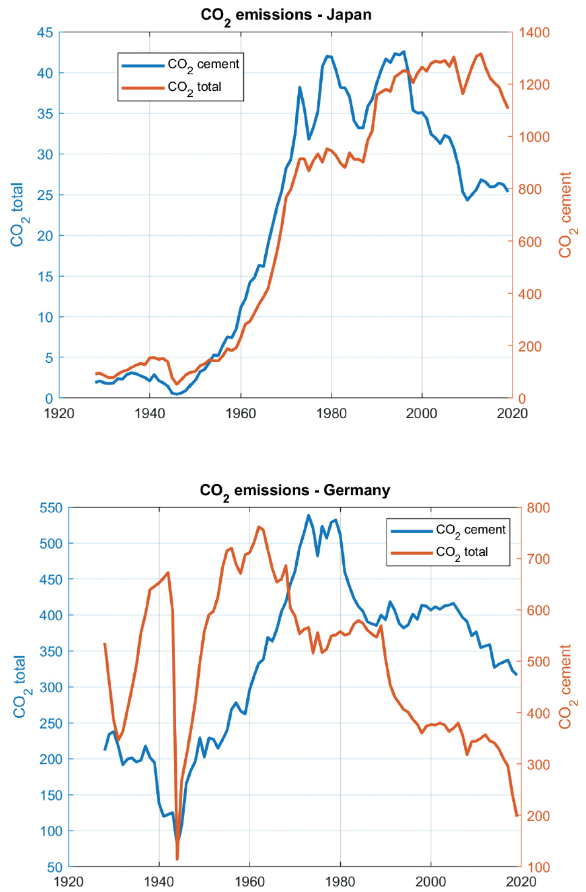


Summarizing ou results so far: if we focus on cement-related emissions as a proxy for emissions that are difficult to curb via renewables,[18] we distinguish three clear different patterns: i) for strongly developing countries such as China and India, they are growing roughly at the same pace as total emissions; ii) for developed countries, they are in general falling faster than total emissions are; iii) for still-to-develop countries they are growing at a faster pace than their total emissions, as shown in Exhibit 10.

Exhibit 7: The total CO_2 emissions and the cement-production-related CO_2 emissions for Japan and Germany as representative of group-3 countries.

(a) Emissions (Japan)

(b) Emissions (Germany)



These qualitative observations can be made more precise by carrying out a regression of the fraction of CO_2 emissions due to cement production, *frac*, against the GDP/person, *GDP*, for several developed and developing countries (that together make up for more than 85% of global emissions):

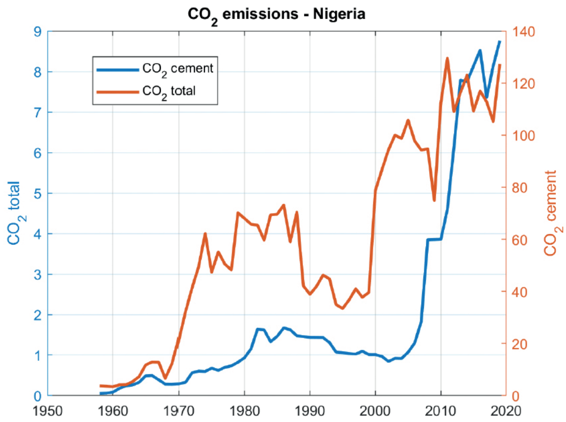
$$frac = \alpha + \beta \times GDP + \epsilon \tag{1}$$

The slope is statistically very significant (with a *t* statistic of 4.25 and an R^2 of 0.52) and shows a clear negative dependence between how rich a country is, and how much it of its emissions are due to the difficult-to-abate production of cement.[19] Again, this is important, because the only countries that have so far shown significant reductions in emissions are those in the $40,000-plus GDP/person cohort.

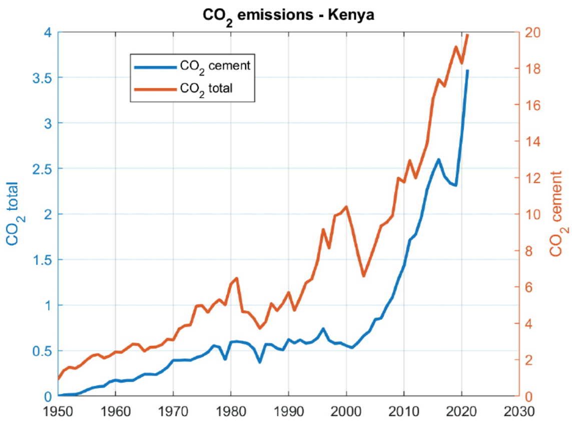
18 - Carbon sequestration and storage could be more promising, but is at the moment non-economic.
19 - To minimize COVID-related distortions, we have taken for the right-hand variable the average of the 2015-2020 GDP/person.

Exhibit 8: The total CO_2 emissions and the cement-production-related CO_2 emissions for Nigeria and Kenya as representatives of group-4 countries.

(a) Emissions (Nigeria)



(b) Emissions (Kenya)



Finally, we observe that the CO_2 emissions due to international trade have been steadily rising (excluding the COVID-related dip), and are larger than the total emissions from a country as large as Germany. Also this is significant, because to date very few technological solutions have been found to use renewable sources of energy for long-haul transport. These trade-related emissions therefore also add to the tally of the 'recalcitrant' emissions.

Exhibit 9: The fraction of the cement-related emissions to total emissions against the GDP/person (x axis, average of the 2015-2020 data) for 20 countries. The solid line shows the result of the best fit to the function frac = $\alpha \times GDP^{beta}$, which gives a slightly better fit because of the 'outlier' associated with Kenya.

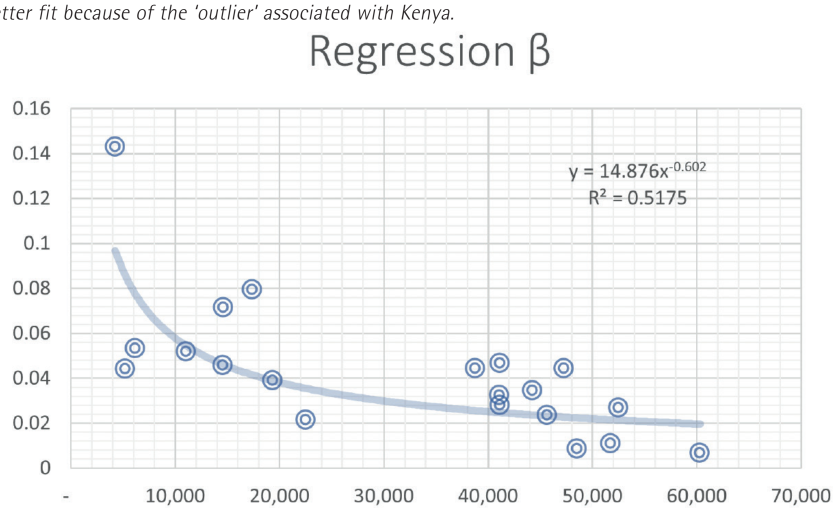
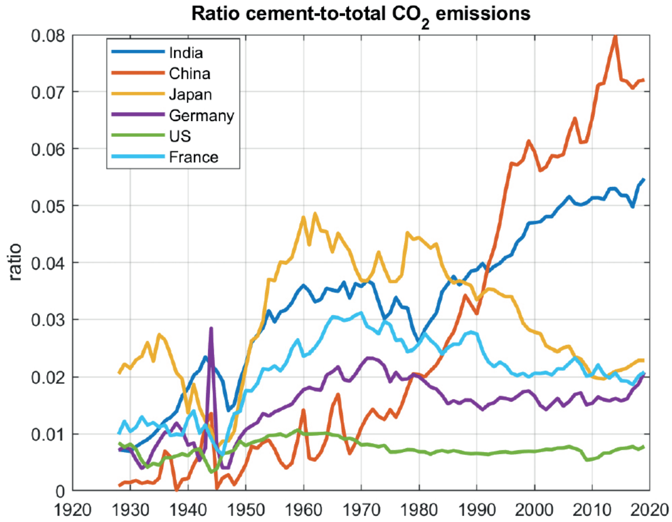


Exhibit 10: Ratio of cement-related to total CO_2 emissions for India, China (group 1), Japan, Germany (group 2), US and France (group 3).



To summarize the argument so far: the reductions in emissions needed to remain, on average, within 2 C of warming by 2110 are technically not impossible, but require an extremely fast reversion of current trends. Has such a reversion been observed anywhere?

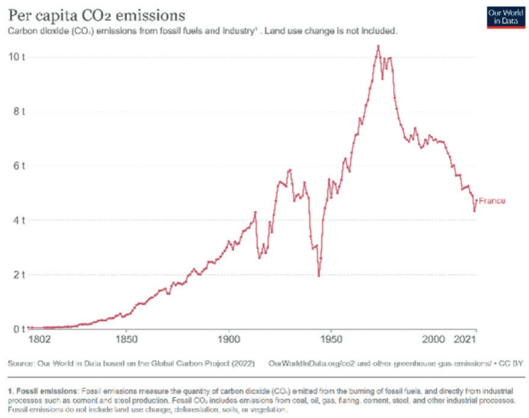
An Optimistic Estimate

The analysis conducted so far tries to estimate how likely it is that the international community will be able to engineer a soft-climate landing – to enact a set of policies, that is, which would limit the increase in global temperature to under 2 C by 2100. From the discussion, it is clear that significant emission reductions have so far only been achieved by the strongly developed countries. Let us be optimistic and assume that the rate of emission reduction similar to what has been achieved by the best-in-class (ie, by the countries that rely more strongly on renewable or low-emission sources for their energy requirements) can be adopted globally (perhaps via the transfer of advanced energy technologies). If replicated on a global scale, would the cuts in the emissions carried out by the most 'aggressive' countries be enough to meet the 2 C target? More precisely: if everybody started cutting emissions tomorrow at the fastest sustained pace so far observed anywhere in the world, would the global abatement curve be as steep as the right part of the graph in Exhibit 4?

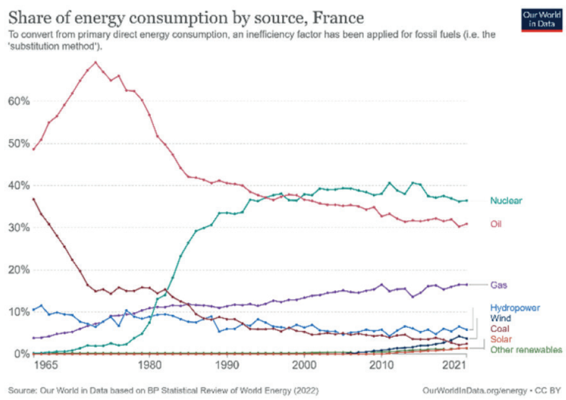
Using the same set of data, among the large economies France stands out as the fastest emission abater. Exhibit 11, which shows the per-capita CO_2 emissions (left panel), and the share of energy consumption by source, (right panel), also helps understanding what has been so special about France: the resolute embrace by this country of nuclear energy in the late 1970s. The French experience has been unique: the most pronounced drops in CO_2 emissions per capita to date have occurred in the Western world, and, as far as we have been able to ascertain, in no major country have the drops been faster than in France. Since few countries share the same enthusiasm as France for nuclear energy, it is difficult to see this pace of abatement repeated elsewhere. In Germany, for instance, despite its enthusiastic embrace of sources of renewable energy, the pace of abatement has been 50% slower than in France. And, in any case, even looking at how quickly the 'best in class' have managed to abate can be seriously misleading. As Exhibit 6 shows, all European countries have 'exported' a significant part of their emissions (by having parts of the goods they consume manufactured elsewhere – often in parts of the world with lower emission standards). When imported emissions are taken into account, China has grown emissions some 10% less than its headline figure, but, depending on the country, European emission figures should be increased by up to 68% (for Sweden).[20]

Exhibit 11: The per capita CO_2 emissions for France, and the share of energy consumption by source, also for France. Source: Our World in Data.

(a) Per capita CO_2 emissions (France)



(b) Share of energy consumption by source (France)



When one considers that the fast pace of emission reduction experienced by the fastest abater (France) was due to a nuclear choice that currently few countries seems likely to embrace; that even if the French rate of emission reduction were somehow universally adopted, we would in all likelihood still fall short of the 2 C target; that many highly emitting countries are still increasing (let alone reducing at a fast pace) their carbon emissions – when all these considerations are taken into account, it seems very unlikely that the pace of abatement will be as high as required by a trajectory such as the one shown in Exhibit 4. Muttit, Price, Pye, and Welsby (2023) reach very similar conclusions

20 -Author's calculations based on data from Our World in Data.

when considering the socio-political feasibility of coal power-out, and find that "in countries heavily dependent on coal – China, India and South Africa – this translates to a national decline twice as rapid as that achieved historically for any power technology in any country".

A soft-landing scenario therefore implicitly relies
1. on all countries in the world adopting abatement policies faster than what has been observed for the fastest abaters to date – keeping in mind that the the fastest rate of abatement has been achieved by a country (France) with a unique commitment to nuclear energy – and faster than the current pledges;
2. on technological breakthroughs occurring very soon in carbon sequestration and storage, in direct carbon removal, and in large-scale non-fossil-fuel solutions for the production of cement, steel and nitrogen and for international trade.
3. on these breakthroughs being shared (presumably with accompanying subsidies) with developing economies.

As we have argued, requirement 1 should be viewed with suspicion. A recent study by Climate-Action-Tracker (2022) calculates that, if current policies and actions are followed, we can expect a median warming of 2.7 C ([2.2–3.4] C); this figure falls to 2.4 C([1.9–2.9]) if the current Nationally Determined Contributions (NDCs)[21] targets are met (in these scenarios temperatures, however, continue to rise after 2100); and to 2.0 C ([1.6–2.5]) only if both NDC targets and pledges are met. Requirement (1) above is made even more daunting by the observation that every emission-related pledge to date has been broken (Pindyck (2022)); that no solution to the very serious free-rider problem has been found (Nordhaus (2021)); and that no framework of sanctions is currently envisaged (let alone accepted) for countries that fail to comply with their stated pledges. Furthermore, these projections are based on the behaviour of present emitters, with no large new emitter countries or regions appearing on the scene. If currently economically underdeveloped regions of the world (such as large areas of Africa) were to embark on a development path anywhere close to the one that China has experienced, all these emission projections would have to be drastically revised. If this seems unlikely, let's recall that China's GDP as recently as 1990 was only $360m (in current US dollars), and in 2020 reached $17.7bl. In sum: it is technologically possible that unprecedented international coordination will allow a reduction in emissions likely (but not certain!) to limit global warming by 2100 just under 2 C. However, this cannot be taken as a central scenario. It should not be the market expectation of climate outcomes. Yet, to come back again to the same point, prices do not appear to have reflected so far significant climate-related adjustments.

21 - NDCs 'embody efforts by each country to reduce national emissions and adapt to the impact of climate change'. Paris Agreement, Article 4, §2: 'Each Party shall prepare, communicate and maintain successive nationally determined contributions that it intends to achieve.' Note that the following §3 then states that NDCs should reflect a country's 'highest possible *ambition*' (emphasis added). There is a big gap between a 'highest ambition' and a realistic commitment.

The Effect of Discounting

We have argued so far that unmanaged climate risk is likely to have large effects on aggregate economic output, and that hoping for a 'soft climate landing' is far from a central scenario. These two conclusions, and the observation that prices seem to have responded so little to climate news, seem to suggest that prices may not be properly reflecting climate risk. But, as we mentioned, we still have one possibility to take into account. Perhaps prices move so little in response to climate news not because damages will be small, but because they will occur so far in the future, that, after discounting, their impact on current valuation becomes negligible. The argument is appealing, but not quite as simple as it *prima facie* appears.

First, we observe that, for a single security, it is certainly true that, for any reasonable market discount rate, cashflows (positive or negative) thirty or fifty years in the future will have a very small impact on its valuation. However, what applies to a security in isolation need not be valid for the market as a whole. To see why this is the case, recall that we have concluded that, if climate damages are expected to be small, this would mean that climate risk has been effectively managed, and *that this would have left a signature in the repricing of different sectors of the economy*. But, if we really aim for something like net zero by 2050, we cannot leave all of the attending rewiring of the economy for 2049. As Exhibit 4a shows, large changes should begin in five to ten years' time. Large changes in this context means that many sectors should be strongly affected in the near future. If this is the case, sectoral differentiation should not be 'washed away' by a very high discounting. However, as we have discussed, these sector differences are barely noticeable.

If the projected adjustment the economy is modest, then, as argued, the climate economic effects should be large. We are therefore left with examining the effect of discounting when damages are large, but very distant. We argue that, despite the remoteness in time of these damages, today's prices could still change. This can be seen as follows.

The key quantity to examine is the discount rate. Consider the simplest case (no uncertainty, time-separable CRRA utility functions) of the Ramsey equation, which derives the discount rate, r, as

$$r = \delta + \gamma g \tag{2}$$

where δ is the rate of impatience (the utility discount rate), γ is the inverse of the elasticity of intertemporal substitution, and g is the rate of consumption growth ($\Delta \log c$) – closely linked to the rate of growth of the economy.

Now, in the business-as-usual scenario we are considering future consumption is very likely to be negatively affected by climate damages, reducing g, reducing the discount rate, and therefore increasing the value of distant cashflows. Note that there are two competing effects at play: first, the future damages are longer 'invisible' because of the lower discount rate; however, the same decrease in discount rate increases the present value of all cashflows, thereby *increasing* today's valuation. (If this seems paradoxical, recall that we have observed these dynamics at play in the aftermath of the 2009 financial crisis, when, in the face of dire economic prospects, the prices of all assets rallied because of the decline in discount rate brought about by conventional monetary operations and, subsequently, by quantitative easing.) While mathematically possible, it is very unlikely that the combined effect of different expectations and different discounting should conjure to produce such small price changes as to make them virtually undetectable.

Is Ramsey's equation (which, after all, is derived under assumptions of zero uncertainty) too crude? A slightly more sophisticated version, obtained under uncertainty, (see, eg, Cochrane (2001), page 13) gives

$$r = \delta + \gamma g - \underbrace{\frac{\gamma^2}{2}\sigma^2(\Delta \log c)}_{\text{precautionary saving}} \tag{3}$$

where $\sigma^2(\Delta \log c)$ denotes the variance of consumption growth.[22] If anything, the presence of *additional* uncertainty due to climate risk would increase the variance of consumption, and the precautionary-savings term would make the discount rate even lower.

If recursive utility function of the Epstein and Zin (1989) type were used, the expression for the discounting rate would become more complex still:

$$r = \delta + \frac{1}{\psi} g - \underbrace{\frac{\theta}{2\psi^2}\sigma^2(\Delta \log c)}_{\text{precautionary saving}} - (1-\theta)\frac{\sigma_m^2}{2}, \tag{4}$$

but the conclusions would not change (σ_m is now the market volatility – plausibly *enhanced* by climate uncertainty –, ψ is the elasticity of intertemporal substitution, and $\theta = \frac{1-\gamma}{1-1/\psi}$).

One may argue that the expressions for the discount rate presented above apply to the riskless rate, and that one should take corrections for risk into account. However, as Giglio, Kelly, and Stroebel (2021) point out, the sign of the climate risk premium (the difference between the discounting rate and the riskless rate) is moot (it depends on whether climate damages occur in states of high or low consumption); and, in any case, to affect prices the market price of climate risk must be mediated by a climate beta, which, as discussed, has to date remained elusive.

Finally, one may say that there such a large degree of uncertainty about the correct discount rate, that any firm conclusions about its effects are unwarranted. This is not correct, as Weitzman (1998), Weitzman (2001) in his work on gamma discounting shows: in the case of uncertainty about the correct discount rate, for distant cashflows one should use the lowest possible rate – the more distant the cashflow, the lower the rate of discounting.[23] And, with a not-particularly low discounting rate of 3%, cashflows in 30 years' time do not disappear – they are reduced by 60%.

Therefore, even if climate damages were a very long way in the future, they would still produce a change in discount rate – the more so if we consider uncertainty about consumption, non-separable utility functions, imperfectly-known risk premia and uncertainty about the correct discount rate. Barring near-miraculous cancellations, this change in discounting should have affected today's prices. But, as we have argued many

22 - The result is obtained for the case of time-separable, CRRA utility functions. The coefficient γ appearing in the precautionary term therefore incorporates aversion to static risk.
23 - By forwarding rather than discounting cashflows, Gollier (2004) had obtained the opposite result. However, in a joint paper Gollier and Weitzman (2010) reconciled the approaches, and confirmed that the lowest discount rate is the correct one to use.

times, there is little evidence that this has been the case. Also the explanation that, at first blush, appeared the simplest is therefore problematic.

Conclusions

Simplifying greatly, a black-and-white description of the current global-warming predicament points to two polar scenarios: if we control effectively climate change, the world economy will have to undergo a transformation that macroeconomist Pisani-Ferry (2021) describes as 'precipitous' (and he is just referring to the higher 2 C target); or we venture into uncharted climate waters, with temperatures fast approaching and perhaps exceeding levels (3 C) never experienced by the species Homo Sapiens. There are, of course, shades of grey between these two extremes, but between these white and black outcomes there is not much room for manoeuvre: just one more decade of 'muddling through' would effectively close most realistic pathways to 2 C by 2100. All of this plays out against a background of much greater uncertainty about the physics of the problem (let alone the damages) than we usually acknowledge. And even benign scenarios hide, behind the facade of a smooth aggregate transition, profound macroeconomic shifts (see again Pisani-Ferry (2021) and references therein), which must have deep sectoral price reverberations.

Against this backdrop, markets seem to have adjusted prices to a very limited extent – at least judging from of how difficult it has proven so far to detect a robust and economically significant 'climate beta'. Ultimately, in either of the polar scenarios above, and in all the intermediate outcomes, transition and physical climate risk will have large aggregate and/or differential impacts on cashflows of firms and governments. If, as we have suggested, these have not been properly factored in current valuations, significant price adjustments can be expected.

If these price adjustments will be gradual, this will create a long-term drag on portfolio returns (as the expectation part of a price is gradually revised). This would be the most benign form of repricing. There are precedents, however, of much more sudden price adjustments. If these were to occur, additional price volatility and loss of liquidity can also be expected, with potential macrostability implications. (See again the discussion in Acharya, Berner, Engle, Jung, Stroebel, Zeng, and Zhao (2023).) To strike an analogy, in the recent subprime banking crisis, the sudden nature of the price readjustment for *all* non-conforming mortgage-related instruments (not just subprime, but also relatively 'safe' mortgages)[24] caused a near freeze in the market, with price uncertainty making inventory holders afraid to unwind their positions, lest they would cause by their action a repricing of their own long positions. Typically, at the start of a financial crisis, trading desks liquidate their liquid, not their troubled and illiquid, positions first. As the market conditions deteriorate, the illiquid positions become extremely difficult to sell, bid-offer spreads widen further and, ultimately, the market freezes.

The possibility that the market may be 'asleep at the wheel' is therefore a novel source of significant risk, to which little attention has been paid so far, but that should be of great concern for long-term portfolio managers, pension funds and, in general, strategic investors (and regulators).

The weakest part of the analysis we have presented has been the inference that the price adjustments so far have been limited, both in the aggregate and at the sector level (while

24 - All non-conforming mortgages –including Jumbo and Alt-A, which are not intrinsically riskier but simply 'non-standard' – were affected by the 2007-2008 repricing.

we have argued that they should have been significant). Work is under way to strengthen this part of the argument.

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About EDHEC-Risk Climate Impact Institute

Exploring double materiality – studying the impact of climate-change related risks on finance and the effects of finance on climate change mitigation and adaptation

Institutional Context

Established in France in 1906, EDHEC Business School now operates from campuses in Lille, Nice, Paris, London, and Singapore. With more than 110 nationalities represented in its student body, some 50,000 alumni in 130 countries, and learning partnerships with 290 institutions worldwide, it truly is international. The school has a reputation for excellence and is ranked in the top 10 of European business schools (Financial Times, 2021).

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In the Fall of 2022, EDHEC-Risk Institute became EDHEC-Risk Climate Impact Institute (EDHEC-Risk Climate). This transition reflects the importance assigned by the School to sustainability issues and builds on the foundations laid by EDHEC-Risk Institute research programmes exploring the relationships between climate change and finance.

Mission and Ambitions

EDHEC-Risk Climate's mission is to help private and public decision makers manage climate-related financial risks and make the best use of financial tools to support the transition to low-emission and climate-resilient economies.

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EDHEC-Risk Climate also aims to play a central role in helping financial supervisors and policy makers assess climate-related risks in the financial system and provide them with financial tools to mitigate those risks and optimise the contribution of finance to climate change mitigation and adaptation.

The delivery of these ambitions is centred around two long-term research programmes and a policy advocacy function.

The research programmes respectively look at the Implications of Climate Change on Asset Pricing and Investment Management and the Impact of Finance on Climate Change Mitigation and Adaptation.

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