PUBLISHED BY | MARCH 2025 | VOLUME 1 NUMBER 39 | A SUPPLEMENT TO PENSIONS & INVESTMENTS

P&I | CUSTOM CONTENT

Research for Institutional Money Management

EDHEC CLIMATE INSTITUTE
London, Nice, Paris, Singapore

EDHEC BUSINESS SCHOOL

INTRODUCTION

Introduction to the Research for Institutional Money Management supplement in *Pensions & Investments*, March 2025

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It is with great enthusiasm that I introduce the EDHEC Climate Institute issue of the EDHEC Research for Institutional Money Management supplement to Pensions & Investments (P&I).

The EDHEC Climate Institute follows the long-standing research tradition of EDHEC Business School and represents a collective effort to address the pressing challenges of climate change by promoting interdisciplinary research with a more integrated vision, drawing on historical expertise in climate finance while leveraging new complementary fields to produce concrete insights and applications.

On the trail of the EDHEC-Risk Institute and the EDHEC-Risk Climate Impact Institute, the recently formed EDHEC Climate Institute addresses the diversity of climate-change-related issues such as evaluating the financial implications of climate change on equity valuation, assigning probabilities to climate scenarios, integrating high-resolution climate data, assessing decarbonization and resilience technologies, and discussing transition finance, which is a main driver for climate transition.

While climate finance often emphasizes transition risk, initial work from Riccardo Rebonato highlights the critical importance of physical climate risk, which may have an even greater impact on financial markets. The research shows how physical damage impacts equity valuations under different policy and climate scenarios, revealing potential market mispricing. It underscores the need to better incorporate physical risks into financial models, as current valuations may miss their true economic effects.

Climate risk assessments often use separate scenarios that focus on extreme transition risk or severe physical risk, neglecting the probabilistic interplay between these outcomes. The study by Riccardo Rebonato proposes methods to attach probabilities of various emission abatement scenarios, integrating technological, fiscal, and policy feasibility into the analysis. This research also highlights a low probability of achieving the Paris Agreement target and the need for a more realistic alignment between economic recommendations and policy action.

Hurricanes devastate coastal cities, droughts cripple agricultural plains, and wildfires ravage forests. Climate change impacts are localized, yet global averages fail to reflect these disparities. Climate risk assessments must take advantage of granular spatial data surpassing their complexity and inherent computational challenges. Such data enables precise identification of geo-sectorial vulnerabilities, allowing cities and businesses to allocate resources, develop targeted adaptation strategies, and build resilience. This is what Nicolas Schneider explores in his work on how advances in data and modeling are transforming climate risk management, ensuring investors are equipped to account for localized risks and grasp the true economic cost of adaptation.

On the latter, understanding the technologies behind resilience and decarbonization measures is a game changer. Ambitious goals and net-zero pledges dominate the conversation but remain vague or lack actionable pathways. Focusing on the technological possibilities allows one to move beyond abstract commitments. This is illustrated by the *infra*Tech 2050 initiative, which is a science-driven approach offering systematic evaluation of technologies and strategies for decarbonizing and strengthening resilience of 101 infrastructure asset subclasses with granular information. The article by Conor Hubert, Rob Arnold, and Nishtha Manocha, illustrates this with a concrete example on data infrastructure, a critical backbone for modern economies.

The successful adoption of resilience and decarbonization technologies depends on effective regulatory mechanisms. Therefore, transition finance is critical to decarbonization. In this issue, Frédéric Ducoulombier assesses the role given to transition finance in the EU Sustainable Finance Framework and highlights the gaps and flaws that hinder transition investment. He then draws on industry best practices and recent regulatory developments to propose key areas for reform aimed at improving transition finance integration.

We hope that these articles inspire and inform readers and provide valuable perspectives. We express our special thanks to P&I for their invaluable partnership in this endeavor.

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Climate Shocks or the Death by a Thousand Cuts? The Effect of Climate Change on the Valuation of Equity Assets

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- The uncertainty of climate and economic outcomes and the state dependence of discounting are two key and much neglected contributors to changes in climate-aware equity valuation.
- The magnitude of portfolio losses depends on the aggressiveness of emission abatement policy, the presence or otherwise of tipping points, and on the extent of central banks' willingness and ability to lower rates in states of economic distress.
- Severe impact on equity valuation can be obtained with very plausible combinations of policies and physical outcomes; and there is considerably more downside than upside risk – more than 40% of global equity value is at risk unless decarbonization efforts accelerate and losses could exceed 50% with near climate tipping points.
- If prompt and robust abatement action is taken, losses can be kept below 10% even in the presence of tipping points.

RETHINKING EQUITY VALUATION IN THE FACE OF CLIMATE CHANGE

How large can we expect the impact of physical climate risk on the value of global equities to be? At a very fundamental level, does climate change matter for asset valuation? We look at the impact of climate change on the price of a global equity index, and we show that, for plausible combinations of abatement policies, the impairment on equity values can be large.

Providing an answer to the motivating questions above is of obvious importance to investors. However, policymakers and prudential regulators and asset managers should also be interested. Regulators want to make sure that the portfolio of the institutions under their watch may not become so severely impaired as to cause instability in the financial institutions themselves. For policymakers, equity valuation can be a bellwether of broader economic conditions: avoiding states of severe equity impairment is one indicator of a safe policy course. And as for asset managers, their profitability comes not just from the fees they charge and on the nominal amount of investment they manage, but also on the mark-to-market of their assets under management.

Climate risk can affect asset valuations both via the transition-risk and via the physical-risk channels.[1] Transition risk has received more attention than physical risk: for example, the scenarios prepared by the Network for the Greening of the Financial Sector (NGFS) have historically focused on assessing the economic and financial impacts of a (potentially disorderly) shift to a low-carbon economy. Indeed, studies that have tried to detect the impact of physical climate change on asset prices have either concluded that physical climate risk is currently not priced in (but transition risk is – see, e.g., Bolton and Kacperczyk (2023)), or, that the effects, while statistically significant, are economically small. But should the effect of physical risk on asset prices really be so negligible? To address this question, we combine tools from the macro-asset pricing literature that examine how long-term macroeconomic uncertainty affects current valuations (Bansal and Yaron (2004)) with an extended version of the Dynamic Integrated Climate-Economy (DICE) model (Nordhaus and Sztorc (2013)), the prototypical model for integrated climate-economic assessment. What we find is that the largest downwards revisions of equity values occur for the least aggressive abatement schedules, i.e., when temperatures are allowed to rise to levels for which physical damages become important. To the extent that abatement costs can be thought of as a reasonable proxy for transition costs, our conclusions point to the fact that the highest equity losses are incurred because of physical, not transition, risk. Actually, robust abatement (though costly) can effectively limit the valuation impairment even in the case of a much more severe dependence of damages on temperature than it is currently estimated. Even from a narrow equity valuation perspective, prompt and decisive abatement action represents an insurance premium well worth paying.

The approach we follow to estimate the value of global equities has solid theoretical foundations, but is also very intuitive. What the holders of securities receive in the form of dividends is the fraction of what the economy produces that accrues to the providers of capital. The greater the impairment to net economic output due to physical damages and abatement costs, the smaller the future expected dividends. The value of equity stock then comes from discounting back to today these future cash-flows – and, as we discuss, this is where state-dependent discounting plays an important role. The only ingredient missing from this thumbnail sketch of our procedure is that equities are a *leveraged* claim to what the economy produces, and this leverage (as leverage always does) magnifies both the upside and the downside.

One key result of our study is that the state-dependence of climate damage introduces two opposite effects: while climate damages reduce 'consumption dividends', they also lower the stochastic discount rate, thereby increasing the present value of these impaired dividends. The overall impact on valuation is the outcome of this tug of war.

When we estimate the impact of physical climate risks on the value of a synthetic global equity index using this approach, we find that the effects can be substantial. This is particularly the case in a world with climate tipping points; however, even in the absence of tipping points,[2] we estimate a difference in the valuation of global equities with respect to a no-climate-damage world ranging from less than 10% if prompt and robust abatement action is taken, rising to more than 40% in a close-to-no-action case. In the presence of climate tipping points, this range widens from less than 10% for robust abatement to more than 50% in the case of very low abatement.

As we discuss at greater length below, we find that for equity values to be mildly affected by physical climate risk three conditions must be met:

- an emission-abatement policy much more aggressive than that currently followed should be pursued;
- the threshold temperatures of tipping points should be located well above the temperatures that we may reach with moderate abatement policies; and
- monetary authorities should be able and willing to cut rates aggressively in periods of economic distress (of low consumption).

None of these conditions is *a priori* implausible (with the greatest uncertainty surrounding the location and effect of tipping points), but none should be taken for granted. Great uncertainty therefore surrounds the estimation of physical climate impact, with very plausible combinations of policies and physical outcomes producing very severe effects on equity valuations, and with considerably more downside than upside risk.

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[1] *Broadly speaking, physical risk pertains to the direct impacts on output, capital, or economic growth resulting from anthropogenic climate change. Transition risk, on the other hand, encompasses the economic costs incurred during the shift to a low-carbon economy aimed at mitigating future physical risks. These costs can be exacerbated by either a rushed or delayed implementation of mitigation strategies.*

[2] *Tipping points are critical thresholds in the Earth's climate system, above which small temperature changes can trigger swift, significant and often irreversible, changes in environmental conditions.*

We present our results by calculating the difference in equity valuations when different abatement policies are implemented and the valuation that would apply in a world in which global warming did not affect the economy, and therefore had no impact on valuation. The latter scenario is useful as a reference point, but hardly realistic. The truly relevant question is to what extent our findings, if correct, are already embedded in the prices of equities. We present indirect evidence that current equity prices seem to reflect only marginally the effect of climate change – and that, to the modest extent they do, they seem to reflect transition, but not physical risk. If, as we show, the effect of weakly unabated climate change on equity valuation is large, this could give rise to a substantial revaluation. For a fuller discussion of this point, see the introductory section.

HOW WE MODEL THE IMPACT OF CLIMATE ON GLOBAL EQUITY VALUATIONS

To arrive at the change in the value of equity due to climate change first we have to estimate the future dividends, and then we must discount them. Just as dividends are the fraction of the net revenues of a firm which is not reinvested for future production, so, from the macroeconomic perspective we are taking, consumption (i.e., the fraction not channeled into savings/investments) is the 'dividend' of the global wealth portfolio, W_0, given by

$$W_0 = \sum_i E[m_i \cdot c_i] \tag{1}$$

where m_i and c_i denote the time-i state-dependent discount factors and consumption streams. We calculate both these quantities using a much-enriched version of the DICE model (see Rebonato, Kainth, and Melin (2024) for a detailed description). In essence, with our approach we account for some of the deep uncertainties inherent to the problem, related to:

- carbon climate dynamics and the presence of tipping points;
- future economic output;
- economic damage functions;
- the pace of future abatement.

In particular, as customary in the literature, the damage functions, $\Omega(T)$, (the function, that is, that relates temperature increases to economic damages) is modelled as

$$\Omega(T) = a_2 \cdot T^{a_3} \tag{2}$$

where T denotes the temperature anomaly. There is little agreement in the literature about the value of the damage exponent, a_3, which controls how quickly damages increases with temperature. We therefore center this value around the consensus estimate from the literature (see, e.g., Nordhaus and Sztorc (2013), Howard and Sterner (2017), Rudik (2020)), but allow for significant dispersion around this value, as shown in Figures 1 and 2.

In our study we present results both without and in the presence of tipping points. To model their impact on economic output, we used a simplified approach where damages increase slowly at first, then accelerate around a critical temperature threshold, T_{crit}, and finally level off at a maximum damage level, H. This behavior is captured by an S-shaped (sigmoid) function, which describes how the fraction of economic output lost increases with rising temperatures:

$$\hat{\Omega}^{TP}(T) = \frac{H}{1 + \exp(-k \cdot (T - T_{crit}))} \tag{3}$$

where $\hat{\Omega}^{TP}(T)$ is the fraction of economic output lost because of tipping-point-induced climate damages,

FIGURE 1

The damage fractions as a function of the temperature anomaly (degrees C, *x* axis) for different values of a_3

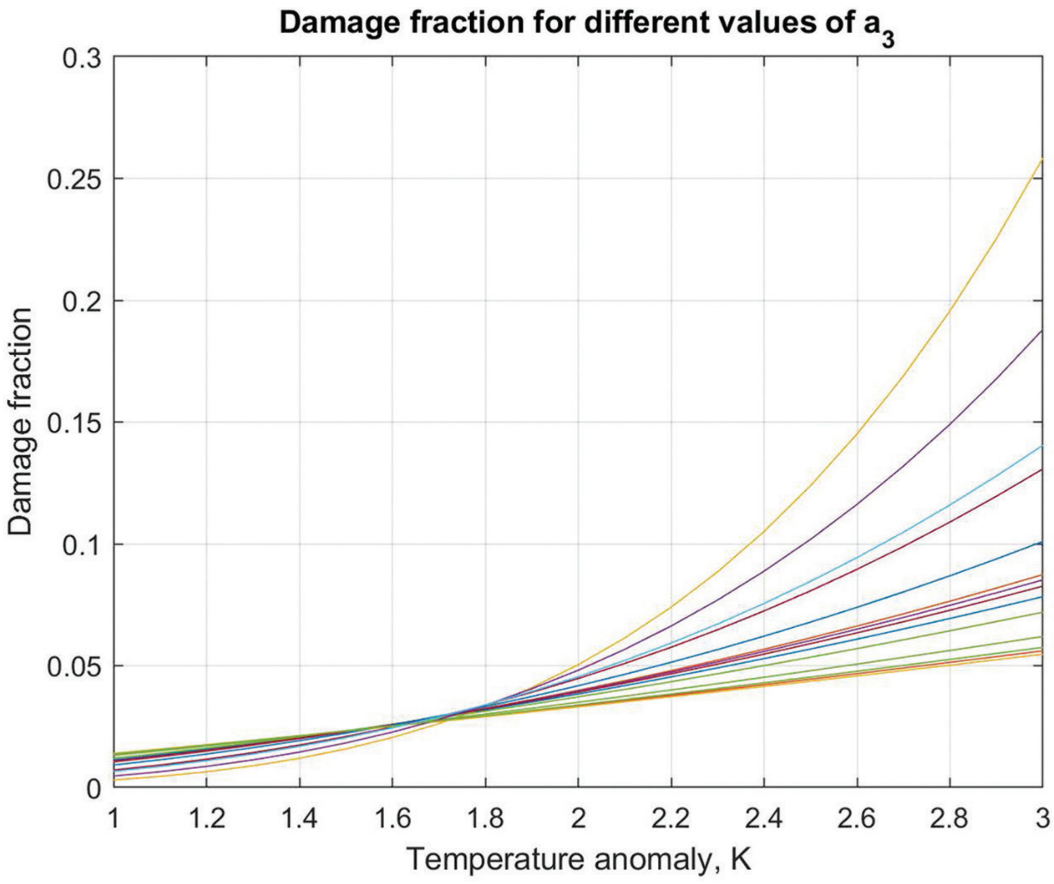


FIGURE 2

The histogram of the damage exponents, a_3, obtained by the stochastic process described in the text for the year 2100

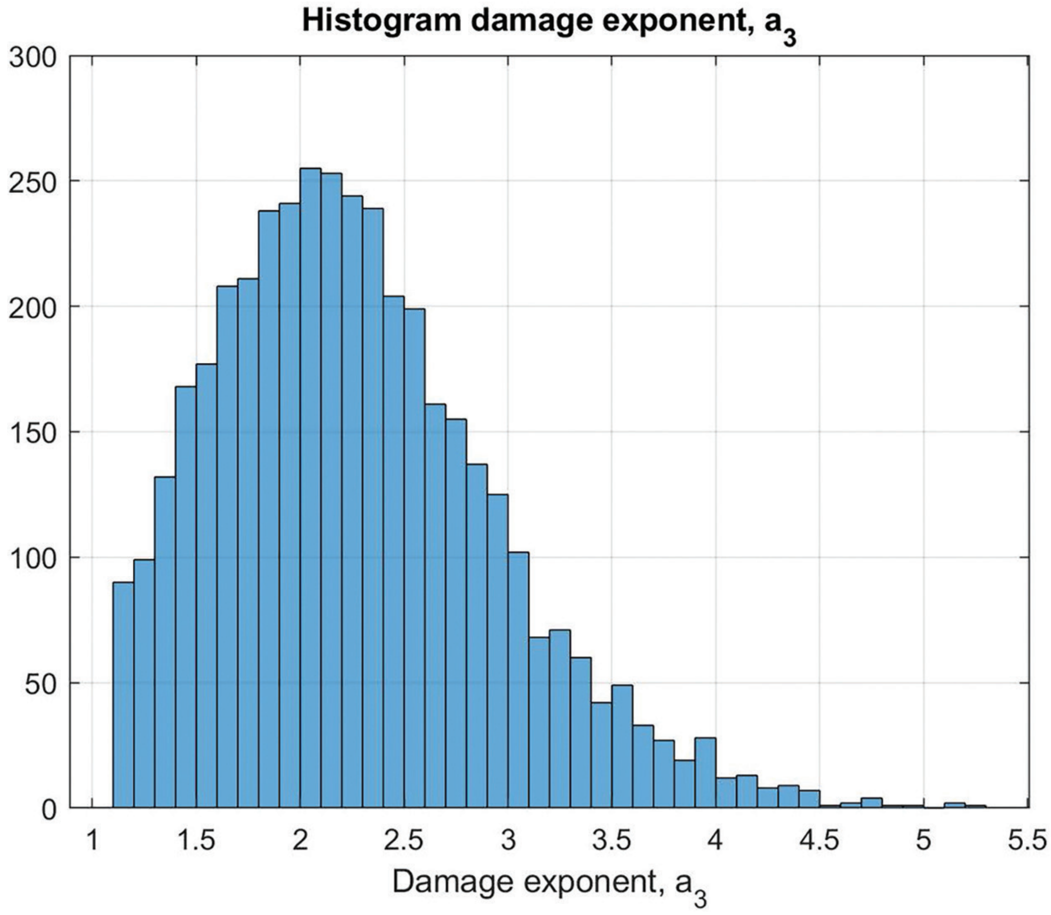
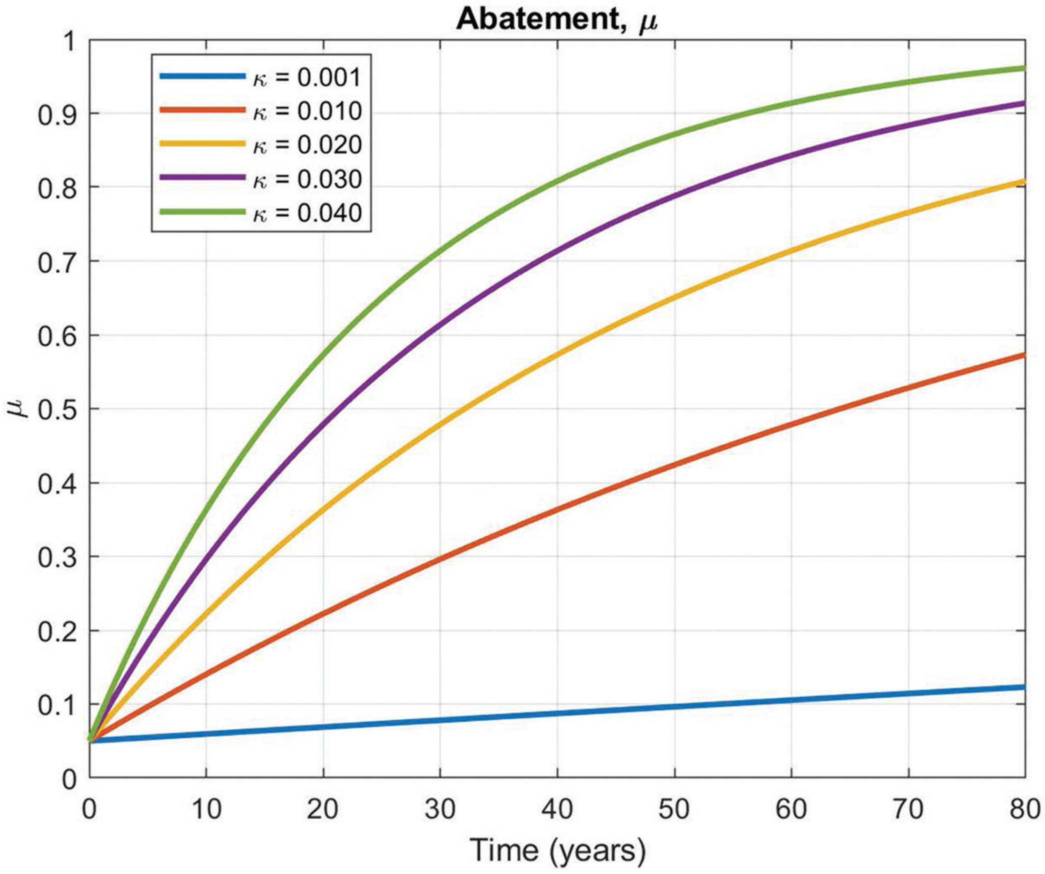


FIGURE 3

The abatement functions, $\mu(t) = \mu(0)e^{-\kappa t} + (1 - e^{-\kappa t})$, with the four reversion speeds used in our study



H denotes the maximum damage fraction associated with the tipping point(s), T_{crit} the level at which the damage fraction reaches $H/2$, and k regulates the speed of 'ramp-up'. We have chosen $H = 0.30$, $T_{crit} = 2.5$ and a speed $k = 16[°C^{-1}]$. The choice of the threshold level, T_{crit}, has been informed by the estimates in the most recent report by the Intergovernmental Panel on Climate Change and in Lenton et al. (2008) of its nearest plausible level.

We do not claim that our location for the threshold of the tipping point is the most likely, or that the maximum loss associated with its inset is known with any precision. We simply want to explore what the equity valuation implications would be of a severe but plausible tipping point specification. Given the large uncertainty surrounding this topic, investors should at the very least have this possibility at the back of their minds – not for nothing, in its comprehensive study of abrupt climate change (NRC, 2002), the National Research Council refers to tipping points as 'inevitable surprises'.

Another very important component is economic growth: higher economic output gives in fact rise to greater emissions, greater concentrations, higher temperatures and higher damages. We model economic growth using the seminal 'long-run-risk' model by Bansal and Yaron (2004), as adapted to climate-change problems by Jensen and Traeger (2014). This model is described in detail in Rebonato, Kainth, and Melin (2024). Here we simply recall that this model (when coupled with Epstein and Zin (1989) utility functions) allows the simultaneous recovery of the equity risk premium and of the level of rates. These features make it very suitable to the asset pricing analysis we are interested in.

A last modeling feature that we should discuss is the set of chosen abatement schedules. As we have explained, we consider two sets of cases: an economy without climate-change damages; and an economy with climate-change damages, and different degrees of abatement 'aggressiveness'. For the latter, the speed of abatement, i.e., the emission abatement function, $\mu(t)$, is controlled by a single parameter, κ, (the abatement speed) in the function

$$\mu(t) = \mu(0)\exp(-\kappa \cdot t) + (1 - \exp(-\kappa \cdot t)) \qquad (4)$$

where t denotes time in years from today, and μ_0 is today's (observed) level of abatement.

The abatement function, $\mu(t)$, is implicitly defined as in Nordhaus and Sztorc (2013) by

$$e_{ind}(t) = \sigma(t)(1 - \mu(t))y_{gross}(t) \qquad (5)$$

where $e_{ind}(t)$ denotes industrial emissions and $\sigma(t)$ is the time-t emission intensity of the economy (emissions per unit of gross economic output, $y_{gross}(t)$). We consider in our study five possible values for the abatement speed, κ: 0.001, 0.01, 0.02, 0.03 and 0.04 years^{-1}.

Clearly, a variety of abatement patterns, much more complex than the simple functions shown in Figure 3 can occur in real life, and our choice of four stylized abatement patterns may seem unduly restrictive. However, it is possible to show that the functions $\mu(t)$ in Equation 4 are actually more general than they at first blush appear.[3] The decay constant, κ, in Equation 4 is therefore a very useful statistic to capture in a synthetic way most of the information embedded in a number of potentially complex abatement schedules.

To give an idea of the aggressiveness (or lack thereof) of the abatement schedules we have chosen, the fastest (associated with $\kappa = 0.04$) produces average temperature anomalies by the end of the century of about 2°C (just within the upper limit of the Paris Accord range), and implies that the 'distance' to full decarbonization will be halved every 17 years. As for our slowest abatement speed ($\kappa = 0.001$) it corresponds to a 2100 forcing (balance of energy in minus energy out) of 7 W/m^2. We recall that a forcing of 8 W/m^2 has been described by Hausfather and Peters (2020) as implausibly high (i.e., as implying an excessively slow decarbonization process), but has been defended by Schwalm, Glendon, and Duffy (2020) as being actually consistent with the pace of decarbonization observed to date. Our values therefore bracket reasonable optimistic and pessimistic scenarios for abatement. Table 1 shows how the abatement speed, μ, in Equation 4 can be associated with a degree of forcing.

Within this framework, the value, $P_{eq}(0)$, of a global equity stock today can be obtained as the expectation over the discounted payoff:

$$P_{eq}(0) = \int_0^{\infty} dt \int_{\Sigma} ds \cdot \underbrace{m_{0,t}(s)}_{discounting} \cdot \underbrace{C^{\lambda}(t,s)}_{dividend} \cdot \underbrace{p(t,s)}_{probability} \qquad (6)$$

where $p(t, s)$ represent the probability of the state variables being in state s at time t, $C(t, s)$ and $m_{0,}t(s)$ are the consumption and discount factor (to time zero) in state s at time t. We then integrate over the whole of the state space (denoted by Σ) and over all times. Despite the forbidding appearance, Equation 6 is easy to interpret: the term $m_{0,t}(s)$ denotes the discount factor from time t to today (time 0), with the argument s indicating that the magnitude of the discounting depends on the state, s, of the economy; the term $C^{\lambda}(t, s)$ signifies the time and state-dependent 'dividend', which is just consumption raised to the exponent, λ, to account for leverage; and, finally, the term $p(t, s)$ denotes the probability of being in state s at time t. The inner integral means, for each time, a sum over all the states, and the outer integral carries out a sum over time. So, Equation 6 simply carries out the valuation of a global equity stock along the lines of well-known expected-discounted-cashflow models.

TABLE 1

The year-2100 forcings (W/m^2, right column) associated with the reversion speeds, κ (years^{-1}, left column), used in Equation 4

κ	Forcing (2100)
0.001	7.0
0.010	5.0
0.020	4.5
0.030	3.5
0.040	3.0

EQUITY VALUATIONS UNDER CLIMATE CHANGE: KEY FINDINGS

Our computational procedure is described in detail in Rebonato, Kainth, and Melin (2024), who also carefully identify the contribution to valuation impairment associated with stochasticity in economic growth and uncertainty about the damage exponent. Here we present a more succinct account of the more salient features of that work.

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[3] *One can show that, under mild assumptions, all abatement functions which have the same emission-weighted average abatement to a given horizon produce the same horizon CO$_2$ concentrations, and hence, given a climate model, the same temperatures.*

We quantify the change in valuation caused by climate damages by computing the ratio of the equity value with climate damages to the value without climate damages. More precisely, we define the *loss ratio* as

$$\text{Loss Ratio} \equiv 1 - \frac{\text{Sum discounted dividend cashflows with damages}}{\text{Sum discounted dividend cashflows without damages}} \qquad (7)$$

This is the quantity reported in Tables 2 and 3 for the no-tipping-point and tipping-point case, respectively. In both tables the number in square brackets show the loss ratio when the discounting is assumed to be non-state-dependent. The different rows refer to plausible choices for a key parameter, the elasticity of intertemporal substitution (EIS), of the utility function which is maximized by our chosen model.[4]

TABLE 2

The loss ratio (defined as the ratio of the value of equity stock with climate damages to its value in the absence of climate damages) for the values of the abatement speed, κ displayed in the top row, for the values of the EIS shown in the first column, in the absence of tipping points, and in the case of the leverage exponent, λ, equal to 2 when both the TFP and the damage exponent are stochastic. in each box the first entry shows the price obtained when the risk premia are accounted for, and the second entry, in square brackets, shows the no-risk-premium price. The bottom row shows the loss ratio averaged across different values for the EIS

EIS	$\kappa = 0.001$	$\kappa = 0.01$	$\kappa = 0.02$	$\kappa = 0.03$	$\kappa = 0.04$
0.875	20%[29%]	14%[20%]	9%[13%]	7%[9%]	5%[7%]
0.925	23%[30%]	15%[21%]	10%[13%]	8%[9%]	7%[7%]
0.975	25%[32%]	15%[22%]	10%[14%]	8%[9%]	5%[7%]
1.025	27%[34%]	17%[23%]	11%[15%]	8%[10%]	7%[8%]
1.075	28%[35%]	18%[24%]	12%[15%]	9%[10%]	7%[8%]
1.125	30%[36%]	19%[24%]	13%[15%]	9%[10%]	8%[8%]
1.175	31%[37%]	20%[25%]	13%[15%]	9%[10%]	8%[8%]
1.225	33%[38%]	21%[26%]	13%[16%]	10%[11%]	8%[8%]
Average	27%[34%]	17%[23%]	11%[15%]	8%[10%]	7%[8%]

TABLE 3

Same as Table 2 (i.e., both TFP and damage exponent stochastic) in the presence of a tipping point. The number in square brackets report the loss ratios without risk premia

EIS	$\kappa = 0.001$	$\kappa = 0.01$	$\kappa = 0.02$	$\kappa = 0.03$	$\kappa = 0.04$
0.875	43%[57%]	37%[51%]	29%[50%]	16%[40%]	9%[17%]
0.925	46%[59%]	40%[53%]	32%[52%]	18%[40%]	9%[17%]
0.975	49%[61%]	43%[55%]	35%[53%]	20%[40%]	9%[17%]
1.025	52%[63%]	46%[56%]	36%[54%]	21%[41%]	10%[17%]
1.075	54%[65%]	47%[58%]	39%[55%]	22%[42%]	10%[18%]
1.125	56%[66%]	49%[58%]	40%[56%]	24%[42%]	11%[18%]
1.175	58%[67%]	51%[60%]	42%[56%]	25%[42%]	12%[19%]
1.225	60%[68%]	53%[60%]	44%[57%]	26%[42%]	12%[19%]
Average	52%[63%]	46%[56%]	37%[54%]	22%[41%]	10%[18%]

The first observation is that in the case of slow abatement the losses can be large, especially (but not only!) if tipping points are present (see the columns on the left of the two tables). Conversely, the impact even of nearby tipping points on valuation can be mitigated by strong and early action (see the columns on the right of the two tables). Note that a robust and costly abatement can limit the loss ratio to about 10% even if tipping points are as severe and 'nearby' as we have assumed.

Second, the fact that the highest loss ratios occur for the lowest abatement schedules implies that physical damages have a far greater impact on equity valuations than abatement (transition) costs. It is usually argued that transition costs may be smaller in absolute value, but, by virtue of being 'front-loaded', are discounted less and therefore have a greater valuation impact than the larger but remote physical damages. The infinite-maturity nature of equity assets suggests that this is not necessarily the case, and that the correct discount factor should be a result of a proper analysis, not of our prejudices.

This naturally brings us to the third point, i.e., the effect of discounting. We note from the tables that taking stochastic discounting into account *reduces* the magnitude of the valuation impairment. (Loss ratios in square bracket in the two tables are obtained with the same *average* discount factor, but after suppressing its state dependence.) This happens because in states of high climate damage consumption growth is reduced, and hence discounting rates, r_t, which can be approximately written as

$$r_t = \delta + \gamma \cdot g_c \qquad (8)$$

are also reduced. (In Equation 8 δ, γ and g_c denote the pure impatience discount rate, the coefficient of risk aversion, and consumption growth, respectively.) This dependence of the rate of discounting on the state of the economy is not just a theoretical feature, but finds a parallel in the actions of the monetary authorities that, inflation permitting, tend to lower rates in periods of subdued economic growth (the philosophy underpinning the 'Greenspan put'). This is the origin of the tug of war between the expectation effect of higher damages, and the discounting effect, which pull in opposite directions.

CLIMATE SHOCKS OR DEATH BY A THOUSAND CUTS? KEY MESSAGES FOR INVESTORS

The magnitude of the equity impairment that we have estimated (and which has been obtained with conservative modeling choices) raises the question of the extent to which these effects are already embedded in equity prices. It is difficult to answer this question with certainty. However, as noted in Rebonato (2023), studies of the so-called climate beta (i.e., of the sensitivity of prices to climate news) and of the climate risk premium (how much the return of climate-sensitive securities should differ from the riskless rate) have so far yielded either null, or contradictory, or statistically-but-not-economically significant results. Given the number of studies which have been devoted to the topic, and the inconclusive results that have been obtained, it seems unlikely that equity prices fully embed this information. If our analysis is correct, a substantial aggregate equity repricing could be expected.

What could the timing of this repricing be? It is extremely difficult to see. It is however hard to imagine that either a new climate event or scientific report could shift the current muted embedding of climate risk in asset prices. What *is* more likely is that the equity losses that we estimate may come about as a series of negative, and individually rather minor, revisions of expected economic results. If this is correct, the eventual equity repricing may come about as the result of a steady negative 'headwind'. Indeed, many studies (see, e.g., Burke, Hsiang, and Miguel (2015), Kotz and Wenz (2021), Bilal and Kaenzig (2024), Park (2024)) suggest that an impairment to productivity, rather than headline-grabbing catastrophic losses, may be the financially most likely channel through which climate change could affect economic output.

In sum, the key messages for investors are:

- From the perspective of a professional investor, our study provides help and suggestions that go beyond the presentation of the range of potential equity losses. One important take-away lesson is the huge uncertainty that surrounds all these estimates. Point estimates (and especially point estimates with many decimal points) are not only foolhardy,

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[4] *The elasticity of intertemporal substitution is the inverse of the aversion to uneven consumption. The higher the EIS, the lower this aversion. A lower aversion to uneven consumption means that agents are less disinclined from investing in costly abatement today despite the fact that they expect their descendants to be richer.*

but dangerous. After all, whatever one may think of the Black and Litterman (1991) model, one enduring contribution of their approach is that, whatever one's 'view' about the returns to be expected from an asset class, our uncertainty about this view radically changes the optimal allocation.

- The second important message to investors from our work is that the discounting of future cashflows is less straightforward than one often assumes. Rule-of-thumb approaches for discounting future cashflows, such as using a weighted average cost of capital, can work well for the settings for which they have been created, but may not be transportable to the valuation of climate-dependent cashflows. Whether they are or not depends on the specific application, and, as we have seen, the difference can be large. An example that a one-size-fits-all discount factor may not be suitable to all climate-change setting is the difference between transition costs and physical damages: the former are probably weakly of the state of the economy; the latter are certainly strongly correlated with it.
- Finally, we note that the central banks' ability to lower rates in periods of distress (which would normally undergird the equity valuation) may be more limited for the poorer countries, which tend to have little fiscal space. Unfortunately, some of these are exactly the countries that are more likely to be severely affected by climate change.

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Why We Need Climate Scenario Probabilities and How to Get Them

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- **The Need for Probabilities:** Current climate scenarios, built on decades of modeling, are now a cornerstone of climate analysis. However, their deliberate avoidance of probabilistic information hinders effective assessment of climate risks for asset valuation and regulatory focus.
- **A Two-Pronged Approach:** We show how to estimate probabilities: first, by applying a least-committal approach that uses minimal information beyond essential constraints; and second, by incorporating economists' recommendations for the social cost of carbon, adjusted for the historical realities of political implementation.
- **Key Findings:** Both methods suggest a median 2100 temperature anomaly around 2.7°C and an expected anomaly of approximately 2.95°C, with a very low probability of limiting warming to 1.5°C and significant risks of exceeding 3°C.
- **Implications and Urgency:** Without significant policy changes, high-temperature scenarios remain likely, increasing the probability of severe climate impacts. Greater investment in abatement could shift the distribution of outcomes toward safer temperature thresholds.

THE IMPORTANCE OF PROBABILITIES IN CLIMATE SCENARIO ANALYSIS

When investors and policymakers are faced with the garden-variety uncertainty associated with financial quantities, they have at their disposal well-established statistical tools, such as Value-at-Risk or Expected Shortfall (see, e.g., McNeil, Frey, and Embrechts (2015)). Knowing that there are more things between heaven and earth than are dreamt of in the statisticians' philosophy, the same investors and policymakers often also make use of scenario analysis. The two approaches complement themselves: as the slogan goes, statistical tools are backward-looking and scenarios (can be) forward-looking.

Financial scenarios are rarely, if ever, accompanied by explicit probabilities. However, the 'expert knowledge' of the end users allows them to understand whether a given scenario represents a clear and present danger, or whether it belongs to the meteorite-falling-on-Earth category. And, if they so wanted, the same users could avail themselves of a hundred-years-plus of financial data to carry out a formal assessment of the scenario likelihood. So, with financial scenarios, probabilities are at least in the back of the users' mind, and can be brought center stage with relatively little effort.

Climate scenarios are different. Since the effects of climate change on the real economy and on financial assets are only just beginning to become apparent, a 'climate Value-at-Risk' based on experienced losses is hardly feasible, closing the backward-looking route to climate-risk assessment. Scenarios understood as the contemplation of yet-never-experienced climate outcomes therefore become particularly important. However, the expert knowledge of the same scenario users is of little help in gauging the likelihood of different climate futures. Any portfolio managers worth their salt should have an opinion on the severity of a scenario such as 'a parallel move in yields by 100 basis points'. How confident would the same portfolio manager be to opine about the relative likelihood of a 4.5 versus an 8.5 end-of-century forcing – assuming, that is, that they understand what that means?

Leaving more or less extreme outcomes to one side, investors sorely need a probabilistic dimension to climate analysis. As Finance 101 teaches, prices are the sum of discounted *expected* cashflow. The 'expected' bit in the valuation slogan means that we need probabilities in order to value securities: it is not enough to know what can happen, and how to discount these future cashflows; we also need to have an idea of how likely the different cashflows will be. So, without a probabilistic dimension the whole valuation project grinds to a halt.

This state of probabilistic confusion is not confined to investors. The Intergovernmental Panel on Climate Change (IPCC) has produced several carbon pathways of different severity (with the severity expressed as radiative forcing, i.e., the imbalance between energy in and energy out). The same body, however, has not provided any probabilistic guidance as to how 'seriously' the various forcings should be taken. In their research (see, e.g., Burke, Hsiang, and Miguel (2015) and Kotz, Leverman, and Wenz (2024)) climate scientists and economists have predominantly made use of the severest Representative Concentration Pathway (RCP), the so-called RCP8.5. Despite this profligate expenditure of analytical resources, Hausfather and Peters (2020) have argued that this scenario should never be considered, because it is virtually impossible (Schwalm, Glendon, and Duffy (2020), by the way, disagree). Are they correct? Without some form of probabilistic framework, we cannot tell. If we do not want to be condemned to the fate of the drunkard in the night who looks for his keys under the lamppost because that is where light is, we need some probabilistic indication of where we should focus our analytical gaze.

Having probabilities for climate outcomes would be nice, it is often claimed, but it is well-nigh impossible. We may be able to say something meaningful about the uncertainty in economic growth, in the climate physics, or in the function that translates temperature increases into damages. But, the prevailing argument goes, *policy* uncertainty is so intractable as to kill the probabilistic project in the bud. We agree that policy uncertainty is indeed the most difficult aspect of the problem to model; and we also agree that we will never arrive at 'sharp', two-decimal-places probabilities. What we want to show is that the idea that we cannot compare the likelihood of different abatement policies because of irreducible uncertainty is overly pessimistic. While it is true that some outcomes are uncertain and hard to predict, we believe it is possible to make informed assessments and weigh the probabilities of different outcomes based on the evidence we have. We therefore intend to propose two avenues to arrive at imprecise but actionable probabilistic statements about future climate outcomes.

ESTIMATING POLICY PROBABILITIES: TWO COMPLEMENTARY APPROACHES

How aggressive can an abatement policy be? Can we 'quantify aggressiveness'? Abatement policies are obviously bounded from below by the strategy of doing (close to) nothing. However, there are also upper bounds to how quickly the economy can decarbonize. The limits are technological (how many, say, wind turbines can be produced in a year), but also fiscal/monetary. Much as we like to wax lyrical about the green dividends of the de-carbonization of the economy, any serious modeling approach shows that a part of net economic output must be diverted from consumption and investment to costly abatement. Pre-climate-change economic agents only had to choose how much of the GDP to consume and how much to save to produce greater future consumption. Post-climate-change agents are faced with a more difficult choice, because tomorrow's greater consumption, if powered by fossil fuel combustion or contributing in other ways to increased concentrations of greenhouse gases in the atmosphere, will reduce the day-after-tomorrow's consumption because of climate damages. How great is the optimal diversion of resources to costly abatement (how aggressive, that is, can we expect the abatement policy to be)? Ultimately this is the vexed size-of-carbon-tax question. We can't know for sure, but we can have some indications.

A carbon tax of 100% of GDP is obviously a hard bound. But, in practice, we can find much tighter constraints. Globally, we spend approximately 3% of GDP on education and defense. Healthcare absorbs between 8–10% of world GDP. It is difficult to imagine that a much greater fraction of GDP would be devoted to climate control. To give an example, Russia is at the moment devoting about 8% to its war machine, and, by so doing, greatly distorting its economy (with rampant inflation, a weakening currency and unemployment just above 2%). And even in the darkest hours of World War II no country devoted more than 40% to military expenditure. We can therefore start by imposing soft bounds that become more and more binding as we exceed the amount of GDP devoted to healthcare and we move towards the theoretical limit of 100% of GDP. So, if we take the social cost of carbon (often used interchangeably with 'carbon tax,' though it encompasses broader societal costs) as a reasonable proxy for the abatement aggressiveness, we already know that its probability distribution should begin falling pretty quickly as we exceed that healthcare-expenditure level, and go to zero when we reach 100% of GDP.

Is there anything else that we can say? The European market for emissions permits has been active for 20 years and has now entered a mature phase. If we equate the observable cost of a permit with a carbon tax, we can say that the expectation (the average value) of the possible carbon taxes should be equal to the observed cost of a permit. When we do so, we have bounded the distribution, and we have specified its first moment.

Can we bring more information to bear on the shape of the distribution? It depends on what we mean by 'information'. If we ask for direct information, the answer is 'probably no'. If this is our answer, then we are embarking on the route that will take us to our first approach to probability estimation. There *can* be, however, some additional information – no doubt, imperfect and partial, but information nonetheless. It is to be found in the expert opinion of professional economists about the optimal social cost of carbon. This information will have to be curated and bias-corrected, but, once we do so, will lead to the second path to our probability estimates.

If we take the first approach, we are embracing the so-called least-committal (maximum-entropy) approach. This method has solid theoretical foundation, being rooted as it is in the pioneering work in information theory by Shannon (1948). Beyond the theoretical appeal of the model, it is the range of successful practical applications, in fields as diverse as biological systems (see, e.g., DeMartino and DeMartino (2018)), natural language processing (see, e.g., Berger, DellaPietra, and DellaPietra (1996)) or statistical physics (see, e.g., Jaynes (1957)), that has made it the go-to probabilistic model when one wants to use in the most effective way what one does know about a system, without adding any unwarranted information.

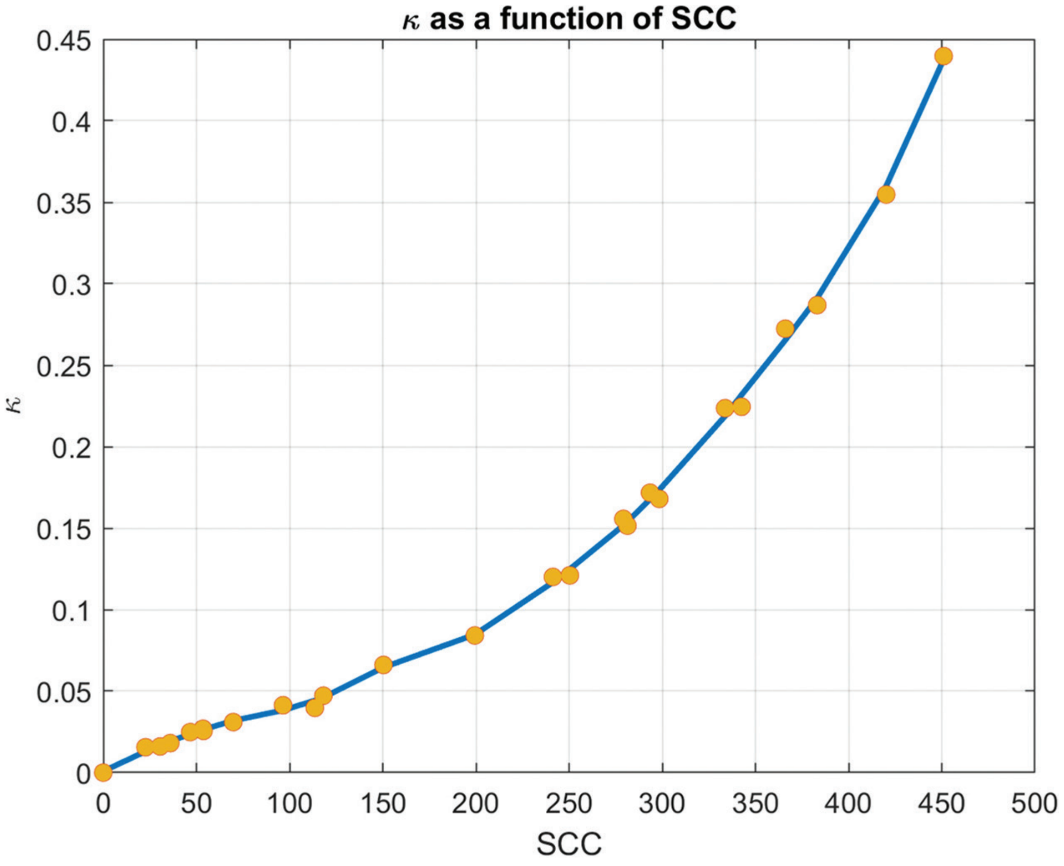
If we take instead the second approach, then our task will be to make the distribution of expert opinion elicited from economists consistent with our bounds, and to correct it for what we call the politician-economists bias (the fact, that is, that, unlike politicians, economists do not face re-election). We briefly present the two approaches below. What is reassuring is that, despite the seemingly very different starting points, the probabilistic projections they produce turn out to be very similar.

In both cases, our proximate goal is a probability distribution for different values of the 'carbon tax.' This is close to, but not quite, what we need: a probability for policy aggressiveness. To make this last step we use a surprisingly robust empirical result: if we characterize the abatement policy by an effective abatement speed (roughly, by how much, in percentage terms, we reduce emissions per year), we can show that there is a strong (monotonic) relationship between the optimal social cost of carbon and the abatement speed, as shown in Figure 1.

FIGURE 1

Abatement speed as a function of the optimal social cost of carbon

Notes: The abatement speed, κ_1 (years^{-1}, y axis) as a function of the optimal social cost of carbon (USD/tonne CO$_2$, x axis). The continuous curve is a LOWESS (Cleveland (1979)) quadratic smooth fit to the calculated points, shown as filled yellow dots.



Thanks to this one-to-one correspondence between the social cost of carbon and the policy aggressiveness, if we have a probability distribution for the former we can easily find the distribution for the latter. We therefore focus, in what follows, on how to find the distribution for the social cost of carbon.

A MINIMALIST APPROACH: EXPLORING THE LEAST-COMMITTAL DISTRIBUTION

If we follow the maximum-entropy route to solving this problem, a straightforward application of functional calculus gives for the social cost of carbon, x, the following (exponential) distribution:

$$\phi(x) = K\exp(-\lambda \cdot x) \tag{1}$$

with K and λ derived in Rebonato (2025). So, according to this solution, the probability a given carbon tax decreases as the tax increases – reasonable enough behavior given common voter preferences.

EXPERT INSIGHTS: HARNESSING ECONOMISTS' RECOMMENDATIONS FOR PROBABILISTIC ANALYSIS

With the second approach, we say that we actually know something more than 'voters don't like taxes', and that the expert opinion about how much we should spend to contain climate change does have some bearing on voters' choice. Note that we are *adding* information – that we 'claim to know more' – and, as a result, the distribution we obtain will be different from the maximum-entropy distribution.

As mentioned, economists do not face the same incentives as politicians do, and their opinions will therefore be 'biased' (upwards, towards more aggressive distributions). Furthermore, they do not always take into account the 'soft constraints' we have mentioned above. This means that the distribution of their opinion must be curated in a variety of ways, as described in detail in Rebonato (2025). When this exercise in data curation is carried out, we arrive at the distributions shown in Figure 2 (one curve shows the empirical distribution and the other the fit obtained using a mixture of truncated Gaussian and lognormal distributions). For comparison Figure 3 then shows the maximum-entropy distribution (yellow line); the non-bias corrected economists' distribution (red line) and the corrected (shifted) economists' distribution (blue line).

We have presented our approach with a very broad brush, and we have omitted many important details (again, see Rebonato (2025) for a fuller description). We are, however, already in a position to discuss some interesting results.

KEY FINDINGS: PROBABILITIES FOR TEMPERATURE OUTCOMES AND POLICY IMPLICATIONS

When it comes to economic and financial applications, the assumption is almost universally made that temperature increases (commonly referred to as 'temperature anomalies') are a powerful statistic of impairment to GDP (see, e.g., the seminal studies by Burke, Hsiang, and Miguel (2015) and Kotz, Leverman, and Wenz (2024)). There still is little consensus about the correct mapping from temperature to damages (and our research group is engaged at the forefront of this exciting topic); for the purpose of this analysis, we therefore limit our analysis to assigning probabilities to temperature outcomes. We choose the end of the century as our reference horizon.

Before presenting our results, we must make clear that the final temperature distribution will depend not only on the distribution of abatement speeds, but also on our assumptions about economic and demographic growth, and about climate uncertainty.

FIGURE 2

Original and fitted SCC distribution

Notes: The fit to the empirical distribution obtained using a mixture of a truncated Gaussian and a lognormal distribution. Social cost of carbon in 2010 USD on the *x* axis.

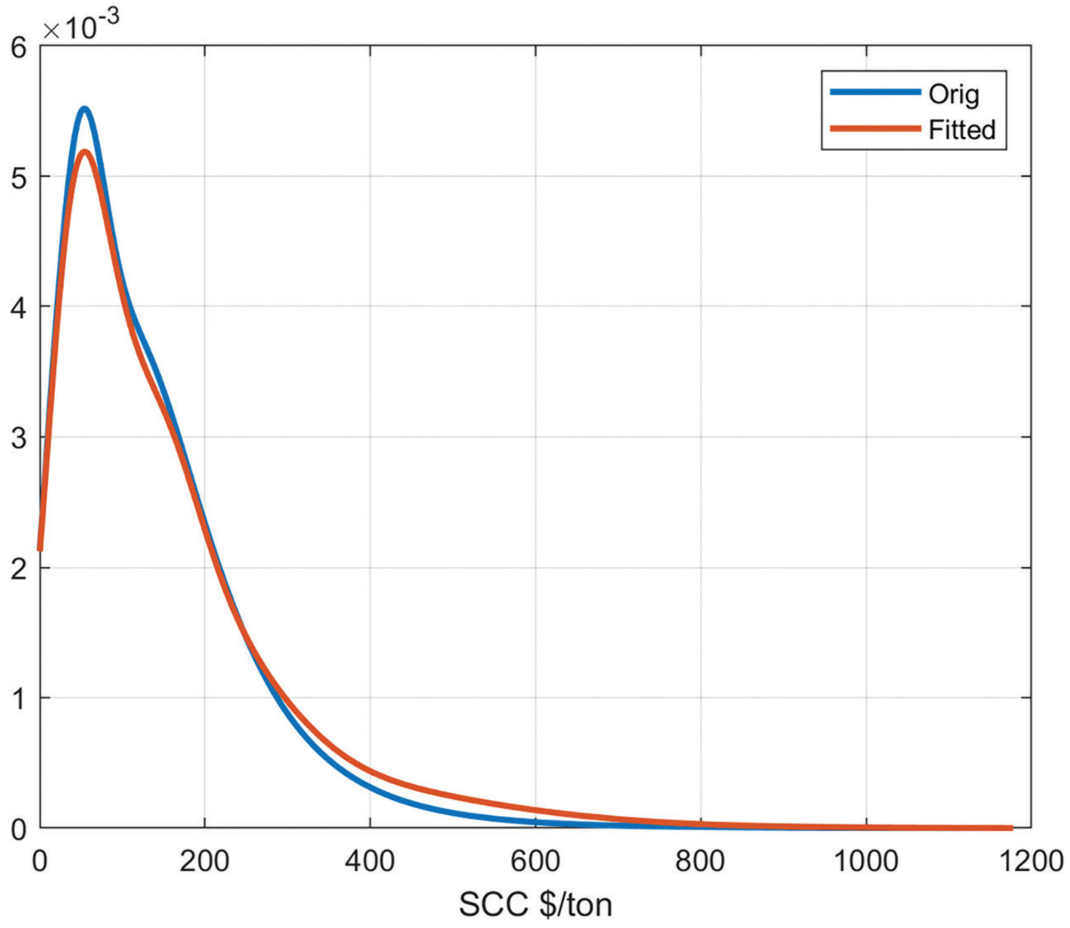
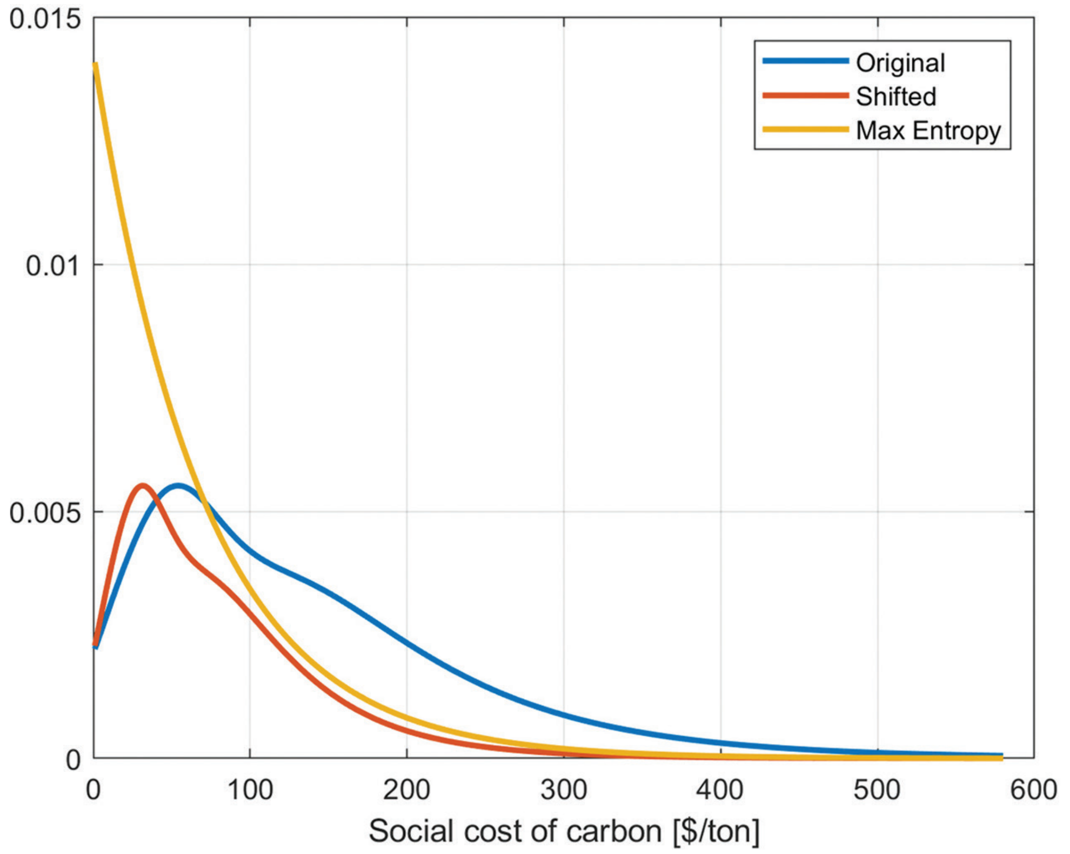


FIGURE 3

Original, shifted and maximum entropy distributions

Notes: The original (blue line), shifted (red line) and maximum-entropy (yellow line) distributions. Social cost of carbon in 2010 USD on the *x* axis.



We document our choices for these quantities in Rebonato (2025), but we stress that our original contribution is in how to deal with the 'intractable' (i.e., the policy) part of the problem. In this respect, our contribution is non-policy-model agnostic, and transportable to different scenario engines.

In a typical configuration, we find the temperature distribution shown in Figure 4. The first observation is that the likelihood of limiting end-of-century temperature increases to 1.5°C is very small: the exact value depends on the modeling choices, but these probabilities are never larger than a few percentage points. We stress that the goal is technologically achievable, but it would require a major and sudden alignment of actual abatement policy with the consensus (median) recommendations of economists. Since economists have put forth these abatement recommendations for the best part of half a century, and their suggestions have gone largely unheeded, our method finds that the probability of an imminent correction of the politician/economist disconnect is highly unlikely. Since the highest transition (abatement) costs are associated with the achievement of the 1.5°C target, this has direct asset valuation implications, as it gives low weight to the most 'costly' abatement paths.

Next, we find that the median 2100-temperature anomaly (around 2.5°C) is well above the 2.0°C end-of-century target, and that there is a significant probability (around 35–40%) that the temperature will exceed 3°C (again, its precise value depends on the specific modeling choices, but, no matter which reasonable model configuration we choose, it is never less than 20%). To put these figures in perspective, the human species, let alone civilization, has never experienced temperature anomalies of 3°C or higher. Such high temperatures would push us into uncharted territory, increasing the likelihood of tipping points – sudden and potentially irreversible climate shifts triggered by crossing critical thresholds. These events, while difficult to predict, would severely challenge adaptation efforts and lead to significant physical damages. In any case, the large probability mass that we estimate for relatively high temperatures suggests that physical damages are likely to be greater than transition costs. Another way to look at our results is that our estimates assign low probabilities to high-transition-cost scenarios.

The distribution in Figure 4 was obtained using the 'informative' approach. How different would our conclusions be if we had used the maximum-entropy approach? How robust, in other words, are our results? We find that the expected 2100 temperature anomalies obtained with the economists' and the maximum-entropy distributions are very similar (2.75°C and 2.80°C for the elicited and maximum-entropy distributions, respectively). All the temperature percentiles obtained using the maximum-entropy distribution are higher, but the differences are always small. And it is easy to understand why the economists' distribution gives rise to somewhat smaller temperatures: if we take the economists' views into account, we add the information that extremely low abatement speed should be unlikely (see again Figure 3), and this marginally reduces the terminal temperature.

CONCLUSION: SOBERING PROBABILITIES IN THE FACE OF MISALIGNED POLICIES

These are sobering results. If our analysis is correct, the likelihood of a relatively safe 'climate landing' is small – much lower than the probability of ending up with unprecedentedly high, and probably very dangerous, temperature increases. What would it take to change the probabilities of these outcomes?

There has been no dearth of dire warnings about the dangers of poorly controlled climate change. What has been lacking has been a link between this expert knowledge and the actually implemented policies – this, after all, is at the origin of the shift in the economists' distribution, and of the centering of the maximum-entropy distribution that play such an important part in our approach. The shift is large, and it is due to the fact that the actual carbon tax (or, rather, its proxy, the cost of emission permits) is still very far from what the economists recommend it should be. In simple terms, we are not diverting enough of our disposable income towards climate abatement to buy for ourselves and our children a meaningful amount of climate insurance. As long as this remains the case, both the economists' and the maximum entropy distributions will remain shifted towards the little-abatement end of the spectrum.

One can quibble with the precise quantification of the probabilities we arrive at – probabilities that, in any case, are not at all intended to be sharp. However, unless there is a major shift in our willingness to fund, via costly abatement, the green transition, the mass of the probability distribution will remain shifted towards the low-abatement end of the axis. The temperature distribution we show in Figure 4 should give investors, policymakers, and citizens in general, food for climate thought.

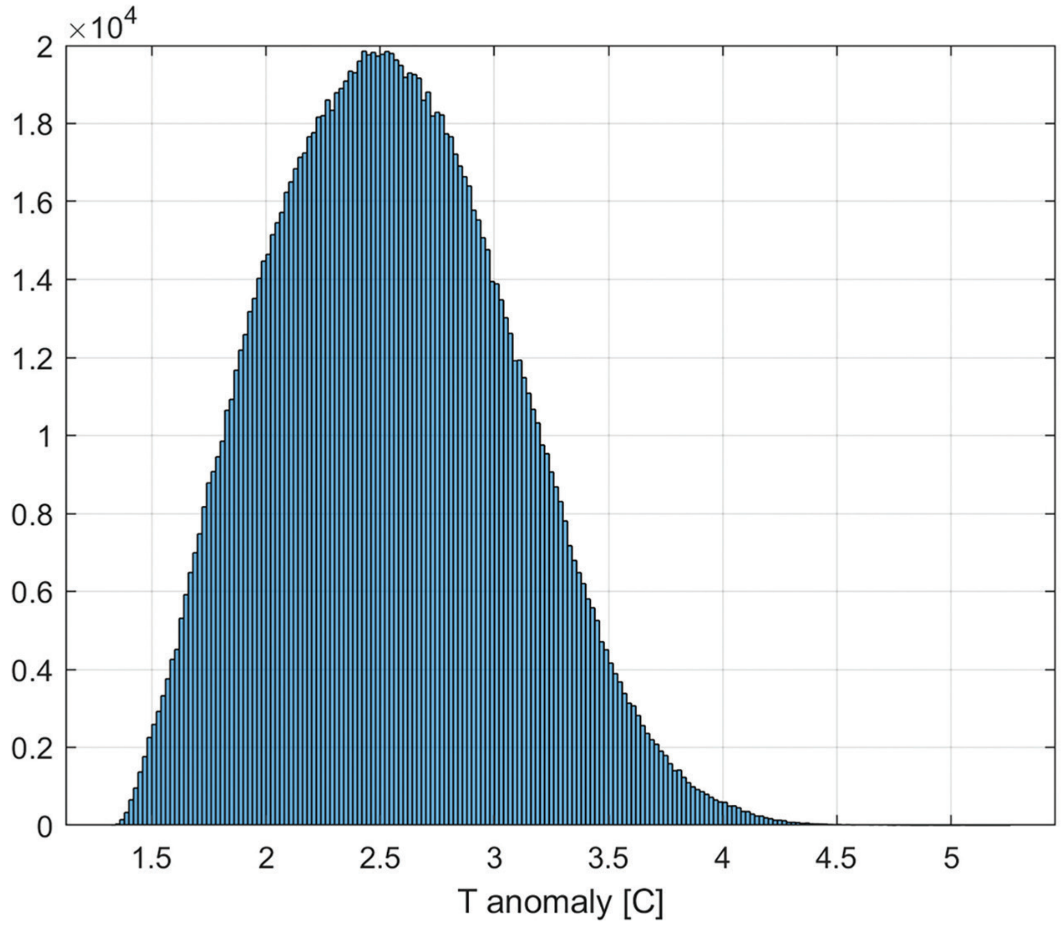
ACKNOWLEDGMENTS

It is a pleasure to acknowledge substantial contributions to this work offered by Dr D. Kainth. Thanks are also due to Dr L. Melin, Dr F. Zhang and Mr F. Ducoulombier.

FIGURE 4

Histogram T(2100) – Informative Distribution

Note: Histogram of the 2100 temperature anomaly for a typical configuration (informative distribution, shift $m = 50$).



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From Global Averages to Local Insights: Harnessing High-Resolution Data for Climate Risk Assessment and Resilience to Physical Shocks

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- **Global risks, local realities:** Climate change impacts geographies and industries unevenly. High-resolution climate damage projections uncover specific vulnerabilities.
- **Building resilience to physical shocks:** Enhanced projections enable businesses, governments, and investors to anticipate and manage localized climate risks.
- **Quantifying Uncertainty by Design:** Treating uncertainty as an integral part of climate projections enables decision-makers to manage risks more effectively.
- **Physical is Essential:** Early integration of high-resolution insights enables investors to address localized and sector-specific climate risks proactively.

Climate change is a global phenomenon, but its impacts are profoundly uneven, varying significantly across regions and industries. Global averages often obscure these disparities, failing to capture the localized and sector-specific vulnerabilities that matter most to decision-makers. Recent advances in data, modeling, and computing allow for unprecedented granularity in physical risk assessments. These tools not only enhance our ability to anticipate localized climate shocks but also empower decision-makers to allocate resources effectively, identify adaptation opportunities, and build resilience.

We present the first replication of the influential study by Kotz et al. (2024), which has become a benchmark in climate economics and is now integrated into prudential analyses. Beyond replication, our work validates the robustness of their findings by testing their sensitivity to various datasets and assumptions. Building on this solid foundation, we extend the analysis of physical risks and damages to an unprecedented level of spatial granularity, uncovering new insights into intra-regional climate variability. By aggregating damages from the bottom up, we refine global physical risk estimates, revealing more severe outcomes than prior studies. Importantly, this high-resolution modeling provides actionable insights for policymakers, businesses, and investors aiming to adapt to climate change and mitigate risks.

Overall, this article explores how spatially granular climate insights can transform the way business, administrations, and investors approach climate risk management. By integrating these insights early, stakeholders can not only address immediate vulnerabilities but also position themselves at the forefront of climate adaptation and resilience.

BEYOND AND BENEATH GLOBAL AVERAGES: LOCALIZING CLIMATE RISK FOR BETTER DECISION-MAKING

Global production systems, particularly weather-sensitive sectors such as food and energy, are projected to face mounting challenges from rising demand and the impacts of a changing climate over the coming decades (Bodirsky et al., 2015). Global warming is predicted to make extreme heat events more frequent and intense over the course of this century (Orlowsky and Seneviratne, 2012). Climate shocks however will be heterogeneously distributed across space and sectors. Understanding and anticipating these localized and sector-specific vulnerabilities is crucial to navigating this shifting risk environment—this is where we find our contribution.

Recent advances in large-scale spatial econometric regressions and the development of global climate databases have brought about a significant shift in the climate-economics literature. Increased level of spatial granularity and a finer understanding of the potential climate drivers of global productivity have gone beyond standard predictions of global averages. Just as Quetelet's *'average man'* represents no real individual, global predictions of climate change economic impacts fail to reflect the specific vulnerabilities and risks faced by individual regions or sectors. However, the implications of these new-generation tools for regional economic outputs remained unknown until quite recently.

The challenge is partly technological: the most recent raw climate data, whether observed or projected, offer daily or even hourly frequencies and spatial resolutions of 1 km x 1 km, resulting in terabyte-sized datasets.[5] Processing these datasets requires advanced computational tools, such as High-Performance Computing (HPC) systems and Shared Computing Clusters (SCC). These tools enable researchers to incorporate millions of climate simulations into global economic models, linking macro-financial outcomes to year-to-year fluctuations in climate exposure. When applied effectively, these innovative approaches significantly enhance the precision of regional risk assessments, providing high-resolution projections of future impacts on production systems and asset performance. Moreover, these projections are grounded in robust empirical data, offering insights that go beyond theoretical estimations. Together, these advancements underscore the strong competitive edge offered by the granular modeling methods at the core of our research.

Early climate models focused on agriculture and relied on country-level data. These studies consistently showed a non-linear relationship between temperature and crop productivity: as growing-season temperatures rose, crop yields and farmland values declined at an accelerating rate (Schlenker and Roberts, 2009; Burke and Emerick, 2016; Mendelsohn and Massetti, 2017). The findings suggested that rising temperatures would reduce the profitability of croplands due to direct productivity losses (and thus production) causing major 'global' crop caloric supply disruptions with implications for food prices and land supply. However, these so-called 'global' estimates were actually based on U.S. and E.U. agriculture data, and thus hardly extendable to other regions or sectors.

Broader implications came with a new generation of damage models ushered in by the work of Burke et al. (2015), who scaled up the non-linear microeconomic relationship reported in the agriculture sector into macro-level damages covering the wider economy (namely Gross Domestic Product (GDP)). They were the very first to establish a direct link between country-level GDP damages and temperature exposure, and to use the predictive structure of their equations to extrapolate the macroeconomic implications of shifts in temperature to a global level (166 countries). Among their key results, they empirically confirmed the non-linear amplifying effect of temperature on aggregate economic production and thus enabled a major move forward in the climate-economics literature. From a methodological standpoint, they showed that a 'bottom-up' approach produces consistent results, as it averages grid-cell-level climatic exposure by country (while accounting for intra-country population density distribution), prior to aggregating up country-level projected GDP damages globally. But, most importantly, Burke et al. (2015) also

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[5] *See for instance: NCAR–USGS' highly-resolved hourly 4-km gridded surface weather for continental North America offering intra-day variability (Rasmussen et al. (2023), https://www.usgs.gov/data/conus404-four-kilometer-long-term-regional-hydroclimate-reanalysis-over-conterminous-united); NASA DAYMET Project Version IV's 1-km surface gridded daily downscaled meteorological fields (Thornton et al. (2022), https://daymet.ornl.gov/); the Thermodynamics Global Warming Simulations Dataset containing hourly 12 km x 12 km data limited to the US extent (IM3/HyperFACETS from Srivastava et al., 2023, https://tgw-data.msdlive.org/); and the NASA's Earth Exchange Global Daily Downscaled Projections (NEX-GDDP CMIP6) that bias-corrected and downscaled outputs from an ensemble of 30 distinct global climate models (GCMs) simulated under the Coupled Model Intercomparison, Phase VI (CMIP6, Eyring et al., 2016) exercise in time (to days) and space (to a 0.25 deg. grid) globally (https://www.nccs.nasa.gov/services/data-collections/land-based-products/nex-gddp-cmip6).*

found that global estimates of GDP losses obtained by aggregation were higher than those produced by standard implementations of Integrated Assessment Models (IAMs), which simulate the interactions between climate change and the macroeconomy at a high level.

Kotz et al. (2024) expanded on Burke et al. (2015) by conducting their analysis at a much finer spatial resolution—1,660 sub-national administrative areas instead of 166 countries. This approach produced the first-ever intra-country distribution of projected gross regional product damages from future climate shifts. More than simply offering a clearer view of regional variations, their work demonstrated that using higher spatial resolution (e.g., provinces instead of countries) results in larger estimates of globally aggregated damages. This finding highlights how more granular data and advanced impact estimation methods not only enhance our understanding of local climate risks but also provide a more accurate assessment of global climate change damages. In our research, we have taken this evolution one step further. First, for consistency, we have reproduced the pioneering Burke et al. (2015) and Kotz et al. (2024) temperature-per-capita GDP response functions published in *Nature* and we have confirmed their robustness by testing different gridded climate fields data and collapsing methods, as well as econometric specifications of the constant terms in the panel framework. Second, for innovation, we have extended projections of economic damages from 1,660 to 3,672 sub-national provinces. By doing so, our geographic coverage contains provinces responsible for 95% of global economic production (see Figure 1). The resulting global damage function exhibits a slightly more severe shape than in Kotz et al. (2024). Our work shows that accounting for small-scale variations in localized climatic exposure and intra-country economic heterogeneity yields aggregated losses that substantially alter the conclusions of previous global GDP models. By way of illustration, considering end-of-century damages under RCP8.5 and employing the most relevant model specifications, our globally averaged estimated economic damages reach 67% of GDP, compared to 25% in Burke et al. (2015). This demonstrates the transformative benefits of high-resolution-based modeling. Our figures are comparable to the approximately 62% damages in Kotz et al. (2024), with remaining differences reasonably attributable to the finer-grained spatial distribution of our projection analysis (notably, we recover their results when adopting their resolution). The resulting global damage function exhibits a slightly more severe shape than in Kotz et al. (2024). Therefore, our work shows that accounting for small-scale variations in localized climatic exposure and intra-country economic heterogeneity yields aggregated losses that substantially alter the conclusions of previous global GDP models – including Burke et al. (2015)'s.

In sum: our work has dual importance and progresses our understanding in two opposite directions: downwards, towards higher spatial granularity; and upwards, towards more accurate global assessments of climate risk impacts on economic production.

QUANTIFYING MID-CENTURY PHYSICAL RISKS FOR BETTER ADAPTATION

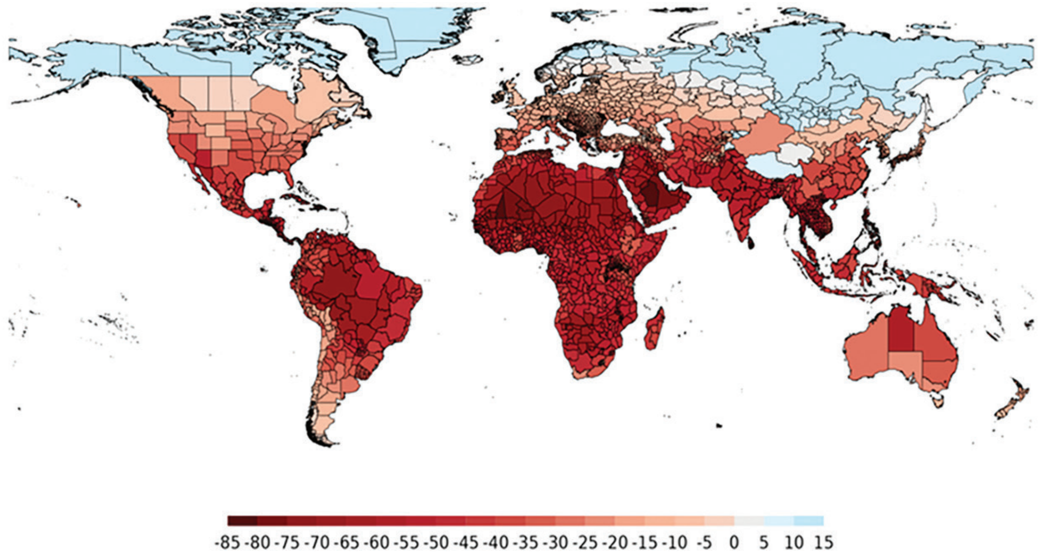
Kotz et al. (2024) represents a breakthrough in climate economics, influencing our research in three main ways. First, they extend Burke et al. (2015)'s country-level temperature-GDP response functions to provinces, highlighting their heterogeneous exposure to climate shocks.

FIGURE 1

***Extending Kotz et al. (2024)*: spatially distributed province-level projections of climatically driven temperature shift impacts (%) on gross regional output per capita, epoch 2099 compared to historical baseline**

Notes: Estimated projections are econometrically structured from sub-national administrative region-level climatic data matched with year-to-year gross regional per capita product realisations (à la Kotz et al. (2024)). Color gradient shows the multi-model median impacts of 15 'likely' CMIP6 global climate models (GCMs) simulated under a SSP5-8.5 vigorous warming scenario.

Source: EDHEC Climate Institute.



Second, they incorporate components of extreme weather events—such as the annual number of wet days, extreme daily rainfall, and daily temperature variability—into their empirical framework, addressing factors previously excluded from climate econometric analyses. When projecting climate-driven changes in per capita regional output, they combined their estimated responses with global climate model simulations, incorporating not only average temperature anomalies but also future changes in the frequency and intensity of extreme weather events and the lasting effects of climate shocks.

Third, the Network for Greening the Financial System (NGFS) incorporated the Kotz et al. (2024) damage function into its latest generation of climate scenarios (Phase V), recognizing its ability to comprehensively capture physical risk impacts on the economy. Outputs from this revised 'climate scenario engine' have significant implications for central banks, policymakers, and investors.

Building on these developments, our work contributes in several key areas: (i) we cross-check the validity of their results using alternative climate data products and statistical models, including parametric, non-parametric, and semi-parametric approaches; (ii) we expand the spatial resolution and geographic coverage of projected economic damages; (iii) we refine the granularity of the latest simulations of the Intergovernmental Panel on Climate Change (IPCC), while addressing biases in models that tend to overestimate warming ('hot models').[6]

It is widely acknowledged that mitigation strategies are likely irrelevant over a mid-century horizon. Climate-change simulations for this timeframe provide a practical and near-term window for decision-making. Moreover, both the simulations used by the Intergovernmental Panel on Climate Change (IPCC) and projections of macroeconomic outcomes are considered more robust and reliable for mid-century scenarios. This is because they rely on shorter-term extrapolations, whereas 100+ year projections carry significant uncertainties regarding future climate dynamics and economic production systems. This highlights a common challenge for economists attempting to quantify long-term economic shocks. For most, 2040–2050 feels like 'tomorrow,' in contrast to the distant horizon of 2100. Looking backward, the technological disruptions of the 20th century make it implausible to assume that the 2100 economic system will resemble that of 2025. Similarly, the past three decades of rising global surface temperatures make it difficult to discuss climate impacts relative to a hypothetical baseline without climate change. Yet, due to scientific conventions and methodological constraints, this counterfactual baseline is often used to frame findings.

Our work indicates that mid-century scenarios already show substantial physical damages from climate shocks across many sectors (e.g., calorie crop supply, energy demand for adaptation and associated infrastructures), with significant regional variations in impact. For instance, the tropics, due to their vulnerability to heat stress, crop failure, and extreme weather events such as hurricanes and cyclones, are highly likely to face significant impacts by 2050. Low-lying coastal areas and small island nations are particularly exposed to rising sea levels, storm surges, and coastal erosion threatening infrastructure, freshwater availability, and economic viability. Arid and semi-arid regions are projected to suffer from increased desertification, water scarcity, and reduced agricultural productivity due to prolonged droughts. Finally, high-latitude agricultural regions–and particularly the mid-western agricultural

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[6] The availability of 30 Global Climate Models (GCMs) simulated under the Coupled Model Intercomparison Project Phase 6 (CMIP6) exercise represents a golden opportunity to use the most complete time and spatially downscaled global warming simulations as part of our macroeconomic projection modeling. However, a subset of CMIP6 GCMs may be "too hot," with representations of cloud feedback in some models associated with higher-than-consensus global surface temperature response to doubled atmospheric CO2 concentrations—equilibrium climate sensitivity (ECS) and global warming after 70 years of a 1% per annum increase in CO2—transient climate response (TCR). To mitigate the threat of bias potentially introduced by this phenomenon, we follow Hausfather et al. (2022)'s recommended procedure of excluding models with TCR and ECS outside "likely" ranges (1.4–2.2 degree C, 66% likelihood, and 2.5–4 degree C, 90% likelihood, respectively). That leaves us with 15 "likely" GCMs that form the basis of our macroeconomic projections.

belt of the U.S.–are predicted to experience substantial shifts in the planting and growing seasons. These changes are largely driven by higher atmospheric CO2 concentrations (CO2 'fertilization') forecast for mid-century (reaching >600 ppm according to the most severe warming scenario: a 53% increase from the historical baseline of 2010).

What does this tell us? For a long time, climate policy has focused primarily on *mitigation* targets, aiming to reduce fossil fuel combustion to avoid catastrophic end-century outcomes. However, the near certainty of extreme weather events and climate shocks at mid-century, regardless of the IPCC scenario, suggests that the time has come to put at least as much emphasis on *adaptation*.

As physical risks intensify by mid-century, maintaining economic productivity in exposed regions will require significant additional inputs, such as irrigation, fertilizers and mechanization in the agriculture sector, or energy-intensive cooling systems in infrastructure. Much as economists often say that there are no 'free lunches', here we underline that one cannot assume 'free adaptation capabilities' either. The most immediate and unavoidable response is thus investment. But where should this investment go, and how much is required?

The adjustments needed to offset future productivity losses are not distributed homogeneously, even within clusters of physical infrastructures. Assets tied to economic output linked to regions and sectors most heavily exposed to mid-century risks will show increasing sensitivity to climate impacts. Additional analytics are needed to assess this sensitivity, evaluate how well it reflects localized risks, and determine whether there is a threshold where divestment, followed by reallocation to less vulnerable assets, becomes more cost effective.

Our research aims to address these critical questions for investors seeking to understand climate risks:

(i) What are the scales of future climate shocks at the local level, and how do these compare to global averages?
(ii) In a warmer future, how much will it cost to produce the same output as today?
(iii) Who will bear these costs, and what are the asset pricing implications of these adjustments, such as a potential climate premium?

Answering these questions is a core focus of our institute's work.

ACCOUNTING FOR UNCERTAINTY: INTEGRATING CLIMATE UNCERTAINTY INTO DECISION-MAKING

Uncertainty is often viewed as a limitation, but in climate research, it reflects how much research remains to be understood—and how much potential there is for refining projections. The scientific community typically reports results for both severe (RCP8.5) and moderate (RCP4.5) warming scenarios. This approach provides two distinct medians of expected economic damages, which are sometimes complemented by an intermediate scenario. The duo can also be interpreted as forming a wide confidence band that includes *the most likely climate outcomes* falling somewhere between moderate and extreme warming.

In general, there is value in exploring both 'central estimates' and 'tail events.' Neither, in isolation, tells the whole story. Ideally, we would like to have a full probability distribution for the various climate outcomes–and, indeed, our team is actively conducting innovative research in this direction. For now we have chosen to keep these two strands of investigation separate, allowing users to focus on one aspect at a time. When presenting extreme results, we align our assumptions on 2100 CO2 concentrations with Kotz et al. (2024), who use the very well-established RCP8.5 carbon pathway. This ensures consistency and allows direct comparisons with Kotz's findings, which have become a benchmark in the field and in public-policy applications. The likelihood of the RCP8.5 scenario is subject to heated debate. While Hausfather and Peters (2020) argue that RCP8.5 is an implausible worst-case scenario, Schwalm et al. (2020) remark that, so far, it is the pathway that best empirically tracks historically realized emissions. Our parallel probabilistic analysis suggests that while RCP8.5 is not central, it is not a complete outlier either. There is therefore prudential value in taking it seriously.

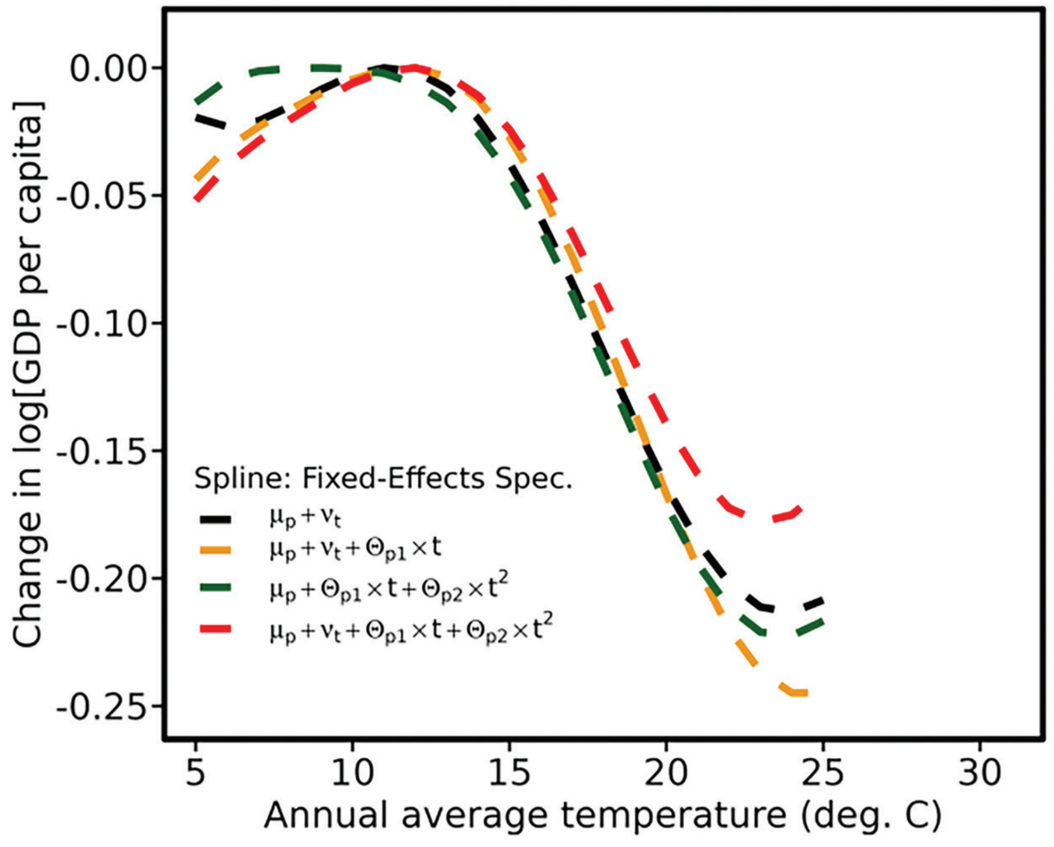
As an answer to this intrinsic uncertainty, we build robust confidence intervals. For each administrative province, we simulate ~520 unique simulated impacts. This *ensemble* combines results from thirty global climate models (GCMs), two Representative Concentration Pathways (RCPs), and nine future horizons. This granular approach enables us to account for investors' preferences for specific GCMs or aversion to certain RCP scenarios, tailoring insights to diverse decision-making needs. Besides, our empirical calibration of historical responses tests for various specifications of the constant terms in our panel equation (see Figure 2); enabling us to ensure that our temperature-GDP responses are empirically determined by both the data and parametric assumptions.

In the context of climate change, the high sensitivity of agricultural supply and energy demand to weather fluctuations, coupled with their pivotal role in the macroeconomic transmission of inflation, makes them crucial focal points of interest for regulators and investors. In the absence of extensive margin of adaptation (i.e., expansion of cultivated lands), global crop producers located near the equator will most likely need to intensify the use of irrigation and fertilizers (i.e., so-called intensive margins of adaptation) to compensate for temperature-shift-driven land productivity declines expected locally. Will this suffice to offset most climatically induced profit losses? Probably not–as shown by recent work suggesting up to 12% global crop yield declines circa-2050 after accounting for producers' local adaptation under a severe warming scenario (Wing et al., 2021). Other medium-run adaptation will include changes in crop varieties, different planting and harvesting dates, and changes in the degree of mechanization. Geography remains a fixed statistic; cultivated lands are not mobile, unlike other production factors. This debate is often delayed, but its *ultimate* and unavoidable relevance lies in how to shift land usage of climate-resilient areas so that it balances out the significant losses expected in the most vulnerable climate zones (e.g., the tropics). Answering this question requires large-scale processing of high-resolution climate and remote-sensing data. The macroeconomic and trade effects from these micro-level adjustments to global climate shocks are also numerous but poorly understood, especially at intra-regional levels. To address this, one line of research involves integrating secular, country-averaged, land productivity

FIGURE 2

***Robustness test:* Parametric FE-OLS global log [GDP per capita] responses to administrative province-annual average temperature exposure per year [deg.°C] against varying specifications of the Fixed-Effects (FEs)**

Notes: Parametric FE-OLS splines are restricted with a 3rd polynomial order function of average temperature exposure. Predicted responses are obtained by multiplying point-level estimated coefficients with the average temperature distribution reflected in the x-axis. Assuming index p denotes administrative provinces of the estimation dataset; red, green, orange, and black dashed lines indicate the following specifications of the constant terms (respectively): province-by-year fixed effects and province-specific quadratic time trends ($\mu_p + \nu_t + \Theta_{p,1}t + \Theta_{p,2}t^2$); province fixed effects and province-specific quadratic time trends ($\mu_p + \Theta_{p,1}t + \Theta_{p,2}t^2$); province-by-year fixed effects and province-specific linear time trends ($\mu_p + \nu_t + \Theta_{p,1}t$); province-by-year fixed effects excluding province-level time trends ($\mu_p + \nu_t$). For all FE-OLS regressions, standard errors are clustered at the administrative province-level. Across all FEs specifications, parametric FE-OLS cubic functions of average temperature show highly similar non-linear shapes that empirically confirm our main parametric FE-OLS results.



shocks into a log-linear (Heckscher-Ohlin) model of global agricultural supply. Solving this program (using General Algebraic Modeling Language software) allows the implications for land supply and prices to be quantified.

FROM DATA TO DECISIONS: HARNESSING GRANULARITY FOR BETTER RISK MANAGEMENT

Enhanced granularity of data can revolutionize our understanding of phenomena but requires computational challenges to be met. This cannot go without improving the performance of data wrangling methods and statistical models in large dimensional contexts. For instance, in our work on *spatially distributed projections of climate-driven macroeconomic impacts*, we processed terabyte-sized datasets containing 249,000 unique grid-cells, multiplied by 365 days, 30 GCMs, 2 RCPs—resulting in 5.4 billion rows per *year of data*.

Increased granularity reveals spatial patterns of past and future changes, but it necessitates high-memory nodes via remotely accessed super-computers. While this involves major entry cost, particularly human capital investment, the marginal cost of usage of some High-Performance Computing (HPC) platforms has experienced a significant decline.

This is the entry door to the production and supply of tailored composite visualization products targeting single infrastructures, regions, counties, and sub-sectoral components; and which can be directly taken up by end users. Combined with parametric insurance products, which set precise triggers in relation to localized risks and conditions such as regional weather patterns or natural disasters, high-granularity risk assessment can usher in better management of physical risk, from the ground up.

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Technological Solutions to Mitigate Transition and Physical Risks – Introducing the *infra*Tech 2050 Database

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- **Infrastructure faces critical risks from climate change, but current tools fall short:** Both transition and physical risks threaten the resilience and value of infrastructure assets, yet the high-level or narrow scope of traditional analyses hinders the assessment of localized vulnerabilities and the design of effective mitigation strategies from the asset level up.
- **The *infra*Tech 2050 project maps strategies and technologies for emissions mitigation and physical risk resilience:** Its database describes these approaches and quantifies their effectiveness through scientific and engineering reviews, providing critical insights to inform asset-level decisions across 101 infrastructure subclasses.
- **The InfraTech 2050 database empowers stakeholders across the infrastructure value chain:** Developers, operators, contractors, asset owners, managers, and policymakers benefit from fine-grain and actionable risk mitigation insights, supporting decisions that protect assets and promote sustainable and resilient infrastructure.
- **Evidence-based insights into strategies, costs, and effectiveness:** A deep dive into one of the covered subclasses illustrates how the database evaluates over 70 core risk-reduction strategies, offering actionable guidance for managing transition and physical risks across diverse infrastructure assets.

Climate technology research at the EDHEC Climate Institute is designed to develop knowledge on how assets can leverage technology-driven solutions to achieve decarbonization and strengthen resilience against physical climate risks. A key component of this initiative, infraTech 2050, focuses on infrastructure. This forward-looking research stream outlines current and promising future strategies for 101 subclasses of infrastructure assets, evaluating their effectiveness for reducing assets' direct and indirect greenhouse gas emissions, as well as their resilience to climate hazards such as floods, heatwaves, storms, and wildfires, up to a 2050 time horizon. Additionally, the project provides insights into the cost implications associated with each of these strategies.

The project features a comprehensive database of strategies and the enabling technologies required for their implementation, alongside scientific assessments of their effectiveness. It also presents academically rigorous research papers and practical case studies to demonstrate how these strategies can be applied in real-world settings.

By offering a comprehensive, systematic, and comparable overview, infraTech 2050 empowers stakeholders to identify the technologies relevant to specific asset types and their comparative performance. This evidence-based approach provides investors, asset managers, and operators with actionable insights to overcome the uncertainties related to tackling infrastructure's greenhouse gas (GHG) emissions and vulnerabilities to extreme climate hazard events.

In this report, we highlight the significance of the infraTech 2050 database, outline its structure, and present an example of its application by discussing strategies that data centers can use to decarbonize their operations and increase their resilience to extreme heat.

Climate Origins of Infrastructure Risk

Infrastructure companies face two key risks: transition risks from the shift to a low-carbon economy and physical risks from the growing frequency and severity of climate-related hazards.

Transition risks stem from policy and legal changes, technological advancements, market shifts, and reputational challenges, associated with the transition to a low-carbon economy. These risks can manifest as financial impacts, including revenue losses, higher operational expenditures and penalties, impairment of assets and stranding, higher liability, and reduced access to, or higher cost of, capital (TCFD, 2017). Carbon emissions and taxes are commonly used to gauge exposure to these risks. Proactively addressing these challenges through measures such as retrofitting, adopting renewable energy, and improving efficiency can reduce or eliminate transition risks and help maintain business viability.

A frequent challenge for infrastructure is its long-term reliance on fossil fuels. Many assets are built with decades of operational life in mind, which can lock in emissions and make adaptation to a low-carbon economy costly and complex. To mitigate these emissions effectively, it is particularly important to identify the approaches and technologies relevant to various stages of the infrastructure lifecycle and to evaluate their associated costs.

Simultaneously, **physical risks** threaten the operational integrity of infrastructure. These risks can result in physical and material damage to assets, and/or reduced performance and output, which may in turn, affect asset values and liabilities, decrease revenues, or increase operational and maintenance costs.

Physical risks come in acute and chronic forms. **Acute risks** refer to single-hazard events, such as, floods, cyclones, heatwaves, or wildfires that cause sudden and significant damage to assets, disrupt operations, and reduce output. **Chronic risks** emerge from long-term changes in climate patterns, such as rising temperatures, increasing sea levels, or prolonged droughts, gradually impacting operational costs and reducing output and threatening viability. Infrastructure assets face unique challenges due to their extended operational lifespans.

While long-term shifts in climate patterns are being modelled with increasing precision to inform infrastructure planning, challenges remain in accurately modeling the localized impacts of extreme weather events. Transition risks, inherently complex due to their reliance on human decision-making and policy implementation, also present significant challenges for high-resolution modeling. Despite the significance of transition and physical risks, there is a striking lack of information from companies to evaluate whether they are managing them effectively. In our investigation of the sustainability disclosures of approximately 50 major companies with infrastructure assets, the findings were stark:

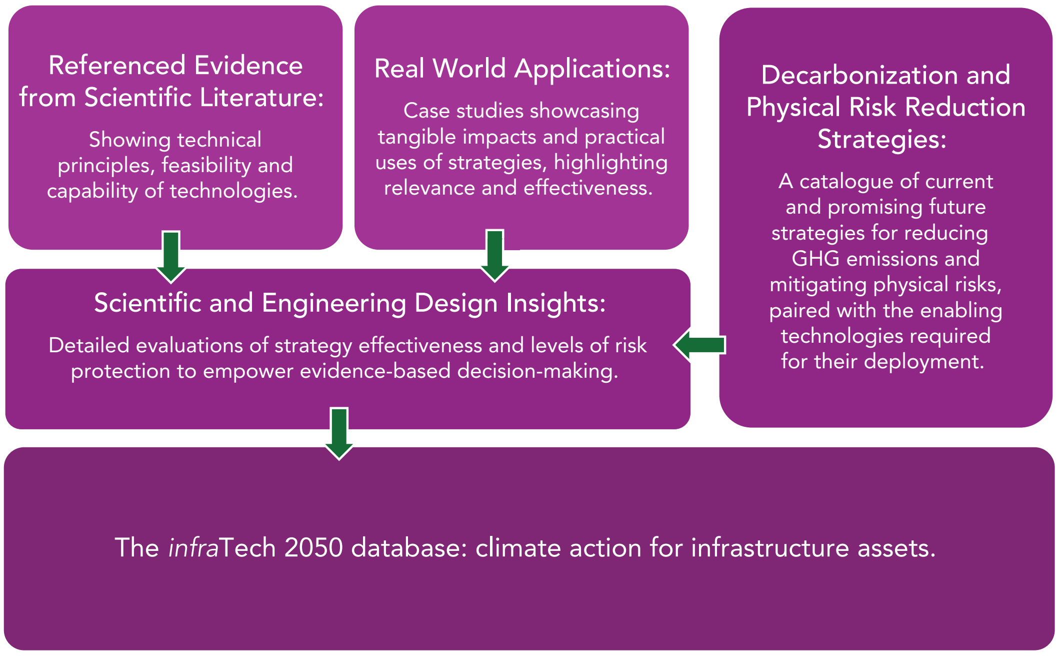
- Less than one-third of the companies disclosed asset-specific GHG emissions data or provided actionable plans on how they could meet emissions reduction targets.
- Even fewer companies – about one-fifth – assessed the vulnerability of their assets to extreme weather or reported their measures to mitigate physical risks.

Most studies on infrastructure decarbonization and resilience focus on high-level city, country, or regional analyses or on isolated engineering designs, limiting the ability to conduct comprehensive reviews of vulnerabilities and available mitigation options (Miyamoto, 2019). This lack of granular, transparent information makes it difficult for investors to link actions to outcomes, quantify residual risks, or assess risk management effectiveness. Without reliable data on transition and physical risks, informed decisions about infrastructure sustainability and longevity are challenging.

*infra*Tech 2050 is a crucial first step in addressing transition and physical risks specific to infrastructure assets, reducing knowledge gaps and supporting a low-carbon, climate-resilient future. The database delivers comprehensive insights into strategies for cutting GHG emissions and enhancing resilience to hazards. Tailored for asset owners and investors, it offers actionable guidelines and comparisons across 101 infrastructure subclasses. While valuable for portfolio-level and industry-wide analysis, it complements rather than replaces in-depth, asset-specific assessments like due diligence studies.

FIGURE 1

Overview of the *infra*Tech 2050 database



METHODOLOGY, STRUCTURE AND VALIDATION PROCESS OF THE *INFRATECH* 2050 DATABASE

Methodology

Approach

The methodology behind the database adopts a top-down approach, drawing on a detailed literature review and case studies to provide a high-level overview of widely applicable strategies for addressing major climate challenges to infrastructure. Unlike a bottom-up approach, which focuses on specific projects and detailed examples, this approach examines general trends and strategic responses across infrastructure sectors.

This approach, presented in Figure 1, identifies current and emerging strategies with broad applicability and significant potential impact, pairing them with the enabling technologies required for their deployment, tailored to the needs of specific infrastructure types. This information is complemented by referenced evidence from scientific literature and real-world case studies, providing a robust foundation for assessing and comparing the effectiveness of each strategy in mitigating climate risk.

Classifying Infrastructure

The *infra*Tech 2050 database classifies infrastructure according to the Infrastructure Company Classification Standard (TICCS),[7] an industry-standard taxonomy that groups infrastructure assets into 8 industrial superclasses, 35 industry classes, and 101 asset-level subclasses. For example:

- Superclass – IC70 Renewable Power
  - Class – IC7010 Wind Power Generation
    - Subclass – IC701010 On-Shore Wind Power Generation
    - Subclass – IC701020 Off-Shore Wind Power Generation

This provides a detailed framework for describing how risk mitigation strategies serve the unique characteristics of specific asset types.

Strategies and Technologies

The methodology distinguishes between:

1. **Strategies** – Broad actions that achieve specific outcomes, e.g., flood protection, often across a wide range of infrastructure types. The database incorporates current strategies and those likely to be used in the foreseeable future.
2. **Key Technologies** – Specific tools or solutions used to execute measures, e.g., concrete flood barriers.

These levels of granularity enable systematic evaluation of potential impacts and costs. Strategies are chosen based on their materiality, technical viability, and relevance to reducing emissions or enhancing resilience. Technologies are assessed based on literature reviews and expert input.

Materiality

To ensure relevance, the database focuses on strategies that are considered material for each risk and asset class. Strategy materiality is assessed against the following criteria:

1. It contributes to significant emissions or physical damage reduction for that asset superclass.
2. It applies to a significant number of assets, asset classes or asset subclasses within that superclass.
3. The technologies are at a basic level of technical viability and could feasibly be employed by asset owners in the short to medium term. This does not necessarily imply current commercial availability or existing examples of functioning systems.
4. It is recognized in industry practice or literature as a key strategy for mitigating transition or physical risks.

Assessing Decarbonization and Damage Reduction

The methodology quantifies decarbonization potential by identifying strategies, assessing the effectiveness of associated technologies, mapping them to emission categories, and calculating their impact on emissions.

A similar approach is applied to resilience, focusing on strategies that mitigate physical risks and evaluating their effectiveness and typical protection level.

Assessing Costs

The capital expenditure (CAPEX) associated with each strategy is evaluated using qualitative ratings (low, medium, high), based on estimated cost ranges as a percentage of asset value.

Accounting for Uncertainty

Given the lack of available data in some areas of research, uncertainty ratings are assigned based on:

- The number of available examples.
- Variability in costs or efficacy.
- The maturity of strategies or technologies (e.g., widely deployed versus emerging technologies).

Strategies or technologies with limited real-world deployment or significant variability are assigned high uncertainty ratings.

Assumptions

Key assumptions include:

- Focusing on retrofitting existing assets,
- Treating risks in isolation,
- Assuming consistent costs across classes.

Broader economic or environmental effects are excluded.

Independent Oversight

To further strengthen the evaluation and validation processes of the *infra*Tech 2050 project, a dedicated review board is being established, bringing together experts from academia, the private sector, consulting, and government. The board will provide independent oversight of every aspect of the project

As for the database, the review board will contribute to:

- Maintaining its credibility.
- Ensuring that strategies are practical and the knowledge base stays relevant.
- Aligning insights with the latest industry practices, regulatory needs, and academic advancements.

Database Structure

The *infra*Tech 2050 database is a comprehensive tool that combines a structured classification of infrastructure assets with rigorous, evidence-based assessments of decarbonization and physical risk mitigation strategies. Figure 2 shows the relationship between strategies, and areas of risk.

Each entry is supported by publicly available evidence from academic research, government reports, and technical documentation, providing a robust framework for guiding infrastructure decarbonization and risk reduction. Each figure is transparently sourced to ensure traceability of the data, thus enabling independent evaluation and, where relevant, challenge or update.

By combining strategy-level information with asset-specific details, the database contains over 1,800 tailored applications. These offer qualitative and quantitative insights, such as technology requirements, effectiveness metrics, and risk protection levels, enabling users to address decarbonization and resilience challenges effectively.

For **transition risks**, applicability of strategies to reduce greenhouse gases is considered separately for each of the three different emission scopes defined by the GHG Protocol (WRI and WBCSD, 2004):

- **Scope 1** – direct emissions from sources owned or controlled by the reporting entity.
- **Scope 2** – indirect emissions from the generation of purchased electricity steam, heating or cooling that is consumed by the reporting entity.

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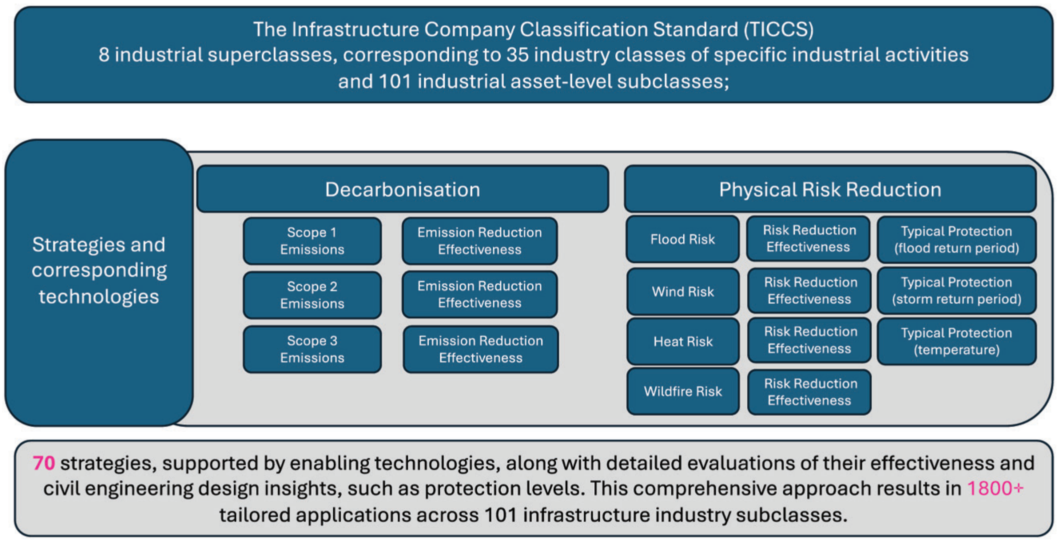
[7] *TICCS (Scientific Infra, 2022) was purpose-designed for the infrastructure asset class and is thus more informative than investment categories inherited from the private equity and real estate universes.*

FIGURE 2

Components of the *infra*Tech 2050 database



The Infrastructure Company Classification Standard (TICCS)
8 industrial superclasses, corresponding to 35 industry classes of specific industrial activities and 101 industrial asset-level subclasses;

70 strategies, supported by enabling technologies, along with detailed evaluations of their effectiveness and civil engineering design insights, such as protection levels. This comprehensive approach results in 1800+ tailored applications across 101 infrastructure industry subclasses.

- **Scope 3** – all other indirect emissions in the entity's value chain, such as emissions from suppliers or customers.

The database presents the effectiveness of a strategy for a specific asset type and scope as a percentage range, representing the potential GHG reduction based on variations in asset characteristics, available technologies, and implementation methods.

Table 1 presents a sample of the database entries for a data center (subclass IC502010 in the TICCS taxonomy) for reducing Scope 1, 2 and 3 GHG emissions.

For **physical risks**, the database provides strategies aimed at mitigating the impact of the following hazards:

- **Floods** – physical damage from pluvial (rainfall), fluvial (river), or coastal flooding.
- **Storms** – physical damage from storms and cyclones.
- **Extreme heat** – operational damage due to high temperatures (including affecting people's productivity).
- **Wildfires** – physical damage from wildfires.

These have been chosen as they were the most common climate-related physical risks to assets over

TABLE 1

Database entries for Scope 1, 2 and 3 decarbonization strategies for data centers

Strategy	Description	Technologies	Scope	Effectiveness
Energy efficiency	Using more efficient server racks, cooling systems and other building mechanical equipment to reduce the overall energy demand.	Monitoring, efficient hardware upgrades, integrated systems.	1, 2 & 3	35%
Offsite renewable energy generation	Purchasing renewable energy from an external energy company to cover company energy use.	Power purchase agreements, renewable energy certificates.	1 & 2	100%
Leakage reduction	Reducing leakage of coolant from cooling systems and replacement with low global warming potential refrigerants.	Leakage detection and monitoring systems, maintaining and upgrading coolant circuit hardware, replacing coolants.	1	40–77%
Low-carbon fuels for generators	Reduces greenhouse gas emissions from backup/emergency generators.	Liquid and gaseous biofuels such as biodiesel blends.	1	34%
Optimize operational practices	Optimizing data center layouts and operating procedures to reduce the energy requirements to be powered by fossil fuels.	Systems design, monitoring and integrated control of systems.	1, 2 & 3	28%
Natural cooling	Using methods such as natural ventilation or evaporative cooling to reduce energy demands and coolant leakage from active cooling systems.	Ventilation, marine submersion, evaporative cooling, vegetation cover to enhance evapotranspiration.	1, 2 &3	47%
Vehicle electrification	Switching to an electric fleet for company or contractor vehicles.	Charging infrastructure, electric cars and light goods vehicles.	1	100%
On-site renewable energy generation	Generating renewable energy on-site through technologies such as solar panels or wind turbines.	Wind turbines, geothermal generation, solar PV.	1 & 2	100%
On-site energy storage technology	Avoids greenhouse gas emissions from backup/emergency generators by replacing them with electricity storage.	Battery, fuel cell, thermal or gravitational energy storage systems.	1	47%–70%
Sustainable procurement	Procuring materials and products through a sustainable supply chain.	Organizational systems in place to enable sustainable procurement.	3	15%
Virtualization	Transferring physical data centers into cloud-based data centers reduces the quantity of hardware required and improves economy of scale for energy use.	Websites and apps, distributed computing and storage, cloud-based data centers.	2 & 3	16%
Downstream recycling	Recycling used equipment, particularly IT equipment given its short useful lifespan.	Recycling facilities and streamlined waste disposal and collection systems.	3	50%

TABLE 2

Defense strategies for data centers against extreme heat

Strategy	Description	Technologies	Effectiveness	Typical Temperature Limit of design
Shade structures	Shade structures are architectural features or built structures designed to provide shade and reduce solar heat gain in outdoor areas. They are strategically positioned to shield sensitive equipment, work areas, or personnel from direct sunlight and excessive heat exposure.	Canopies, shade sails, awnings.	90%	35°C
Mechanical cooling	Mechanical cooling systems use active mechanical equipment to maintain operational temperatures for equipment and facilities within specified ranges.	Chillers, cooling towers, HVAC systems.	70%	40°C
Natural cooling	Natural cooling systems harness the ambient environment for cooling to maintain operational temperatures for equipment and facilities within specified ranges.	Evaporative cooling, thermal insulation, phase change materials, submersion in natural water bodies.	70%	35°C
Heat-resistant construction materials	Heat-resistant construction materials are specially designed or treated materials that can withstand high temperatures and thermal stresses without degrading or losing structural integrity.	Heat-resistant metals, ceramics, composites, and polymers.	36%–52%	50°C
Optimize operational practices	Allowing data centers to operate at higher temperatures and locating them in colder climates reduces the impact from heat stress.	Planning, climate and weather forecasting.	33%	35°C

the previous two decades (United Nations Office for Disaster Risk Reduction, 2020). We assess each strategy's effectiveness in reducing physical damage caused by specific hazard events. Effectiveness is quantified based on the severity of the hazard, or by the level of protection offered, such as safeguarding against maximum temperatures of 50°C.

Table 2 presents a sample of the database entries for protection strategies for a data center against extreme heat.

USING *INFRA*TECH 2050: PRACTICAL APPLICATIONS FOR STAKEHOLDERS

The *infra*Tech 2050 database addresses the diverse needs of stakeholders who are both involved in and affected by infrastructure development, operation, and climate-related risks. From developers and operators to policymakers, public agencies, asset managers, and the broader value chain, the database empowers decision-makers with actionable insights to manage risks and drive sustainable, resilient infrastructure development. Its applications span multiple levels, including asset-specific, sectoral, geographic, and portfolio-wide analyses, making it a valuable tool for both public and private stakeholders.

This section explores the key stakeholder groups, their specific needs, and the ways in which *infra*Tech 2050 supports them. Following this, we detail the database's primary use cases, illustrating its versatility in addressing challenges across infrastructure ecosystems. Understanding the breadth of stakeholders who are involved in or affected by infrastructure development, operation, and risk management—spanning both private investors and public authorities—is critical to appreciating the comprehensive applications of *infra*Tech 2050. Table 3 summarizes the key stakeholder groups and their specific needs, highlighting how each interacts with and benefits from the database.

Use Cases

The *infra*Tech 2050 database is designed to assist stakeholders across the infrastructure value chain in assessing and addressing climate-related challenges at multiple levels.

TABLE 3

***infra*Tech 2050 stakeholder needs**

Stakeholder Group	Needs
Developers, operators, and contractors	Comprehensive guidance for both new construction and retrofitting to enhance performance, efficiency, compliance with standards, and societal expectations.
Asset owners (investors) and managers	Data-driven insights to assess risk exposure and evaluate mitigation costs and benefits, enabling informed investment and risk management at asset and portfolio levels.
Policymakers and regulators	Reliable information to create policies, set benchmarks, and enforce regulations that promote decarbonization, resilience, and accountability in infrastructure practices.
Governments and public agencies	Detailed risk assessments, resource allocation strategies, and guidance to protect critical infrastructure, ensure service continuity, and address climate-related risks at local, regional, and national levels.
The value chain (suppliers, manufacturers, and service providers)	Insights into infrastructure vulnerabilities that impact operations and supply chains, and data to support the development and deployment of resilient, sustainable technologies.

Table 4 highlights key use cases of the database and the stakeholders who benefit from its actionable insights.

Applying *infra*Tech 2050: Data Centers, Climate Risk, and Resilience

To highlight some of the insights that can be gained from the *infra*Tech 2050 database, we conducted a deep dive into the data center asset subclass (TICCS subclass IC502010) and will present the strategies that asset owners can use to reduce their transition and physical risks.

Data centers are a pertinent example as they are increasingly critical for the functioning of modern society, have large emissions profiles, and face clear physical risks from climate change. There were about 11,000 data centers globally at end 2023. About half were located in the United States, while the remainder were widely distributed across other countries (Minnix, 2024). This number is expected to increase dramatically in the coming decades.

- The large emissions signature of data centers is driven by their energy-intensive operations, including the electricity required for computation and cooling equipment (IEA, 2024). Additional emissions from Scope 3 activities such as the purchase and upgrading of IT equipment leads to ongoing Scope 3 emissions from the supply chain, as well as Scope 1 sources such as vehicle fleets and backup generators.

Data centers are exposed to several physical risks from climate change that can cause damage to assets

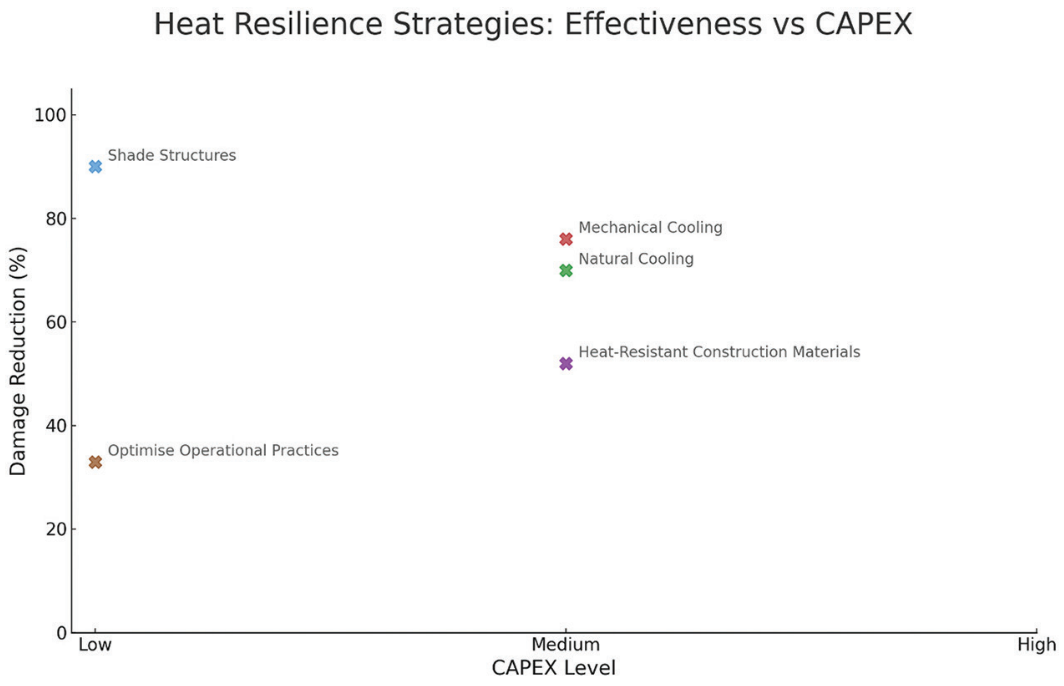
TABLE 4

Use cases of *infra*Tech 2050

Use Case	Description	Example	Stakeholders
Sector-specific risk analysis	Evaluates risks to specific sectors, providing projections of potential outcomes based on risks and available mitigation strategies.	Assessing risks to energy infrastructure and mitigation options.	Policymakers and regulators; Public agencies, Asset owners and managers; Value chain.
Asset-specific risk analysis	Integrates with emissions and climate models to deliver asset-level assessments of risks and mitigation strategies, supporting granular decision-making.	Evaluating extreme heat risks to data centers, prioritizing upgrades.	Developers, operators, contractors; Government; Asset owners and managers; Value chain.
Portfolio risk management	Provides a consistent framework for assessing risk exposure and evaluating mitigation strategies across infrastructure assets enabling portfolio-level risk management.	Assessing overall portfolio exposure to a given type of shock or hazard and considering mitigation options at asset and/or portfolio level.	Asset owners and managers.
Investment prioritization	Identifies high-priority projects by evaluating the cost-effectiveness of emissions mitigation and resilience strategies.	Prioritizing renewable energy adoption or efficient cooling systems for data centers.	Developers and operators; Asset owners and managers; Value chain.
Validation of corporate commitments	Benchmarks corporate climate targets and transition plans against evidence-based insights to assess feasibility and realism.	Validating ambition of emission reduction goals by considering effectiveness and costs of strategies.	Developers and operators; Asset owners and managers, Policymakers and regulators.

FIGURE 3

Cost and effectiveness of heat mitigation strategies for data centers



and have detrimental effects on performance, reducing the asset's effectiveness and commercial viability. The results for all four major climate-related physical risks are assessed in the database, but for brevity, we discuss only the most material – extreme heat centers (Blair Chalmers, 2020).

Physical Risk

Compared to ageing infrastructure assets in different sectors, data centers are relatively new assets that adhere to higher design and construction standards. This usually incorporates a higher level of physical risk protection, resulting in greater inherent resilience and ability to continue operating during extreme hazard events.

Extreme heat reduces component performance and increases failure risks. For example, extreme heat can cause above ground cables to sag excessively and eventually break. It can also overload data center cooling systems causing servers to overheat with reduced functionality. In return, servers must be replaced more frequently, which increases GHG emissions.

Data centers provide services to users outside their immediate geographic area and therefore have a degree of flexibility over location that is unavailable for other infrastructure types. Increasingly, data centers are built in colder locations, such as Iceland, to decrease the level of heat risk. On the other hand, high demand and low energy prices resulted in new developments in Texas, with subsequent higher heat risk.

There is a significant interplay between physical and transition risk reduction. For example, traditional methods of managing high temperatures such as mechanical cooling systems involve high embodied carbon emissions (stemming from their manufacturing, construction, and installation), but also high ongoing electricity usage (approximately 40% of the overall data center electricity demand (Whiting, 2021)). While these systems effectively reduce physical risk, they increase transition risk by increasing the Scope 2 emissions of the data center.

Whilst this is a common approach to reducing extreme heat risk, there are several strategies that either produce no additional operational emissions or even reduce emissions, thereby reducing transition and physical risk. These include passive strategies such as natural cooling using environmental air movement, shading structures that block incident radiation, and heat-resistant construction materials that reduce the rate of heat absorption. Additionally, optimizing operating practices, such as operational temperature ranges, server room layouts, and loading between different servers, has the dual benefit of reducing heat loading and energy consumption and, therefore, emissions.

Cooling systems and heat-resistant construction materials are cheaper to install during construction and can require substantial building retrofit if done afterwards. However, the increased capital expenditure could potentially be offset by lower operational expenditure.

The costs and effectiveness of the respective heat mitigation strategies are shown in Figure 3.

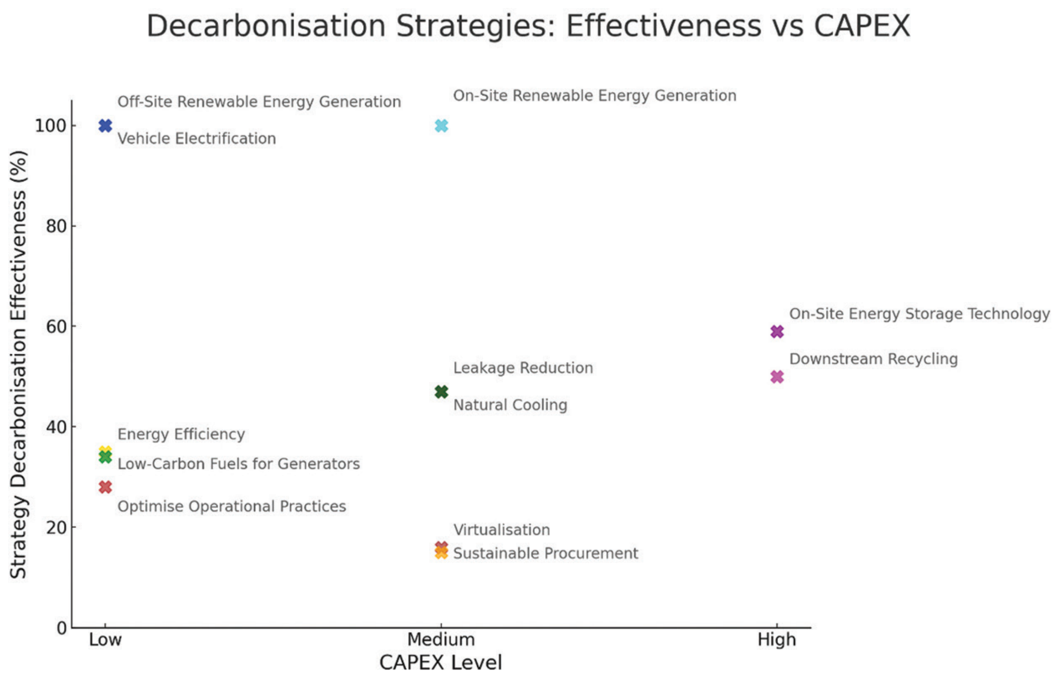
Transition Risk

The growth of data center emissions is influenced by increased construction and usage, driven by rising internet users and traffic (IEA, 2023). In the second half of the last decade, it was largely offset by energy efficiency, renewable energy, and grid decarbonization, resulting in only a 5% emission increase from 2015 to 2020 (Malmodin et al., 2024). However, emissions are expected to rise in this and the coming decades.

The main sources of emissions for data centers are Scope 2 emissions from electricity usage and Scope 3 emissions from the supply chain, mainly due to the high embodied emissions and short lifecycle of the server equipment. The strategies to tackle these emissions are presented in Table 1 and summarized with preliminary cost insights in Figure 4.

FIGURE 4

Cost and effectiveness of decarbonization strategies for data centers



Reducing high-emission electricity demand can be achieved by strategies such as transitioning to renewable energy sources and enhancing energy efficiency. Key measures include upgrading to energy-efficient equipment and optimizing operational practices, like improved server room layouts and temperature management to reduce energy usage.

Decarbonizing the electricity supply through renewable energy represents the most significant opportunity for impact. However, in many regions, grid capacity constraints limit the availability of renewable energy supply. Using on-site renewable energy generation (e.g., solar panels) in combination with on-site energy storage can overcome this limitation. While this approach may involve higher upfront costs than sourcing renewable energy from third-party providers, it addresses grid limitations, minimizes delays in construction timelines, and ensures long-term energy resilience.

Another evolving relationship between data centers and low-carbon energy sources is that of large private sector data center owners signing power purchase agreements with nuclear energy providers. This includes a mix of strategies such as upgrades to existing (i.e., large) nuclear reactors and the potential restart of shut down plants. Some companies have expressed interest in future data centers being powered by purpose-built small modular reactors (on the potential of challenges of SMRs, refer to IEA (2025)).

Additional effort is required to find lower-carbon equipment with longer lifespans that reduce the embodied emissions in data center supply chains. Sustainable procurement practices, virtualizing services and servers, and improving recycling practices can all reduce Scope 3 emissions from these sources but will require collaboration with third parties to achieve.

There is a notable opportunity to align decarbonization and resilience efforts. The dual objectives of reducing transition and physical risk in data centers can be harmonized with specific strategies that reduce both simultaneously for reasonable costs compared to the potential costs of inaction.

Discussion

Data centers, designed with modern standards, feature advanced physical risk protection, making them more resilient to physical risks than older infrastructure assets. However, as climate risks intensify, even these modern assets face significant challenges, particularly from extreme heat.

Location: A Decisive Factor

The geographic location of data centers plays a pivotal role in their exposure to heat risks. Facilities in colder regions inherently benefit from reduced cooling demands, resulting in lower operational risks and emissions. Conversely, centers in hot regions are often strategically located but face greater heat stress. Balancing location advantages with climate resilience is a key consideration for data center operators.

Policy and Business Risks

The increasing focus on sustainability brings both regulatory and business risks for data centers. Policymakers are introducing stricter energy efficiency and emissions regulations, pushing operators to adopt greener technologies. Failing to address these risks can result in operational disruptions, reputational damage, and reduced investor confidence. Investors, customers, and regulators alike demand more transparent and robust climate adaptation measures.

A Path Forward: Innovation and Collaboration

To navigate these challenges, data centers must adopt a multi-pronged strategy. Investments in renewable energy, such as on-site renewable energy generation combined with energy storage, can reduce dependency on grid electricity and mitigate construction delays caused by grid capacity constraints. The high energy demand and relative wealth of data center asset owners provides ample opportunity for funding collaborations necessary to achieve a low-carbon energy supply, both for renewable energy and nuclear power.

Downstream use of waste heat from data centers can reduce the energy use of other assets and provide additional sources of revenue to data center asset owners, for example using waste heat as an input to a district heating network.

Policymakers also contribute by creating incentives for sustainable cooling systems and renewable energy integration. Pricing mechanisms that reward energy efficiency can accelerate the transition to low-carbon operations.

Data centers are uniquely positioned to lead the way in climate resilience and decarbonization. By leveraging advanced design standards and adopting innovative cooling and operational practices, the industry can address the twin challenges of extreme heat and emissions. Proactive measures, combined with strong policy advocacy and industry collaboration, will enable data centers to operate sustainably while ensuring long-term reliability. In doing so, they not only mitigate risks but also set a benchmark for other sectors to follow in the transition to a low-carbon future.

CONCLUSION

Understanding and mitigating climate-related risks is now essential to preserving the value and functionality of infrastructure assets. Reliable, low-carbon infrastructure is critical for reducing GHG emissions and adapting to climate change whilst safeguarding society's living standards. Yet, systematic and comparable information on climate risks and mitigation strategies for infrastructure assets has hitherto been conspicuously absent.

The *infra*Tech 2050 database offers a structured and evidence-based approach to addressing climate-related risks for infrastructure. Developed by the EDHEC Climate Institute, the database serves as a tool to assist asset owners in identifying ways to reduce risks while enabling comparisons between asset types and strategy impacts. It evaluates over 70 core risk-reduction strategies, linking them to relevant asset types across 101 infrastructure subclasses and assessing their effectiveness. With over 1,800 tailored applications supported by academic research and technical documentation, *infra*Tech 2050 empowers stakeholders to understand the role of infrastructure assets in reducing climate risks in a systematic and actionable way, bridging gaps in knowledge and decision-making.

The database empowers users to address climate risks systematically, overcoming current knowledge gaps, and make informed decisions.

Key applications of *infra*Tech 2050 include:

- **Risk Assessment:** Evaluating climate-related risks and opportunities at both asset and portfolio levels.
- **Strategy Identification and Decision Making:** Identifying and prioritizing high-benefit, low-risk decarbonization and resilience projects.
- **Stranded Asset Mitigation:** Aligning assets with regulatory, market, and societal expectations to minimize the risk of loss of market value, custom or asset stranding.
- **Enhanced Decision-Making:** Improving planning and ensuring sustainable long-term financial performance by understanding the cost-effectiveness of climate strategies.

*infra*Tech 2050 is envisioned as a dynamic and evolving resource designed to remain relevant and robust in addressing the challenges of climate-related risks for infrastructure. It will be independently reviewed by sector experts to ensure strategies are practical and the knowledge base remains relevant to industry practice.

*infra*Tech 2050 represents a new approach to creating a systematic and comparable knowledge base for climate resilience and decarbonization opportunities for infrastructure. By aligning expertise and providing actionable insights, it empowers stakeholders to address the dual challenges of decarbonization and physical risk reduction while supporting the broader transition to a low-carbon, climate-resilient future.

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Charting a Pathway for Transition Finance – Lessons from the EU Framework

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- **Transition finance is essential** for decarbonizing high-emission sectors, enabling the adoption of low-carbon technologies, retrofitting facilities, and phasing out unsustainable infrastructure.
- **The EU Sustainable Finance Framework falls short** in integrating transition finance due to the Taxonomy Regulation's strict screening criteria, which disqualify many investments under its narrow definition of transitional activities; the SFDR, which disincentivizes transition finance products and starves investors of actionable information by granting excessive leeway to providers; and flawed, backward-looking climate benchmarks that punish allocation to high-emission transition sectors.
- **Science-based criteria, pathways, and robust transition plans** are essential for channeling investments toward the decarbonization of key sectors, as demonstrated by private-sector initiatives.
- **An extended taxonomy** that classifies sustainable, transitional, and unsustainable activities, along with improved transition planning disclosures, is critical to scaling transition finance—complemented by clear product classifications and updates to benchmark regulation.
- **Collaboration between public and private sectors,** evidence-based classification of transition activities, and transparent reporting of decision-relevant metrics are vital to supporting investor choice and directing financial flows toward the transition at scale.

Transition finance is essential for decarbonizing high-emission sectors through cleaner technologies, operational retrofits, and decommissioning outdated facilities. Despite increased investments over the last decade, funding remains far below the levels needed to meet Paris Agreement goals. According to the Intergovernmental Panel on Climate Change (IPCC, 2023), mitigation investments must grow three- to six-fold this decade to limit warming to 2°C or 1.5°C, underscoring the urgent need for clear governmental support and signaling.

However, the absence of a globally accepted definition of transition finance, coupled with inconsistent regulatory frameworks, hampers the alignment of financial flows with Paris Agreement commitments. Surprisingly, even the European Union (EU), often seen as a leader in sustainable finance, struggles with gaps and inconsistencies in addressing transition finance, limiting its effectiveness.

This article examines the definitional challenges of transition finance, the obstacles within the EU Sustainable Finance Framework, and the role of private-sector initiatives in advancing practical solutions.

It concludes with key policy recommendations for integrating transition finance into sustainable finance frameworks.

THE CONTEXTUAL NATURE OF TRANSITION FINANCE

Achieving net-zero requires three types of investments:

- **Climate solutions:** Investments in activities central to a net-zero economy, including low-emissions energy, clean transportation, energy efficiency, and waste management.
- **Transition investments:** Support for decarbonizing high-emission sectors lacking low-emission substitutes, such as adopting low-carbon processes, retrofitting industrial facilities in hard-to-abate sectors like steel and cement, or decommissioning unsustainable fossil fuel power plants and other carbon-intensive facilities.
- **Carbon sinks:** Investments to offset unavoidable emissions through nature-based or technological solutions, such as restoring ecosystems, enhancing soil and ocean carbon absorption, and advancing carbon capture technologies.

When excluding power generation and household fossil fuel use, the bulk of greenhouse gas emissions arise from industry, transportation, commercial buildings, and agriculture. Reducing these emissions requires significant investment, particularly when behavior-based solutions, such as curbing high-emissions lifestyles or adopting plant-based diets, face socioeconomic and cultural barriers. Transition finance bridges the emissions gap for high-emission sectors that cannot immediately align with net-zero targets but remain integral to the global economy. It complements climate solutions investments and helps mitigate risks such as economic disruption[8] and stranded assets.

Global climate governance acknowledges the principle of "common but differentiated responsibilities,"[9] reflecting the diverse circumstances shaping transition needs and capacities across countries. This variability complicates efforts to define transition-related activities and finance globally, as their scope must adapt to national and sectoral contexts.

In response, national and regional authorities have developed tools to qualify transition investments at activity and/or entity level. Besides the Nationally Determined Contributions (NDCs) required under the Paris Agreement, these tools have included regional/national and sectoral ambitions and/or pathways, taxonomies, and guidelines that differ in their degree of specificity (OECD, 2022).

The European Union regulation on the establishment of a framework to facilitate sustainable investment (hereafter Taxonomy Regulation), sits at one extreme of the spectrum as it provides highly granular activity "Technical Screening Criteria" (TSC) and mostly quantitative thresholds to determine which assets are eligible, in the sense of being regarded as making a substantial contribution to at least one of six sustainability objectives, and potentially aligned, in the sense of not significantly harming the other objectives. Qualification of eligible investments as aligned under this EU Taxonomy also requires entity-level compliance with social and governance standards.

At the other end of the spectrum of detail, the Malaysian Sustainable and Responsible Investment Taxonomy employs principles-based guidance to balance flexibility with sustainability objectives, accommodating varying levels of readiness. It incorporates both asset-level considerations, by providing guidance on classifying specific activities as sustainable, and entity-level considerations, by encouraging organizations to adopt broader social and governance commitments in line with national sustainability objectives.

Both taxonomies allow certain investments by entities in sectors requiring phase-out during the global transition to qualify as transition aligned. Critics warn, however, that this could inadvertently enable greenwashing if financing is not tied to robust, entity-specific decarbonization pathways.[10] Authorities are increasingly emphasizing the importance of robust transition plans, providing detailed guidance on, and requiring disclosure of, corporate transition plans, and in rare cases, mandating that they be aligned with decarbonization goals.

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[8] *While the prioritisation of current socio-economic structures contributes to perpetuating systemic inequities or sidelining the needs of less affluent or vulnerable communities, the avoidance of economic dislocation aligns with the imperatives of a just transition of the workforce as mentioned in the Paris Agreement.*

[9] *The principle is enshrined in the 1992 United Nations Framework Convention on Climate Change (UNFCCC) treaty.*

[10] *Tandon (2021) argues that transition finance is, and should remain, investee-specific, as it must depend on the unique characteristics, needs, and decarbonization pathways of the entity or sector in question.*

Building on this global context, we turn to the EU Sustainable Finance Framework, often regarded as the world's most comprehensive regulatory effort to support sustainable investment. Despite its ambition, the framework has critical gaps that allow transition finance to fall through the cracks.

TRANSITION FINANCE IN THE EU SUSTAINABLE FINANCE FRAMEWORK

In 2016, the European Commission (EC) established the High-Level Expert Group on Sustainable Finance (HLEG) to provide strategic guidance on aligning the bloc's financial system with its climate and sustainability objectives. The group's 2018 report proposed a comprehensive framework, including a tricolor taxonomy (green, amber, and red) to classify economic activities (into sustainable, enabling/transitional, and unsustainable), phased sustainability disclosures starting with corporates and followed by financial market participants (FMPs), and incentives to channel investments into sustainable and transitional activities.

Although the EU Sustainable Finance Package drew heavily from HLEG recommendations, it diverged significantly from the group's holistic vision. Key regulations were prioritized inconsistently, such as the 2020 update to the Benchmark Regulation, while some recommendations faced delays or incomplete implementation, shaping the framework's current gaps.

To understand how transition finance fits within this framework, its three key elements must be examined: the Taxonomy Regulation, the Sustainable Finance Disclosure Regulation (SFDR), and the Regulation pertaining to the EU Paris-aligned and Climate-transition Benchmarks (PAB/CTB, hereafter referred to as EU Climate Benchmarks):

- **The Taxonomy Regulation (TR)** establishes a comprehensive framework for classifying sustainable activities, initially focusing on climate change mitigation and adaptation, and later expanding to another four environmental objectives. Detailed TSC identify activities making a substantial contribution to one or several of these sustainability objectives while avoiding significant harm to others, in line with the Do No Significant Harm (DNSH) principle. For investments to be Taxonomy-aligned, entities must also comply with "Minimum Safeguards", i.e., they must comply with internationally recognized norms for responsible business and human rights and with the bloc's specific social and governance standards. The voluntary EU Green Bond Standard requires funds raised through green bonds to be used for Taxonomy-aligned activities, but financial incentives such as lower capital requirements, recommended by HLEG, have not been implemented.
- **The Sustainable Finance Disclosure Regulation (SFDR)** imposes transparency requirements on FMPs regarding sustainability risks, principal adverse impacts (PAIs), and sustainability policies at the entity level, as well as sustainability objectives and processes at the product level. In a cart-before-the-horse manner, the 2019 Regulation on sustainability-related disclosures in the financial services sector introduced granular disclosure requirements on a host of (often ill-defined) sustainability areas for which there were no readily available and standardized corporate disclosures. The Corporate Sustainability Reporting Directive (CSRD) was meant to belatedly address the data gaps while also encouraging companies to integrate sustainability considerations into their strategic planning and operations and thus ensure better access to capital. However, successful interest group pushback has diluted[11] and delayed corporate disclosure obligations, perpetuating the consequences of this illogical sequencing.
- **The Regulation establishing EU Climate Benchmarks (BMR)** was meant to provide investors with tools to align investment strategies with net-zero goals by setting uniform portfolio construction requirements for indices claiming the PAB/CTB labels, with a view to increasing comparability and mitigating the risks of greenwashing. However, the regulator's decision to ignore industry feedback has produced regulation that does not allow for meaningful product-level comparisons and institutionalizes greenwashing by giving the stamp of regulatory approval to strategies that do little to channel funds towards key transition sectors and issuers delivering real-world decarbonization.[12]

Together, these three texts establish a framework to classify, disclose, and incentivize sustainable activities. Yet, the role of transition finance—a critical lever for decarbonizing high-emission sectors—remains unevenly integrated, leaving significant gaps. Exploring each text in detail sheds light on how transition finance is addressed and highlights areas for improvement.

- **Transition Finance in the Taxonomy Regulation**

  The TR provides detailed criteria for identifying environmentally sustainable activities but focuses primarily on already aligned 'green' activities, limiting its support for broader transition needs. In contrast, a traffic light taxonomy could classify activities across a wider spectrum, including unsustainable practices requiring urgent transition or decommissioning.

  In addition to 'green' activities that "contribute substantially" to one or more of the Taxonomy's environmental objectives, the framework recognizes "enabling activities" that facilitate such contributions and narrowly defined "transitional activities—high-emission operations without feasible low-carbon substitutes, provided they achieve "best-in-class" performance aligned with 1.5°C pathways. However, the related TSCs are particularly stringent, excluding many *bona fide* investments aimed at decarbonizing these activities. Even when such activities meet the TSC requirements, the DNSH principle imposes an additional restrictive layer, disqualifying those that significantly harm other environmental objectives. Furthermore, the framework does not address the retirement of unsustainable infrastructure.

  The TR includes a forward-looking provision that allows companies to classify investments in currently non-sustainable activities as Taxonomy-aligned, provided they are part of a clear transition plan. This plan must be approved by the company's management and should outline the steps to achieve alignment within five years, or up to ten years in exceptional cases. Companies are also required to disclose annually the proportion of total capital expenditures (CapEx) allocated to this transition to ensure transparency and accountability. However, this provision remains constrained by the TSC and DNSH criteria that apply to already aligned activities. Additionally, the medium-term timeframe limits its practicality for high-emission sectors requiring phased decarbonization over longer horizons.

These limitations—the stringency of the TSC, rigid DNSH application, omission of decommissioning efforts, and narrow CapEx exemption—significantly constrain the Taxonomy's capacity to support the breadth of transition finance initiatives needed to meet climate goals.

- **Transition Finance in the Sustainable Finance Disclosure Regulation**

  Primarily a disclosure regulation, the SFDR also shapes capital allocation by defining, categorizing, and imposing requirements that influence how investments are mobilized—often with unintended consequences for transition finance.

  Under Article 2(17), a sustainable investment is defined as one that "contributes" to an environmental or social objective without significantly harming other such objectives and is carried out by investee companies following "good governance practices, in particular with respect to sound management structures, employee relations, remuneration of staff and tax compliance". However, "contribute" is undefined, nor is it linked to the substantial contribution and TSC of the TR. This ambiguity allows flexibility for transition investments not aligned with the Taxonomy but increases risks of greenwashing and undermines comparability. Similar ambiguities apply to DNSH and governance screens, which lack prescriptive criteria and thresholds, further complicating standardization. These screens are also applied at the company level, making them inherently more exclusory than the activity-level criteria of the TR.

  The definition of sustainable investment matters for funds promoting sustainability in the sense of the Regulation. SFDR imposes disclosure at entity level for FMPs and a tripartition of disclosure requirements on financial products, distinguishing between Article 6, Article 8, and Article 9 funds.

  - Article 9 funds are those with sustainable investment as their objective. They must explain how this is to be attained and disclose the proportion of taxonomy-aligned investments for environmental objectives.
  - Article 8 funds "promote" environmental or social characteristics alongside other financial characteristics. They must disclose how they promote these characteristics, the share of their investments classified as sustainable investments, and, where relevant, the proportion of taxonomy-aligned investments.
  - Article 6 funds are all other funds. They are required to disclose how they integrate sustainability risks into their decision-making or explain why they consider these risks irrelevant.

  Article 9 funds can include transition finance investments, but only if they qualify as sustainable investments under Article 2(17). However, negative screening creates significant hurdles for transition investments, particularly for companies associated with significant adverse impacts, such as high emissions. These issues are not present for Article 8 funds promoting transition along with other characteristics. This plasticity, however, comes at a high cost since it allows for a wide variety of custom approaches of varying ambition and effectiveness to market themselves as transition investments.

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[11] In July 2023, the EC adopted the European Sustainability Reporting Standards (ESRS) under the CSRD. The ESRS subject the disclosure of key indicators to materiality assessments (except for 'General Disclosures') and render certain key indicators voluntary. This approach diverges from expert group recommendations, which emphasised the necessity for mandatory disclosure of specific sustainability indicators to ensure transparency, comparability across companies, and the provision of data required by FMPs for compliance with existing regulations.

[12] The author provided extensive feedback on design flaws to the EC and its expert group, both formally and informally, privately and publicly, before and after the drafting of the regulation (see Amenc and Ducoulombier, 2019, 2020a and 2020b; Ducoulombier, 2020). Central design issues were later detailed in two peer-reviewed publications (Ducoulombier and Liu, 2021; Ducoulombier, 2021a).

The lack of established standards to objectively label or rate these offerings also hinders the development of a cohesive market for transition finance-oriented funds.

Finally, the requirement to disclose the proportion of Taxonomy-aligned investments may discourage definitional flexibility, while PAI disclosures may deter transition investments in activities with short-term adverse impacts, even when such investments are vital for the transition.

- **Transition Finance in the EU Climate Benchmark Regulation**

The EU Climate Benchmarks aim to support the European Green Deal by guiding investors to reallocate funds toward sustainable activities and improve the climate impact of investments over time.

Minimum standards for PABs and CTBs require a reduction in the weighted average carbon intensity of portfolios by 50% and 30%, respectively, relative to the relevant market benchmark, and an absolute contraction of 7% p.a. to align with a rigorous global 1.5°C pathway. The approach, however, is myopic and backward oriented, relying on selecting and weighting assets based on their cross-sectional intensities to achieve the required portfolio decarbonization. It offers only minimal consideration of corporate commitments or differentiated transition pathways reflecting sectoral and national contexts.

PAB standards also exclude companies with material involvement in fossil fuels and those with majority revenues from power generation activities exceeding an ambitious carbon intensity threshold. As such, they at best channel investments towards green energy—they are not designed to support the transition of the power generation sector required for rapid electrification.

The requirement to halve relative average carbon intensity from the onset further limits exposure to major emitters, missing opportunities to support their decarbonization efforts. The regulation's crude sectoral controls—partitioning assets into high- and low-emission sectors while merely requiring that cumulative exposure to high-emission sectors remain aligned to market benchmark weights—enable portfolio decarbonization to proceed primarily through reallocation across and within (high-impact) sectors.

While the lower market-relative intensity reduction for CTBs does not automatically disqualify high-intensity sectors, at least at onset, the lack of granularity in the framework still promotes divestment from key transition sectors and heavy emitters. Furthermore, the chosen intensity metric, which emphasizes price momentum in capital markets, disincentivizes honest transition finance approaches and undermines the benchmarks' potential to drive meaningful change. This is compounded by the requirement to incorporate unreliable value chain emissions data into measurement. These issues have prompted net-zero investor coalitions to advocate for redesigned transition benchmarks that can drive genuine decarbonization in the real economy (NZAOA, 2022; IIGCC, 2023).

Despite its ambition, the EU Sustainable Finance Framework lacks a cohesive approach to transition finance. The fragmented and misaligned design of the Taxonomy Regulation, SFDR, and Climate Benchmark Regulation creates negative synergies, failing to incentivize the systemic transformation needed to meet climate goals.

PRIVATE-SECTOR INITIATIVES PROVIDING TRANSITION FINANCE GUIDANCE

The finance industry has played a pivotal role in defining and operationalizing transition finance, developing guidelines and frameworks at both instrument and issuer levels to refine sustainable finance approaches.

Transition finance originated in the late 2000s with climate and green bond issuances by Multilateral Development Banks (MDBs).[13] In response to the growing appetite for climate finance, the Climate Bond Initiative (CBI) was launched at the end of 2009 to develop standards to promote high integrity in the nascent market. At the end of 2011, the not-for-profit organization finalized its first Climate Bond Standards, covering wind energy, and announced a certification scheme. Coverage rapidly extended to other renewables and energy efficiency projects while the Certification Scheme developed to ensure that bonds would meet strict climate-aligned criteria through pre- and post-issuance verification. Eligible projects and criteria were formalized in the CBI Taxonomy, first released in 2013, which categorized sectors and activities aligned with a low-carbon economy. From 2020, it began expanding to address the decarbonization challenges of high-emission sectors by introducing criteria for transition-aligned projects. In 2024, the Climate Bond Standards were revised to include a 5% flexibility pocket for use-of-proceeds and expand the certification coverage to general-purpose instruments, assets and entities. The latter further facilitated transition finance by allowing the funding of more incremental, entity-wide investments, while preventing greenwashing by insisting on issuer-level alignment with, or transition towards, science-based transition pathways.

A similar evolution is visible in the work of the International Capital Market Association (ICMA). In 2014, the industry association launched the Green Bond Principles (GBP) to support broader development of the sustainable bond market. Relative to the CBI, the GBP recognized a wider array of "green" projects and adopted principles-based guidance. Issuers enjoyed flexibility in defining sustainability objectives, with ICMA relying on transparency and external reviews to promote market integrity. As the urgency of the transition and the challenges faced by high-emission sectors became better understood, ICMA too recognized the need for a broader approach. In 2020, it introduced the Sustainability-Linked Bond Principles (SLBP) and the Climate Transition Finance Handbook (CTFH). The SLBP shift the focus from project-specific financing to issuer-level performance, offering flexibility in the use of proceeds while requiring that Sustainability Performance Targets (SPTs) be met lest the issuer face a penalty such as a stepped-up coupon or the requirement to purchase offsets to make up for the sustainability performance gap. The CTFH further highlighted the need for credible transition strategies, addressing greenwashing risks associated with green or sustainability-linked instruments.

The financial sector's engagement with transition finance aptly began with debt instruments, which dominate the primary market and enable the direction of capital toward urgent, on-the-ground decarbonization investments by corporates and administrations. Over time, buy-side institutions expanded this effort, exploring the potential to incorporate sustainability considerations more broadly across asset classes and both primary and secondary markets. Broader buy-side engagement in transition finance began to gain momentum in the mid-2010s, aligning with the preparation and subsequent implementation of Paris Agreement commitments.

Notable initiatives like the Montréal Carbon Pledge and Portfolio Decarbonization Coalition highlighted investor interest in climate action and supported the Paris Agreement negotiations. These efforts focused on measuring, disclosing, and reducing portfolio carbon footprints by reallocating capital from carbon-intensive to green activities and encouraging issuers to cut emissions. Though limited in scope, they laid the foundation for more comprehensive transition finance frameworks.

Following the Paris Agreement, buy-side institutions elevated their ambitions from climate-conscious to net-zero investment. In 2019, the Paris Aligned Investment Initiative (PAII) and Net-Zero Asset Owner Alliance (NZAOA) were launched to provide guidelines for aligning portfolios with long-term climate goals. Their early frameworks, released in 2021, focused on incentivizing real-world decarbonization through capital allocation and issuer engagement, even without explicit reference to "transition finance." (Ducoulombier, 2021b, 2022). Critically, both frameworks have provided valuable transition insights since inception. The PAII Net Zero Investment Framework (NZIF) introduced a bucketing approach to classify assets by net-zero alignment, capturing green assets, those transitioning or aligned with net-zero pathways, and the non-aligned (PAII, 2021). The NZAOA Target Setting Protocol (TSP) linked portfolio decarbonization to science-based sector targets, starting with key transition sectors (NZAOA, 2021). While key transition sectors were already subjected to stricter scrutiny than other sectors in the initial NZIF, its 2024 revision insisted on the use of relevant science-based pathways and strengthened the oversight of transition plans, including through enhanced evidencing of CapEx and operational expenditures (OpEx) supporting target delivery alongside board-level accountability (PAII, 2024). While the treatment of transition finance within the TSP has remained largely consistent since its inception (NZAOA, 2021 and 2024), the NZAOA report on developing credible transition plans provided valuable guidance on evaluating the credibility and effectiveness of such plans (NZAOA, 2023).

While asset-owner-driven initiatives paved the way for net-zero alignment frameworks, other financial stakeholders—including asset managers, banks, and insurers—have introduced their own commitments. To enhance coordination across the financial ecosystem, the Glasgow Financial Alliance for Net Zero (GFANZ) was established ahead of COP26 in 2021. GFANZ's 2023 taxonomy of transition finance identifies four key dimensions: scaling climate solutions, financing net-zero-aligned assets, supporting high-emission sectors in transition, and responsibly phasing out carbon-intensive assets. The latter highlights a critical but underdeveloped area, requiring further attention to ensure a just and orderly transition.

ADVANCING TRANSITION FINANCE IN THE EU: FROM GUIDANCE TO REFORM

Active dialogue among stakeholders, regulators, and supervisors has highlighted the EU Sustainable Finance framework's shortcomings in addressing transition finance. Recent initiatives by the EC and European Supervisory Authorities, particularly the European Securities and Markets Authority (ESMA), provide guidance on navigating the current framework while charting a course to enhance the regulatory architecture.

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[13] *The European Investment Bank (EIB) issued the first Climate Awareness Bond in 2007, followed by the World Bank's first Green Bond in 2008. These innovative instruments mobilised private capital for climate projects, complementing public funding—a central theme of the 2007 Bali Action Plan, which set the stage for the Paris Agreement. The Bali Action Plan aimed to advance a successor to the 1997 Kyoto Protocol, which committed industrialised countries to binding emission reduction targets but only entered into force in 2005 after Russia's ratification, following the withdrawal of U.S. support in 2001. Concurrently, the IPCC Fourth Assessment Report provided compelling scientific evidence of anthropogenic climate change, reinforcing the urgency of global action.*

WORKING AROUND THE GAPS: THE EC RECOMMENDATION ON TRANSITION FINANCE

The Recommendation on facilitating finance for the transition to a sustainable economy (EC, 2023) builds on earlier work acknowledging the need to mobilize private funding for the EU's climate and sustainability goals. It defines "transition finance" for the first time, offering guidance for market participants, Member States, and supervisors.

Transition finance is broadly defined as financing investments compatible with and contributing to the transition while avoiding lock-ins of significant harmful activities or assets. It includes investments:

(a) in Taxonomy-aligned transitional economic activities and Taxonomy-eligible economic activities becoming Taxonomy-aligned.
(b) in undertakings or economic activities with a credible transition plan.
(c) in undertakings or economic activities with credible science-based targets, where proportionate, supported by information ensuring integrity and accountability.
(d) tracking EU climate benchmarks.

This inclusive approach acknowledges the diverse starting points and constraints of entities requiring transition finance but warrants careful evaluation.

Extending beyond Taxonomy-defined sustainable investments to include entities with credible transition plans is a pragmatic solution to limitations in the Taxonomy's timelines and stringent safeguards.[14] However, relying on science-based targets instead of detailed transition plans raises concerns about enforcement and accountability in the market's preferred framework, i.e., the Science Based Target Initiative (SBTi). The Recommendation however suggests this should be a fallback option, subject to proportionality and robust safeguards.

The unconditional inclusion of investments tracking EU climate benchmarks in the topline definition of transition finance is puzzling as their design flaws discourage genuine transition practices. However, the section of the Recommendation addressing the use of benchmarks takes a more cautious and conditional tone, suggesting that their methodologies may complement science-based scenarios or pathways and help mitigate the risk of asset stranding.

Ultimately, the Communication underscores the importance of using reliable tools to enhance transparency and integrity in transition finance markets while minimizing greenwashing risks. Its emphasis on linking use-of-proceeds financing to Taxonomy-anchored transition targets and tying sustainability targets for broader financing to science-based criteria reflects a balanced, if imperfect, framework for advancing transition finance.

PUSHING THE BOUNDARIES: THE ESMA OPINION ON SUSTAINABLE INVESTMENTS

While the EC Recommendation offers guidance on transition finance within the existing framework, the July 2024 ESMA Opinion, "Sustainable investments: Facilitating the investor journey," outlines a long-term, holistic vision and calls for significant reforms to make the framework more effective in supporting transition finance. The goal is to ensure good market conduct, equip investors with effective tools and information, and support the EU's sustainability and transition goals while enhancing its capital markets' competitiveness.

ESMA (2024) makes key recommendations in seven areas, three of which focus specifically on transition finance:

1. **Anchoring sustainability assessment in the EU Taxonomy**
   - Expand the Taxonomy to include all activities that can contribute to sustainability, including activities that can transition or need decommissioning.
   - Phase out the SFDR's flexible definition of sustainable investments, first making it more prescriptive and then replacing it with a Taxonomy-based approach.
2. **Strengthening tools for transition finance**
   - Legally define transition investments to facilitate transition-related financial products.
   - Expand disclosures to include revenues and CapEx linked to harmful activities undergoing transition or decommissioning.
   - Ensure consistency in transition planning disclosures across all regulations and levels (activity, project, company, and product).
   - Raise the ambitions of the EU Climate Benchmarks, e.g., by setting sectoral allocation constraints to promote real-world decarbonization, and develop dedicated transition benchmarks, e.g., benchmarks requiring year-on-year increase in share of investments aligned with the taxonomy.
   - Develop high-quality standards for transition/sustainability-linked bonds.
3. **Establishing a Product Categorization System including categories for sustainable and transition investments**
   - Design (retail-investor focused) categories in reference to investor preferences and targeted outcomes,
   - Ensure categorization follows clear, science-based, binding, and measurable eligibility criteria and impose transparency on the outcomes achieved to allow for evaluation of ambition and progress (for transition investments).
   - Require DNSH compliance for sustainable investments; allow harmful activities on a transitioning trajectory or being decommissioned, subject to safeguards.
   - Promote integrity through state-level supervision.

These recommendations address key gaps in transition finance by enhancing regulatory clarity, aligning efforts with market needs, and fostering a more effective sustainable finance framework.

TRANSITION FINANCE: CHARTING A PATHWAY FOR GLOBAL AMBITION

Transition finance is critical to addressing the climate challenge, enabling high-emission sectors to align with net-zero goals through higher-efficiency processes, retrofitting, and phasing out unsustainable assets. While sustainable investments fund activities already aligned with sustainability goals, transition finance bridges the gap for sectors requiring transformation, forming complementary pillars for systemic change.

Transition finance's contextual nature is key to its effectiveness. Decarbonization pathways differ across regions, sectors, and entities due to varying responsibilities and capabilities, necessitating tailored frameworks rather than one-size-fits-all solutions.

While transition finance is globally recognized as essential for achieving net-zero goals, jurisdictions have adopted varying approaches, ranging from principle-based to highly prescriptive. The European Union's Sustainable Finance Framework is often regarded as both highly prescriptive and the most advanced regulatory effort in the sustainable finance space. However, despite its high ambitions and comprehensive scope, it remains incomplete and incoherent in addressing the specific needs of transition finance. Predominantly geared toward sustainable investment, it lacks a robust framework to support the broader spectrum of transition activities essential for decarbonizing high-emission sectors.

This article has highlighted critical gaps in the trilogy of texts that form the foundation of the EU Sustainable Finance Framework. The Taxonomy Regulation is largely a sustainable investment taxonomy, with stringent technical criteria and safeguards that exclude the bulk of transitional activities. The environmental and social safeguards of the SFDR place urgent and *bona fide* transition investments beyond the scope of sustainable investment funds reporting under Article 9, which may still be prioritized by investors for their stricter sustainability criteria. Effectively differentiating the value of transition investment strategies reporting under the catch-all, sustainability-promoting Article 8 remains challenging, particularly for retail investors. Moreover, the interpretative leeway afforded to providers under SFDR renders comparisons across investment options difficult and creates risks of greenwashing and mis-selling. Finally, the deeply flawed Benchmark Regulation disincentivizes transition investments through the imposition of steep market-relative decarbonization requirements (combined with lax sectoral constraints), reliance on backward-looking metrics dominated by capital market momentum, and half-thought through exclusions. These three pieces of legislation also integrate inconsistencies and incompatibilities that create negative synergies, further undermining the effective deployment of transition finance at scale.

Private-sector initiatives have significantly contributed to defining and operationalizing transition finance. Early efforts focused on the sell-side, establishing guidelines for use-of-proceeds instruments and later advancing sustainability-linked debt frameworks suitable for entity-level transition financing. On the investor side, net-zero asset owner alliances have set a new benchmark for credibility and ambition. By emphasizing rigorous target setting anchored in science-based sectoral pathways, developing alignment criteria based on current performance and forward-looking metrics, and insisting on credible transition plans underpinned by appropriate CapEx and OpEx schedules and supported by robust governance and accountability, these initiatives have raised the bar for transition finance and real-world decarbonization. Together, these efforts have driven the evolution of sustainable finance from the funding of isolated 'green' projects to comprehensive, entity-wide transition strategies, while increasingly addressing critical frontiers of early-stage climate solutions and decommissioning.

Recent guidance from the EC and ESMA marks an important step. The EC Recommendation of June 2023 offers a foundational definition of transition finance, emphasizing its role in supporting diverse decarbonization pathways. It proposes linking financing mechanisms to science-based criteria and credible transition plans, while introducing safeguards to enhance integrity and minimize greenwashing risks. The ESMA Opinion of July 2024 takes a more reformative stance, recommending the development of a tricolor taxonomy to classify sustainable, transitional, and unsustainable activities. It calls for strengthened transition planning disclosures, ensuring consistency across all levels. It advocates for sustainable and transitional product categories anchored in science-based criteria and differentiated expectations in respect of harmful activities.

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[14] *The Recommendation does not call for an extension of the Taxonomy but puts forwards tools to address gaps in its coverage. It also suggests anchoring transition investments in the TR when possible, e.g., to define goals of transition plans in relation and capture incremental alignment.*

Looking ahead, the EU has an opportunity to lead by example, creating a sustainable finance framework that balances ambition with practicality. By integrating transition finance into its broader strategy and leveraging science-based tools, robust reporting systems, and clearly defined product categories and labels, the EU can set a global standard for channeling financial flows toward systemic decarbonization. Achieving this will not only support the bloc's climate goals but also provide a blueprint for global action against climate change.

For jurisdictions favoring principle-based approaches, the EU framework offers important lessons. Granting excessive leeway to product providers can undermine transparency and effectiveness. And while granular criteria bring clarity and accountability, they require extensive taxonomy work with lead times that may delay urgent climate action. Principle-based frameworks, by contrast, can foster flexibility and innovation, enabling firms to tailor their strategies to local and sectoral contexts while reducing compliance burdens. However, this flexibility must insist on science-based pathways, criteria, and metrics, and be paired with robust governance and accountability mechanisms to mitigate greenwashing risks and ensure alignment with sustainability goals. By fostering public-private collaboration, embracing evidence-based classification of transition activities and investments, and promoting transparent reporting of decision-relevant metrics, all jurisdictions can design effective frameworks that support investor choice and direct financial flows toward the transition at scale.

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