

# The Impact of Physical and Transition Climate Risk on Asset Valuation

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## **Abstract**

We argue that, from the point of view of an investor, separately handling transition and physical climate risk, as it is usually done, is not helpful. We show that there is a strong inverse relationship between the expectation component of transition costs and the expectation of physical damages, and how this relationship can be estimated. Our results indicate that the uncertainty in transition costs decreases as the abatement policy becomes more aggressive (and physical damage decrease), but remains large as a fraction of the expectation component. We also show that, with the definition we provide, the transition costs we estimate match well, but add information to, the corresponding quantities from the benchmark IPCC scenarios. We show that these findings have important implications for asset valuation.

# 1 Introduction

In the last decades regulators, policy makers and investors have paid a lot of attention to estimates of physical and transition climate risk. Physical risk is usually expressed as the difference in GDP at a given horizon between a world with no climate damages, and a world with climate damages and a given abatement and emission schedule.<sup>1</sup> Since a world without climate damage is a hypothetical counterfactual, more useful estimates of physical climate risk are obtained by taking the differences in GDP associated with different abatement policies – in which case the ‘business-as-usual’ terms cancel out. Despite its limitations (GDP is a *flow* at a given point in time, and poorly conveys the *cumulative* welfare implications to that horizon), this definition has the great advantages of being simple and unambiguous, and of not requiring any discounting, thereby avoiding the thorny question of the appropriate discount rate.<sup>2</sup>

When it comes to transition risk, the definition, and the very meaning of the expression, become much less precise. In a rather narrow meaning of the term, transition risk is sometimes associated with the cumulative costs incurred by companies to manage and adapt to climate change and to the attending regulations. (See, for instance, the definition given by the United States Environmental Protection Agency in EPA (2023).) The European Central Bank (Bua, Kapp, Ramella, and Rognone (2022)) takes a somewhat broader approach, and defines transition risk as the risk that ‘arises from the costly adjustment towards a low-carbon economy.’ An even broader meaning to the term is conveyed by the IMF, when it states that ‘transition risk results from changes in climate policy, technology, and con-

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<sup>1</sup>Sometimes physical risk is expressed as the difference in physical damages between a business-as-usual abatement and a given policy. This definition is more problematic, because it is not obvious what should be defined as a business-as-usual policy. See, in this respect, the exchange between Hausfather and Peters (2020) and Schwalm, Glendon, and Duffy (2020).

<sup>2</sup>The correct-discount-rate debate goes all way the way back to Sidgwick (1907) and Ramsey (1928). A contemporary take in this debate can be found in Stern (2007) and Nordhaus and Moffat (2017). The famous ‘wrinkle in time’ thought experiment is presented in Nordhaus (2007).

sumer and market sentiment during the adjustment to a lower-carbon economy’ (increased costs in energy are included in this definition – see Grippa, Schnuttman, and Suntheim (2019)). Sometimes the term ‘transition risk’ is given the meaning of the *additional* costs of decarbonizing the economy due to a rushed transition. The idea, as Aal, Wanvick, and Dale (2022) suggest, is that a ‘rapid transitions may increase [climate-related] risks even more’. Often, it is assumed that a hard decarbonization target will be met with certainty by a certain date, and that undue delays increase these additional costs (this is the approach taken, amongst others, by Bolton and Kacperczyk (2023)). It is not clear, however, what would impel a country or a company to reach a given decarbonization target almost at any cost, especially if the same country or company have only morosely followed the abatement path up to the point of the sudden transition. More fundamentally, the very term ‘transition *risk*’ is unhelpful: the word ‘risk’ implies variability and uncertainty; however, this variability should be superimposed on an expected transition *cost*. Distinguishing between what is expected and what uncertainty we have around this central estimate is obviously important, but rarely clearly articulated. Unfortunately, in common usage the two concepts are often conflated.

In addition, the two channels of value impairment, the physical and the transition one, are often analysed and estimated separately, and sometimes one of the two aspect is ignored altogether. Generally, more attention seems to have been devoted to transition than to physical risk – which is puzzling, since physical risk must be larger than transition costs for these costs to be willingly incurred in the first place. Yet Bolton and Kacperczyk (2023) find that transition risk appears to be priced in traded securities, but physical risk not so. Similarly, in the popular IPCCARWGIII (2021)-sponsored SSS-RCP scenario approach, physical risk is ignored, and agents in the underlying models do not react to higher damages by adjusting any aspect of their behaviour. At the opposite end of the spectrum, in the recent critique by Keen, Lenton, Giodin, Yilmaz, Grasselli, and Garret (2021) and Keen (2023) of the advice received by the UK pension fund trustees, the focus is mainly on

physical risk, and it is transition risk that now seems to be absent.

This state of affairs is less than satisfactory and, as we argue in Section 4, does not help investors. It is therefore with investors' needs in mind that we propose a comprehensive definition of transition costs as the total economic costs (understood as diversion of disposable income that could be used for consumption) needed to achieve a given level of decarbonization (emission reduction). There are several advantages from looking at transition costs in this manner. First of all, with this definition it becomes clear that physical and transition costs are two sides of the same coin, since the greater the transition effort, the more we can reduce both the expectation and the variability of physical damages. Second, the definition makes clear that any abatement policy will have *expectations* of associated physical damages and of transition costs, and a substantial *variability* around these two central estimates. Broadly speaking, the price of a low transition effort is higher physical damages. However, even high transition costs only reduce our *expectations* of physical damages, but still leave considerable uncertainty. This is why it makes a lot of sense to consider these four quantities (the two central estimates and the two uncertainties) jointly.

One may argue that our definition of transition risk does not answer the questions many investors ask. Transition risk, these critics may say, is often estimated in order to gauge how companies' cashflows (and hence their valuation) can be affected by the changes (technological, regulatory, etc) they have to undertake to comply with an exogenous abatement policy. This seems to be the meaning in EPA (2023), and this is the approach taken with discounted-cashflow valuation models. From this perspective, and given these goals, our definition seems too all-encompassing to be of use. However, we would argue that, to arrive at quantitative estimates of cashflow impairments, it is necessary to assess first the total transition costs, and then to estimate how these costs are spread among taxpayers (eg, via subsidies), consumers (eg, via carbon taxes) and producers (eg, via quantity controls, price controls or explicit taxes). Knowing how the cake is cut is obviously important, but we

would argue that knowing the size of the cake is even more so.

The approach we present can therefore be regarded as a top-down approach to estimating transition costs. Again, there are strong similarities with the analysis of physical damages, that can be carried out in a bottom-up (enumerative) manner, or following a top-down approach (say, using econometric approaches (as in Rudik (2020)), or macroeconomic methods, such as Computational General Equilibrium models). Exactly as in the case of physical damages, top-down approaches have advantages and disadvantages with respect to bottom-up methods. In a nutshell: the top-down approach that we present captures much better the global effects of decarbonization efforts on equity valuation, but cannot be easily apportioned to individual firms; the bottom-up approach knows about the transition costs of the individual firms, but gives us very few clues as to how these show be aggregated. Of course, the most profitable course of action is to explore both avenues of investigation, and to ensure that the two approaches ‘meet in the middle’.

In this paper we therefore try to improve on the current state of affairs in two directions: first, we define and distinguish between expectations and variability of physical and transition costs; second, we show how these quantities are related, and how the magnitude of one can be estimated given the magnitude of the other. More specifically, we use an extension of a popular Integrated Assessment Model (the Nordhaus and Sztorc (2013) DICE model) to estimate a robust relationship between physical and transition costs, and assess the degree of uncertainty associated with these estimates. To give a preview of our results, Fig 1 shows the nature of the relationship between physical and transitions costs that we manage to establish – in the case of uncertainty only in the exact pace of the abatement policy (left panel) and when the full variability of the state variables is taken into account (right panel). These figures prompt many questions: for instance, why do the physical losses in right-hand panel spread out so much? And why is the explanatory power of the physical damages reduced so much in the right-hand panel? In the body of the paper we explain

these features; we present how the ‘clean’ relationship in the left panel has been obtained; and we show how it can be justified. Already at this stage, however, the two figures clearly show how closely related physical and transition costs are, and how important it is to distinguish between expectations and variability for these quantities.

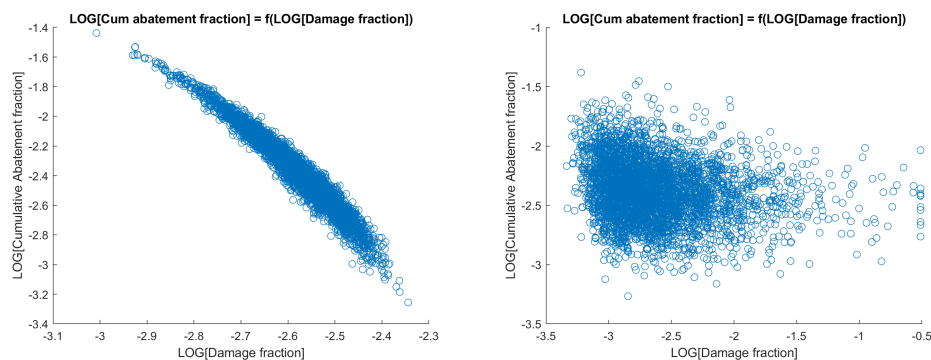


Exhibit 1: Left panel: the relationship between the logarithm of the fraction of GDP lost to physical damages ( $x$  axis) and the logarithm of the cumulative abatement fraction ( $y$  axis) when the only uncertainty is about the exact pace of the abatement policy. Right panel: The same quantities when the state variables of the problem are allowed to be stochastic. The cumulative abatement fraction is the sum of the abatement fractions encountered to the chosen horizon.

Finally, we show in Section 3.1 that one can establish a close, quantitative correspondence between important quantities produced by the benchmark IPCC-sponsored SSP/RCP scenarios and the transaction costs we estimate. We argue that the information that can be obtained from our model is richer than what afforded by the SSP/RCP framework for two reasons: first, because, by linking physical damages and transaction costs, our approach allows a more comprehensive appreciation of the economic effects of a given abatement policy; and second, because it adds a much-needed probabilistic dimension to the outputs of the probability-agnostic SSP/RCP scenarios.

We believe that our results are of direct interest to investors. As we explain in Section 4, investors are interested in the *combined* effect of physical and transition costs on valuation,

not in one or the other component in isolation. The approach we propose can provide a direct input to discounted-cashflow valuation models applied to equity indices, such as the approach pursued by NBIM (2021a), NBIM (2021b), by providing the *joint distribution* of the different sources of cashflow impairment. At a more general level, as we discuss in the paper (and as, at greater length, it is explained in Rebonato (2024)) transition costs are ultimately equivalent to a tax, that is likely to be levied on corporations rather than consumers. So, the more decisive the abatement policy, the higher the ‘effective corporate tax’ that companies will face. But Smolyansky (2023) has shown that the level of corporate taxation has played an important part in the equity price increases of the last thirty years, and has quantified this effect. Our treatment therefore gives investors a way to assess the headwind that global equity valuation will face under different abatement scenarios.

## 2 Definitions and Methodology

As mentioned in the introduction, we start from a popular Integrated Assessment Model (the Nordhaus and Sztorc (2013) DICE model), enriched so as to have stochastic economic output,<sup>3</sup> and uncertainty in the damage exponent as described in Rebonato, Dherminder, Melin, and O’Kane (2024). For reasons that we explain below, we do not use this model as an optimization tool, but simply employ its structure to link economic production to abatement costs on the one hand, and to CO<sub>2</sub> emissions, concentrations, and increases in temperature anomalies on the other. These are then used as input to the so-called damage function, the mapping, that is, from temperature increases to economic (physical) damages. We use for the damage function the formulation in Howard and Sterner (2017), that updates and corrects early results in the literature (as in Tol (2009), Nordhaus (1977)). The choice of the damage function is contentious, and we present our results based on this popular, but not universally accepted, functional dependence simply for illustrative purposes. If other damage functions were thought to be more suitable, the same procedure described below

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<sup>3</sup>The stochasticity in economic output is achieved by using the Bansal and Yaron (2004) long-term risk model, as adapted to climate-change problems by Jensen and Traeger (2014).

can still be followed. In our formulation, the damage function,  $\Omega_t$ , is assumed to have the form

$$\Omega_t = a_2 T_t^{a_3} \quad (1)$$

where  $T_t$  is the time- $t$  temperature anomaly (measured in C or K), and the exponent  $a_3$  is referred to in the literature as the ‘damage exponent’.

In the DICE model, part of the economic output is devoted to consumption and part is saved and invested, as in classic macroeconomic models. However, the agents in the model also realize that economic output contributes, through the non-decarbonized part of the economy, to CO<sub>2</sub> emissions, increased concentrations, temperature increases and hence (physical) damages. Therefore they decide to devote part of the output to costly abatement activities, that reduce the carbon intensity of the economy, and hence damages. When Integrated Assessment Models are used in a normative manner (by maximizing a welfare function), the abatement schedule and the savings rate are control variables, chosen so as to optimize the target welfare. In our study, we do not assume optimality, and allow for the possibility of suboptimal, politically-driven abatement policies. We are aware that this assumption flies in the face of the Lucas (1976, 1981) Rational Expectation Hypothesis, but we think that the wide divergence between the levels of the carbon tax recommended by most models and what has actually been implemented suggests that our assumption of non-optimality is not unreasonable. To give an example, as Litterman (2024) points out, the global emission-averaged carbon tax imposed worldwide was \$18.97/Ton in 2021, and plummeted to \$4.08/Ton in 2022, while a meta-analysis by Tol (2023) reports a median value for the optimal social cost of carbon elicited from professional economists of \$60/Ton. When it comes to climate change, in sum, agents in the real world do not appear to share what Muth (1961) calls the econometrician’s model.<sup>4</sup> Neither choice (to allow or not to al-

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<sup>4</sup>Far from sharing the econometrician’s model, Democrats and Republicans in the US do not seem to agree even on the information set on which they should condition their expectations: for instance, MacRight, Dunlap, and Xiao (2014) report that, in the wake of the unusually warm Winter of 2012, “Democrats [were] more likely than Republicans to perceive local winter temperatures as warmer than usual”. And Blumenthal



low agents to optimize) is unproblematic, but, in the light of these considerations, and of the current glacial pace of abatement compared with the recommendations of most economists, we have preferred the no-optimization assumption.

Irrespective of whether Integrated Assessment models are used in a policy-optimization mode or not, in the models the revenues from carbon taxes are channelled towards the abatement costs that the economy accepts to bear. The key point is that, since these abatement costs account for abatement, adaptation and carbon removal, they can be taken as a reasonable proxy for our definition of the transition costs. An Integrated Assessment Model such as DICE therefore establishes an (inverse) link between physical damages and transition costs. In its original, fully-deterministic, formulation the Nordhaus and Sztorc (2013) model gives rise to a very ‘sharp’ relationship between abatement and damage costs. When the state variables of the problem (say, economic growth) are instead made stochastic, the link between physical costs and abatement becomes noisy, and it is this uncertainty that gives rise to what we call transition *risk*, ie, the uncertainty around the central expectation. Whatever the definition, an Integrated Assessment Model therefore automatically offers, alongside the physical damages on which most users have focussed their attention, also a very reasonable proxy for aggregate transition costs. In the rest of the paper we quantify the nature of the dependence between these two quantities.

To do so, we proceed as follows. First, we have to characterize the aggressiveness of the abatement policy. We do so through a simple and powerful statistic, the effective abatement speed,  $\kappa$ , that controls the speed of abatement,  $\mu_t$ :

$$\mu_t = \mu_0 \exp(-\kappa \cdot t) + (1 - \exp(-\kappa \cdot t)) \quad (2)$$

This assumption that abatement should follow the pattern described by Equation 2 is much less restrictive than it may at first blush appear, because Rebonato, Kainth, and Melin (2021) finds that “72% of Democrats and Democratic leaners say they have noticed extreme weather events in their area compared to just 36% of Republicans and Republican leaners.”

(2024) show that a variety of abatement schedules producing the same terminal concentration can be associated with a single value of the abatement speed,  $\kappa$ . The speed-of-abatement function,  $\mu(t)$ , is then implicitly defined by

$$e_t = \sigma_t \cdot y_t \cdot (1 - \mu_t) \quad (3)$$

where  $e_t$  denotes industrial CO<sub>2</sub> emissions,  $y_t$  the gross economic output, and  $\sigma_t$  is the no-controls GDP intensity (emissions per unit of GDP). The results shown below refer to the case of a deterministic GDP intensity function,  $\sigma_t$ , that decays as a function of time (as in the original DICE model), but very similar results have been obtained when the function has been endogenized.<sup>5</sup>

We then choose a horizon,  $\tau$ , and an *expected* abatement,  $\mu_\tau$ , at this horizon. For instance, a policy target such as (near) complete decarbonization by 2050 would imply  $\tau = 25$  and, say,  $\mu_\tau = 0.95$ . We allow for uncertainty in this expected horizon abatement by assigning to this quantity a truncated log-normal distribution, with percentage volatility,  $s$ , and upper and lower truncation boundaries of 0.975 and  $\mu_0$ , respectively. To each of these sampled values for the function at time  $\tau$ ,  $\mu_\tau$ , we associate a horizon-dependent equivalent abatement speed,  $\kappa_\tau$ , which can be straightforwardly obtained from Equation 2 to be

$$\kappa_\tau = -\frac{1}{\tau} \log \frac{1 - \mu_\tau}{1 - \mu_0} \quad (4)$$

Fig 2 shows in its left panel for each time from today ( $x$  axis) the abatement functions,  $\mu_t$ , from the abatement speeds,  $\kappa_\tau$ , obtained from Equation 4, and shown in the right panel. The right panel shows the histogram of the abatement speeds obtained using Equation 4 for an expected time- $\tau$  abatement of  $\mu_\tau = 0.72$  with standard deviation of 8%. The histogram of the time- $\tau$  values of the abatement function,  $\mu_t$ , are then shown in the middle panel.

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<sup>5</sup>The endogenization was obtained by extracting from the original, deterministic DICE model the relationship between GDP/person and GDP intensity (the function  $\sigma$ ) and assuming that the same relationship (plus noise) would describe the link between GDP intensity and GDP/person when the latter quantity becomes stochastic.

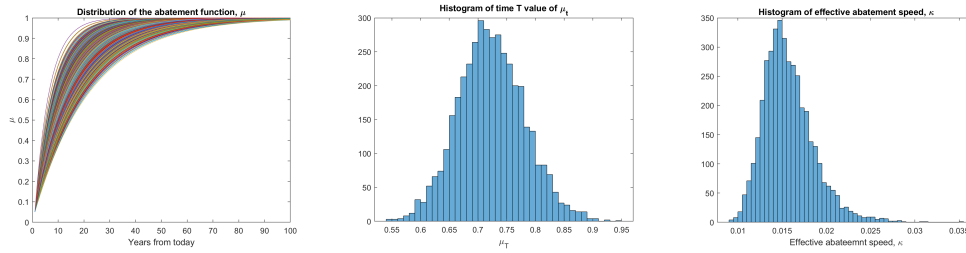


Exhibit 2: Left panel: for each time from today ( $x$  axis) the abatement functions,  $\mu_t$ , from the abatement speeds,  $\kappa_T$ , obtained from Equation 4, and shown in the right panel. Middle panel: histogram of the time- $T$  values of the abatement function,  $\mu_t$ . Right panel: histogram of the abatement speeds obtained using Equation 4 for an expected time- $T$  abatement of  $\mu_T = 0.72$  with standard deviation of 8%.  $T = 25$  years.

Since we have uncertainty in the horizon value of the abatement function, the time- $T$  physical damages will have a distribution, with an expected value and a variance. Two reasonable functions of physical damage are then the change in GDP growth between a world without climate damages and a world with climate damages and a certain abatement schedule, or the ratio of the GDP with and without climate damages,  $\tilde{GDP}_t$  and  $GDP_t$ . Focussing on this simpler quantity for simplicity, this can be easily shown to be given by

$$\frac{\tilde{GDP}_t}{GDP_t} = 1 - \Omega_t - \Lambda_t \quad (5)$$

The expectation of this loss is therefore a function of the expected value of the abatement (transition) costs and physical damages and of the (negative) covariance between the two. In addition, there will an uncertainty in this economic loss, which will be a function of the uncertainty in the physical damages and transition costs, and of the correlation between these two quantities. Intuitively, we expect that, the greater the abatement effort (the transition cost), the smaller the physical damage. It is this precise dependence that we set out to estimate.

### 3 The Dependence of $\Omega_t$ on $\Lambda_t$

In this section we focus on the estimates of the dependence of physical damages,  $\Omega_t$ , on abatement costs,  $\Lambda_t$ . To do so, we make the assumption that the damages at time  $t$ ,  $\Omega_t$ ,

should be a function of the cumulative abatement effort out to the same horizon, plus some residual noise:

$$\log \Omega_t = \log \left( \int_0^t \Lambda(s) ds \right) + \epsilon_t \quad (6)$$

where  $\Omega_t$ , as above, is the damage fraction,  $\Lambda_t$  is the fraction of GDP devoted to transition costs and  $\epsilon_t \propto N(0, \sigma^2)$ . From our calibrated Integrated Assessment we compute, for a given abatement schedule,  $\mu_t$ , characterized by an equivalent abatement speed,  $\kappa$ , the discretized version of Equation 6. We carry out this calculation for two cases:

1. when the expectation of the abatement schedule is known, there is uncertainty about the horizon value of  $\mu_T$ , but all state variables are deterministic;
2. when the expectation of the abatement schedule is known, there is uncertainty about the horizon value of  $\mu_T$ , and economic output and the damage exponent are stochastic.

When we do so, we obtain the clear relationship displayed in Fig 3, which shows the logarithm of the damage function at the horizon,  $T = 2100$  ( $y$  axis) as a function of the logarithm of the cumulative abatement fraction out to the same horizon ( $x$  axis), for the cases of expected abatements at the chosen horizon of  $\mu_T = 0.72$  (left panel),  $\mu_T = 0.60$  (middle panel) and  $\mu_T = 0.45$  (right panel) for the case where all the state variables are assumed to be deterministic. The three cases correspond to an abatement speed,  $\kappa$ , equal to 0.0156, 0.0109 and 0.0069 (the associated half lives are 44, 63 and 100 years, respectively).

As these figures show, there is a clear dependence between the cumulative abatement effort (that we take as a proxy for the transition cost) and the damages. Clearly, the stronger the abatement, the greater the transition cost. We also note for future reference that in this deterministic setting not only the expectation, but also the dispersion of the cumulative abatement costs increases as the abatement speed decreases.

In these figures the variability comes from the uncertainty in the abatement policy, but the state variables are still assumed to be deterministic. This significantly underestimates

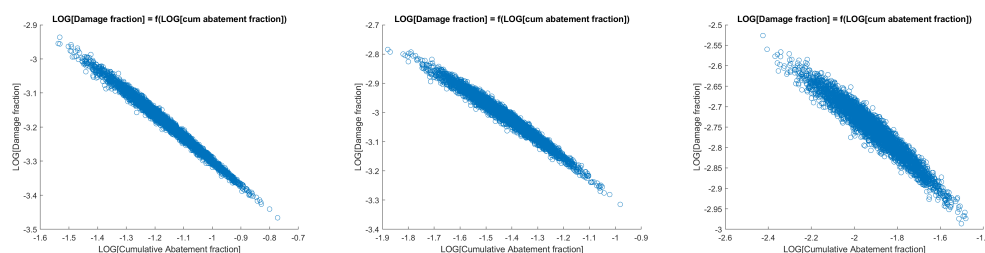


Exhibit 3: The logarithm of the damage fraction at the horizon,  $T = 2100$ , ( $y$  axis) as a function of the logarithm of the cumulative abatement fraction out to the same horizon ( $x$  axis), for the cases of expected abatements for an expected decarbonization target of  $\mu_\tau = 0.72$  (left panel),  $\mu_\tau = 0.60$  (middle panel) and  $\mu_\tau = 0.45$  (right panel) for  $\tau = 2050$ , and when all the state variables are assumed to be deterministic.

the overall variability. As a next step, we therefore switch on the uncertainty in economic output and in the damage exponent. The extra variability in physical damages and transition costs is clearly shown in Fig 4, which displays the same quantities presented in Fig 3, but for the case where the economic output and the damage exponent are assumed to be stochastic.

Why is the explanatory power of the cumulative abatement costs (as captured, say, by the  $R^2$  of the regression) so much lower? The answer lies in the large uncertainty about the damage function, which is the component of the economic modelling about which there is greatest uncertainty (see Kainth (2023) for a discussion). The resolution of this uncertainty over time is independent of the abatement policy, and therefore a great part of the dispersion in the damages for a given level of cumulative abatement depends on whether a high or a low damage exponent is revealed to be true.<sup>6</sup> In practice, this means that, *for a fixed abatement path*, damages can be much higher if a high damage exponent is revealed to be true, but abatement costs are not affected by this discovery (*physical* damages, of course, are). Since, as mentioned, there is great uncertainty in the damage function (particularly so, as Lenton, Held, Kriegler, Hall, Lucht, Rahmstorf, and Schellnhuber (2008) point out, in

<sup>6</sup>In our simulations we have capped GDP losses at 60%: this explain the ‘ceiling’ visible at the top of the three graphs.

the presence of tipping points),<sup>7</sup> this reduces the explanatory power of damages to account for transition costs.

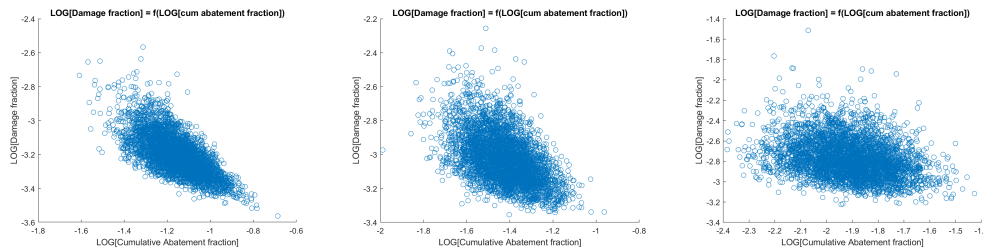


Exhibit 4: The logarithm of the damage function at the horizon,  $T = 2100$ , ( $y$  axis) as a function of the logarithm of the cumulative abatement fraction out to the same horizon ( $x$  axis), for the cases of expected abatements for an expected decarbonization target of  $\mu_\tau = 0.72$  (left panel),  $\mu_\tau = 0.60$  (middle panel) and  $\mu_\tau = 0.45$  (right panel) for  $\tau = 2050$ , and when the economic output and the damage exponent are assumed to be stochastic.

Given the dependence of the cumulative abatement costs on the abatement speed, and our choice of proxying transition costs by this quantity, we can ask another interesting question: how aggressive must the abatement policy be, for the transition costs to be below a certain value at a given confidence level? There are two competing effects at play: first, the higher the abatement speed (the abatement speed,  $\kappa_\tau$ ), the greater the abatement costs: the whole distribution will therefore shift upwards with increasing  $\kappa_\tau$ ; however, a higher speed of abatement reduces the dispersion around the expectation (reduces the pure transition *risk*), and therefore a high percentile does not grow as fast as the expected transition cost. Figure 5, which displays the expectation and the 90th percentile of the horizon-time distribution of cumulative abatement costs as a function of the terminal abatement,  $\mu_\tau$ , shows that this is indeed the case, but that the upward shift in the distribution due to increase in abatement speed dominates.

<sup>7</sup>As Alley, Marotzke, Nordhaus, and et al (2003) clearly point out, ‘[u]npredictability exhibited near climate thresholds in simple models shows that some uncertainty will always be associated with projections.’ Unfortunately, this means in practice that we may only conclusively know the location of the threshold of a tipping point once we have crossed it.

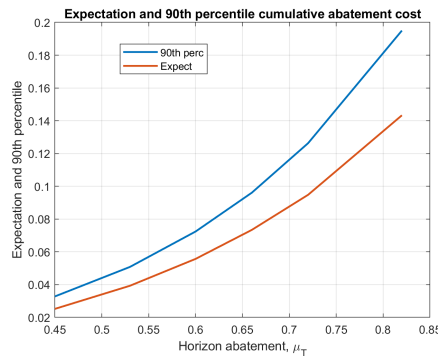


Exhibit 5: The expectation and the 90th percentile of the horizon-time distribution of cumulative abatement costs as a function of the terminal abatement,  $\mu_T$ .

### 3.1 Links with the SSP/RCP scenarios

Our approach to estimating physical and transition costs allows a very interesting link with the popular IPCC-sponsored SSP/RCP scenarios (see IPCCARWGIII (2021) and van Vuurem et al (2011)). With this approach the qualitative narratives described in five Shared Socioeconomic Pathways (SSPs) are matched with a number of Representative Carbon Pathways (RCPs). The latter describe the forcing (in  $\text{W}/\text{m}^2$ ) at the end of the century.<sup>8</sup> Since this quantity is a function of the  $\text{CO}_2$  emissions and concentrations, and these in turn can be linked to temperatures, the SSP/RCP approach links socioeconomic narratives with end-of-century temperatures. Quantitatively, in the SSP/RCP framework the link is carried out through Process-Based Integrated Assessment Models (PB IAMs), whose internal degrees of freedom are set so as to mimic as closely as possible the chosen narrative. (Despite their rather vivid descriptions, narratives ultimately specify the path of population, technological and economic growth: this is what makes their mappings to the parameters of the PB IAMs relatively easy). Once the parameters of the model have been set to reflect the narrative, a single degree of freedom is left to achieve the desired temperature (forcing) target: the carbon tax. In the RCP/SSP approach, all the carbon-tax transfers are assumed to be channelled to abatement activities, which are then chosen on the basis

<sup>8</sup>Forcing is the balance between energy in and energy out per unit time and per unit area.

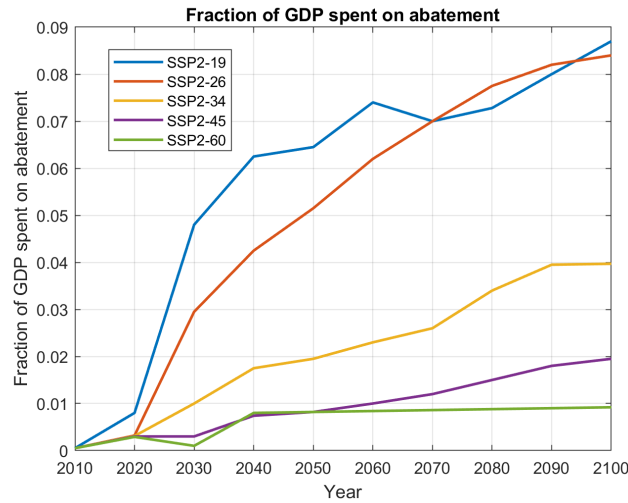


Exhibit 6: Model-implied carbon tax transfer for the SSP2 (“Middle of the Road”) narrative and forcings at  $T = 2100$  equal to 1.9, 2.6, 3.4, 4.5 and 6.0  $\text{W/m}^2$  (top to bottom).

of cost minimization from the marginal cost curves. It is important to note that, since PB IAMs are cost-minimizing but not welfare-optimizing models, there is no need to introduce climate damages in the approach.

The conceptual similarity between the SSP/RCP setup and the approach we have proposed in this paper is transparent. In particular, the cumulative abatement cost in our approach is the exact counterpart of the cumulative carbon tax levied in the SSP/RCP approach to hit a particular forcing target. Our model, however, adds two important components: a link between the transition and the physical-damage cost; and an estimate of the variability around these estimates. This can be seen more precisely as follows.

The most commonly used RCPs correspond to forcings ranging from 1.9 to 6.0  $\text{W/m}^2$ . We make use of a simple but reasonable linear mapping between forcings,  $F$ , and expected



temperature,  $\langle T \rangle$ , of the form<sup>9</sup>

$$\langle T \rangle = 0.5653 + 0.459 \cdot F \quad (7)$$

With this relationship the forcings of 1.9, 2.6, 3.4, 4.5 and 6.0 W/m<sup>2</sup> map into temperatures of 1.4, 1.8, 2.1, 2.6 and 3.3 C, respectively (all the figures refer to a end-of-century horizon). Given these targets, we can then easily calibrate the average abatement speed in our model to obtain any desired expected temperature. The abatement costs in our model are the equivalent of the carbon taxes in the SSP/RCP framework. Welfare-optimization studies invariably find that carbon taxes should grow over time (and this is what the cost-minimization SSP/RCP approach obtains as well). We therefore make the simplest assumption that the carbon tax as a percentage of GDP will grow linearly from today to the final horizon. A glance at Fig 6 suggest that the assumption is not unreasonable.

We are now in a position to compare the projections of abatement costs produced by the SSP/RCP framework and by our model. For illustrative purposes, we focus on year-2100 temperatures of 1.8 and 2.6 C (corresponding to forcings of 2.6 and 4.5 W/m<sup>2</sup>, respectively). When we look at the high-temperature, low-abatement RCP4.5 case, we find that the cumulative abatement cost (carbon tax) ranges from approximately 4% to 11%. With our assumption of linear increase in taxation, this corresponds to a year-2100 taxation level ranging between 0.57% and 1.57%. These values compare well with the terminal value of the corresponding curve in Fig 6 (second curve from the bottom).

We can repeat the exercise for the case of a 1.8 C temperature by year 2100 (which corresponds to an RCP of 2.6 W/m<sup>2</sup>). This is a low-temperature, high-abatement, high-cost case. Indeed, we find that the cumulative abatement cost (carbon tax) is now much higher, ranging as it does from approximately 35% to 55%. This corresponds to a year-2100 taxation level ranging between 5.0% and 7.9%. Again, this compares reasonably well with the value of a bit more than 8% obtained using the SSP/RCP framework, as one can read

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<sup>9</sup>The linear mapping has an  $R^2$  of 0.9811

from Fig 6 (second curve from the top).

We note that in our case we have a distribution of outcomes (corresponding to the different possible values for economic growth and damage exponent), while Fig 6 shows only *the* one value per RCP associated to the chosen narrative (SSP2 in the figure). Adding the values associated with the other narratives would of course create a spread of tax schedules also in the SSP/RCP case. However, this spread could not be interpreted as a distribution, because the SSP narratives are by design not associated with any probability. If one believes that the distribution of the state variables used in our version of the DICE model conveys reasonable probabilistic information, with our approach one can also estimate the likelihood of the different transition cost outcomes.

There is another important advantage associated with our approach: by making use of the information in Figs 3 and 4, one can now associate a distribution of physical damages to each transition cost, and obtain a more meaningful picture of the overall costs and damages associated with any chosen abatement policy. Again, a probabilistic dimension can be added to this combination, as shown in Fig 7 that displays the empirical joint distribution of the damage fraction and cumulative abatement fraction for the low- and high-temperature cases analysed above. Apart from the obvious shift in opposite directions for the distribution of damages and costs when a slower abatement schedule is chosen, note how the correlation between physical damages and transition costs increases with the aggressiveness of the abatement policy (ie, moving from the left to the right panel: for the parameters chosen, the correlation increases from 0.45 to 0.78 ). A world with a strong abatement policy, in other words, is more predictable not just in the climate outcomes, but also in the link between physical damages and transition costs. The residual variability comes, in our model, from the significant uncertainty in economic growth produced by the Bansal and Yaron (2004) model and in the damage exponent – two sources of variability that are by design absent in the output from the SSP/RCP scenarios.

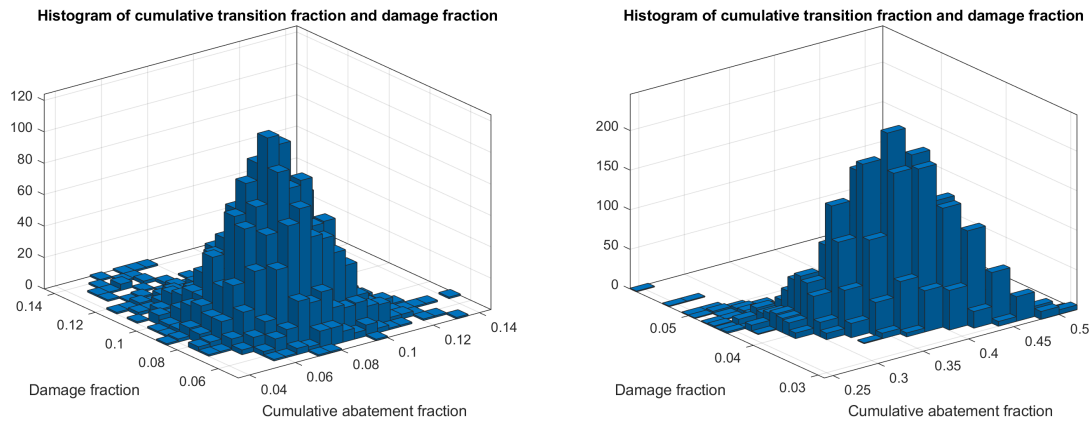


Exhibit 7: The empirical joint distribution of the damage fraction and cumulative abatement fraction. Left panel: year-2100 temperature = 2.6, right panel = year-2100 temperature = 1.8.

## 4 Investment Implications

Our findings have important direct and indirect implications for investors. The direct ones are transparent: the discounted-cashflow models often used to assess the impact of climate change on equity valuations usually start from a projection of future cashflows in the absence of climate risk, and then superimpose *all* the climate-related impairments to these cashflows. When equity indices are the target securities (as in the approach described in NBIM (2021a) and NBIM (2021b)) our approach directly provides the full distribution of the combined effects of physical damages and transition costs – see again Fig 7. And since, as Rebonato, Kainth, and Melin (2024) shows, state-dependent discounting can significantly affect equity valuation, our approach has the added bonus of providing, if required, state- and path-dependent values for damages and transition costs. As we have shown in Section 3.1, investors can also be confident that the estimates that our approach provides are in the aggregate consistent with the estimates produced in the popular SSP/RCP scenario approach.

There is, however, another important impact on valuation that only becomes apparent

at the aggregate level, and that our approach reveals. The reasoning goes as follows. As Rebonato, Kainth, and Melin (2024) discuss in detail, and as we have briefly argued above, transition costs are economically equivalent to a tax that ‘someone’ has to pay. Given how difficult it has proven to impose even modest direct carbon taxes on consumers, it is likely that this tax will be mainly levied on corporates. So, for corporates transition costs are ultimately equivalent to a higher corporation tax. But Smolyansky (2023) has recently shown that the level of corporate taxation has been an important determinant of equity price appreciation in the last 30 years, and has quantified this effect by using a model-independent approach (his results are fully based on accounting identities and empirical estimates). This means, that, depending on the aggressiveness of the abatement policy, one can estimate the equivalent ‘corporate tax’, and from this the associated valuation headwinds that global equities will face in the decades to come.

## 5 Discussion, Limitations and Conclusions

We have decomposed the transition costs associated with a given pace of decarbonization into an expectation component and an uncertainty term (and reserved the term ‘transition risk’ to this latter quantity). We have also shown that, at least within the confines of a relatively stylized model, there is a clear and strong inverse relationship between reasonable measures of economic damages (physical damages) and the associated transition costs. More generally, we have found that there are clear relationships between the first two moments of both distributions: the expectation of the physical damage costs, for instance, has an impact not only on the expectation of transaction costs, but also on their variability. This suggests that the analysis of transition and physical costs should be most profitably carried out in a joint manner, rather than in isolation, as has mainly been done so far.

We have also shown that our approach produces transition costs that are closely aligned with the carbon taxation burden derived by the benchmark SSP-RCP scenarios. Since the transition risk in the restricted, company-specific sense of EPA (2023) depends in great

part on how this taxation levy is spread between companies, consumers and present and future taxpayers, the quantification of the cumulative carbon tax is an essential piece of information for a top-down analysis. Our approach offers the added advantage that, unlike the output from the SP/RCP scenarios, it produces not only an estimate of the transition costs, but also their variability, and (the distribution of) the associated physical damages.

We stress that our estimates of the transition costs should be understood as a lower bound, because in our analysis we have assumed that the agents in our economy deploy their abatement resources in the most efficient way, by careful examination of the marginal cost curves of different abatement and removal technologies, as discussed for instance in Rebonato, Dherminder, Melin, and O’Kane (2024). Unfortunately, there are many examples of inefficient allocation of abatement resources, of which the case of ethanol subsidies, discussed in detail in Richter (2014),<sup>10</sup> is only one example amongst many. Deviations from cost minimization would necessarily increase transition costs. Also, a ‘rushed’ transition – a situation, that is, where an emission target *must* be met by a given date, but abatement policies are delayed until the last moment, causing a sudden catch-up of abatement initiatives – would plausibly increase transition costs.

We have provided some numerical results, but our contribution should be seen as mainly methodological: we have provided what we believe are reasonable results for our version of the popular DICE model, but we have not discussed in detail the precise choice of many of its components, such as the damage function. Different end users can, of course, make different choices for the various modules of their Integrated Assessment Model of choice, and these choices will obviously affect the quantitative results. However, the general idea of establishing a link between the distributions of physical damages and transition costs retains its validity for any *integrated* assessment model, *qua* integrated.

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<sup>10</sup>See Chapter 14 in particular.

Our findings should be of interest to policymakers, but, above all, to investors, because they afford a systematic way to assess the physical and transition impairments to the cashflows that are used as input to discounted cashflow models. Most importantly, our approach provides a *distribution* of climate-related cashflow impairments, from which an expected price can be consistently obtained.

## References

- AAL, C., T. WANVICK, AND B. DALE (2022): “Climate Risks of the Transition to a Renewable Energy Society: The Need for Extending the Research Agenda,” *Weather, Climate and Society*, working paper no 2677, 387–397.
- ALLEY, R. B., J. MAROTZKE, W. D. NORDAHUS, AND ET AL (2003): “Abrupt Climate Change,” *Science*, 299 (5615), 2005–2010.
- BANSAL, R., AND A. YARON (2004): “Risks for the Long Run: A Potential Resolution of Asset Pricing Puzzles,” *Journal of Finance*, 59(4), 1481–1509.
- BLUMENTHAL, M. (2021): “In 2021, Even the Weather Is Politicized,” *YouGov US*, August 14, 2021, <https://today.yougov.com/politics/articles/37350-2021-even-weather-politicized>.
- BOLTON, P., AND M. KACPERCZYK (2023): “Global Pricing of Carbon-Transition Risk,” *Climatic Change*, 78(6), 3677–3754.
- BUA, G., D. KAPP, F. RAMELLA, AND L. ROGNONE (2022): “Transition versus Physical Climate Risk Pricing in European Financial Markets: A Text-based Approach,” *European Central Bank*, working paper no 2677, 1–46.
- EPA (2023): “Climate Risks and Opportunities Defined,” *Reproduced from: Recommendations of the Task Force on Climate-related Financial Disclosures*, 50 (4), 57–91.
- GRIPPA, P., J. SCHNUTTMAN, AND F. SUNTHEIM (2019): “Climate Change and Financial Risk,” *IMF F&D*, pp. 1–4.
- HAUSFATHER, Z., AND G. P. PETERS (2020): “Emissions – The Business-As-Usual Story Is Misleading,” *Nature*, 577, 618–620.
- HOWARD, H. P., AND T. STERNER (2017): “Few and Not So Far Between: A Meta-Analysis of Climate Damage Estimates,” *Environmental and Resource Economics*, 68(1), 197–225.

- IPCCARWGIII (2021): “Climate Change 2022 – Mitigation of Climate Change,” Discussion Paper Chapter 12, WGIII WMO UNEP.
- JENSEN, S., AND C. TRAEGER (2014): “Optimal Climate Change Mitigation under Long-Term Growth Uncertainty: Stochastic Integrated Assessment and Analytic Findings,” *European Economic Review*, 69(C), 104–125.
- KAINTH, D. (2023): “Calibration of Temperature-Related Damages,” *ERCII working paper*, pp. 1–12.
- KEEN, S. (2023): “Loading the DICE Against Pension Funds – Flawed Economic Thinking on Climate Has Put Your Pension at Risk,” *Carbon Tracker*, pp. 1–84.
- KEEN, S., T. LENTON, A. GIODIN, D. YILMAZ, M. GRASELLI, AND T. GARRET (2021): “Economists’ Erroneous Estimates of Dmages from Climate Change,” *arXiv working paper 2108.07847*, Carbon Tracker, 1–6.
- LENTON, T. M., H. HELD, E. KRIEGLER, J. W. HALL, W. LUCHT, S. RAHMSTORF, AND H. J. SCHELLNHUBER (2008): “Tipping elements in the Earth’s climate system,” *Proceedings of the National Academy of Sciences*, 105(6), 1786–1793.
- LITTERMAN, R. (2024): “Can Financial Engineering Save the Planet? Overview of Carbon-Linked Bonds,” *EDEHC technical presentation*, pp. 1–8.
- LUCAS, R. E. (1976, 1981): “Economic Policy Analysis: A Critique,” *Carnegie-Rochester Conference on Public Policy*, Reprinted in *Studies in Business Cycle Theory*, (1981), MIT Press, 1:19–46.
- MACRIGHT, A. M., R. E. DUNLAP, AND C. XIAO (2014): “The Impacts of Temperature Anomalies and Political Orientation on Perceived Winter Warming,” *Nature Climate Change*, 4, 1007–1081.
- MUTH, J. F. (1961): “Rational Expectations and the Theory of Price Movements,” *Econometrica*, pp. 315–335.



- NBIM (2021a): *Climate Change as a Financial Risk to the Fund*. Norge Bank Investment Management.
- (2021b): *Modelling Equity Market Term Structures*. Norge Bank Investment Management.
- NORDHAUS, W., AND A. MOFFAT (2017): “A Survey of Global Impacts of Climate Change: Replication, Survey Methods, and a Statistical Analysis,” NBER Working Papers 23646, National Bureau of Economic Research, Inc.
- NORDHAUS, W. D. (1977): “To Slow or Not To Slow: The Economics of the Greenhouse Effect,” *The Economic Journal*, 101, 920–937.
- (2007): *The Challenge of Global Warming: Economic Models and Environmental Policy*. Yale University, New Haven, CT.
- NORDHAUS, W. D., AND P. SZTORC (2013): *DICE 2013R: Introduction and User’s Manual*. Yale University, New Haven, Connecticut USA.
- RAMSEY, F. P. (1928): “A Mathematical Theory of Saving,” *Economic Journal*, 45(3), 543–559.
- REBONATO, R. (2024): “Climate Physical and Transition Risk and the Valuation of Assets,” *EDHEC Riks Climate Institute working paper*, March 2024, 1–38.
- REBONATO, R., K. DHERMINDER, L. MELIN, AND D. O’KANE (2024): “Optimal Climate Policy with Negative Emissions,” *International Journal of Theoretical and Applied Finance*, pp. 1–32.
- REBONATO, R., D. KAINTH, AND L. MELIN (2024): “The Impact of Physical Climate Risk on Global Equity Valuations,” *EDHEC Riks Climate Institute working paper*, March 2024, 1–48.
- RICHTER, B. (2014): *Beyond Smoke and Mirrors – Climate Change in the 21st Century*. Cambridge University Press.

- RUDIK, I. (2020): “Optimal Climate Policy when Damages Are Unknown,” *American Economic Journal: Economic Policy*, 12(2), 340–373.
- SCHWALM, C. R., S. GLENDON, AND P. B. DUFFY (2020): “RCP8.5 Tracks Cumulative CO2 Emissions,” *Proceedings National Academy of Science*, 117(33), 19656–19657.
- SIDGWICK, H. (1907): *The Methods of Ethics*. MacMillan.
- SMOLYANSKY, M. (2023): “End of an Era: The Coming Long-Run Slowdown in Corporate Profit Growth and Stock Returns,” *Finance and Economics Discussion Series 2023-041*, Washington: Board of Governors of the Federal Reserve System, <https://doi.org/10.17016/FEDS.2023.041>, 1–31.
- STERN, N. (2007): *The Economics of Climate Change: The Stern Review*. Cambridge University Press, Cambridge, UK.
- TOL, R. S. J. (2009): “The Economic Effects of Climate Change,” *Journal of Economic Perspectives*, 23(2), 29–51.
- (2023): “Social Cost of Carbon Estimates Have increased Over Time,” *Nature Climate Change*, pp. 532–536.
- VAN VUUREM ET AL, D. P. (2011): “The Representative Concentration Pathways: An Overview,” *Climatic Change*, 109(5), 5–31.