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The scenario-based equity price impact induced by greenhouse gas emissions

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Non-technical summary

Research question

Since non-financial corporations contribute substantially to global greenhouse gas emissions, their decarbonization plays a decisive role in climate change mitigation efforts. In this context, approaches to quantify corporate risks induced by a transition to net zero carbon emissions have come to the fore. This study explores the equity price impact in response to an assumed revision of market expectations towards climate neutrality in 2050. Changes in equity valuations are modeled as a function of transition-induced incremental carbon costs and deviating output pathways, presuming that investors expect stock corporations to decarbonize at a Paris-aligned pace.

Contribution

We develop a forward-looking metric of transition-induced equity price adjustments at the firm level, which is based on the present value of projected dividend streams net of scenario- and firm-specific carbon costs. To discount these flows, we rely on returns on equity that are implicitly required on the stock market. We refer to scenarios from four multi-regional process-based integrated assessment models (IAMs) and combine regional, sectoral and energy carrier-specific projections these with firm-level dividend expectations and greenhouse gas emissions. Assuming a baseline scenario of continued current policies – and, alternatively, Nationally Determined Contributions –, we compute the equity price impact following an shock in market expectations towards a Paris-aligned transition pathway for 5,050 stock corporations. These firms account for half of the global equity market capitalization and 17% of global greenhouse gas emissions. We interpret the magnitude of derived valuation losses as a reflection of the firms' ability to bear projected carbon costs.

Results

Our analysis suggests that firms are exposed to heterogenous valuation changes across regions and sectors in response to a revision in market expectations. The resulting impact differentials are driven by the cost of greenhouse gas emissions of firms on the one hand and their financial performance on the other. Conditional on a Paris-aligned decarbonization, valuation losses remain in a single digit percentage range for a majority of firms under review. However, up to 18% of all firms (13% of market capitalization under review) lose more than half of their stock market value. The size and frequency of these losses depend largely on the assumed baseline scenario, the cost pass-through and the IAM scenario projections that we leverage. Since the carbon price trajectories required for a net zero transition vary across IAMs under review, this bandwidth is also reflected in derived equity valuations.

Nichttechnische Zusammenfassung

Fragestellung

Da nichtfinanzielle Aktiengesellschaften substanziell zu den globalen Treibhausgasemissionen beitragen, spielt ihre Dekarbonisierung eine entscheidende Rolle in den Klimaschutzanstrengungen. In diesem Zusammenhang werden verstärkt Ansätze zur Quantifizierung von Unternehmensrisiken diskutiert, die aus dem Übergang zu Klimaneutralität entstehen. Die vorliegende Studie geht der Frage nach, welchen Einfluss ein unterstellter Umschwung in den Markterwartungen hin zu Klimaneutralität in 2050 auf Aktienbewertungen ausübt. Bewertungsänderungen lassen sich dabei als Funktion der Mehrkosten von Treibhausgasemissionen und abweichender Outputpfade darstellen, wenn erwartet wird, dass die Unternehmen ihre Emissionen in Einklang mit dem Pariser Klimaschutzabkommen reduzieren.

Beitrag

Wir entwickeln ein Maß für transitionsinduzierte Wertanpassungen auf der Unternehmensebene. Darin werden künftige Dividendenströme abzüglich szenario- und unternehmensspezifischer Emissionskosten mit implizit am Aktienmarkt geforderten unternehmensindividuellen Renditen diskontiert. Unter Rückgriff auf Szenarien aus vier multi-regionalen prozessbasierten Integrierten Assessment-Modellen (IAMs) kombinieren wir regionale, sektorale und energieträgerspezifische Projektionen mit unternehmens-individuellen Treibhausgasemissionen und Dividendenerwartungen. Ausgehend vom Basisszenario fortgesetzter aktueller Politiken bzw. – alternativ – nationaler Klimaschutzzusagen berechnen wir Wertänderungen infolge eines Erwartungsschocks zu einem Paris-konformen Transitionspfad für 5050 Aktiengesellschaften, die rund die Hälfte der globalen Aktienmarkt-kapitalisierung und 17% der globalen Treibhausgasemissionen auf sich vereinigen. Das Ausmaß der Wertverluste interpretieren wir als Ausdruck der finanziellen Tragfähigkeit der projizierten Emissionskosten.

Ergebnisse

Unsere Analyse ergibt, dass ein Erwartungsumschwung zu einer Paris-konformen Transition regional und sektoral heterogene Wertänderungen zur Folge haben kann. Die gefundenen Unterschiede hängen sowohl von den Kosten der Treibhausgasemissionen als auch von der finanziellen Leistungsfähigkeit der Unternehmen ab. Paris-konforme Dekarbonisierungsfortschritte vorausgesetzt, bleiben die Wertverluste für einen Großteil der betrachteten Unternehmen im einstelligen Prozentbereich. Demgegenüber verlieren bis zu 18% der Unternehmen (13% der Aktienkapitalisierung) mehr als die Hälfte ihres Werts. Die Verlusthöhe und -häufigkeit hängen dabei maßgeblich vom unterstellten Basisszenario, der Kostenüberwälzung und den verwendeten IAM-Szenarioprojektionen ab. Dabei varriieren die für Klimaneutralität erforderlichen CO_2-Preispfade zwischen den IAMs. Diese Bandbreite spiegelt sich in den abgeleiteten Aktienwerten.

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Abstract

This paper proposes a forward-looking metric of transition risk that relates financial performance and incremental carbon costs at the firm level. To this end, we use a consistent dividend discount framework augmented with emission costs of firms and climate scenario projections from four large-scale integrated assessment models. Assuming a revision of market expectations from a baseline scenario to a net zero transition, we derive equity price impacts for 5,050 non-financial stock corporations covering half of global equity market capitalization and 17% of global greenhouse gas emissions. Our results suggest considerable disparities in firms' capacities to bear the scenario-implied costs of direct emissions. While especially fossil fuel energy firms and large emitters are exposed to potentially high devaluations and stranding, the majority of capitalization under review is exposed to moderate losses in a single-digit percentage range. We present the bandwidth of results across IAMs under alternative baseline scenarios and cost pass-through assumptions.

Keywords: Transition risk, Asset pricing, Carbon price, Paris alignment, Stranded assets
JEL-Classification: G12, G15, Q42, Q51, Q54

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1 Introduction

This paper proposes a forward-looking metric of transition-induced impacts on asset prices. We investigate how an assumed climate transition shock may affect the corporate sector in terms of equity valuations. Since the non-financial corporate sector contributes substantially to global greenhouse gas (GHG) emissions, its decarbonization plays an important role in global mitigation efforts. To become Paris-aligned and contribute to limiting global warming to 1.5°C (median value), firms must curb their emissions by substantial degrees. One way to quantify the required decarbonization is to leverage projections from large-scale multi-regional process-based integrated assessment models (IAMs). These models are able to derive socioeconomic and climate forcing pathways which form a scenario. They represent the interactions between the global climate system, regional land use and energy systems, and the overall economy. If a transition towards net zero carbon emissions is targeted, these IAMs allow the derivation of feasible, cost-effective transformation pathways. Ultimately, these pathways are a function of social, economic, technological and energy-related factors as well as policy choices.

In the present study, we refer to climate-economic transition scenarios from IAMs to project dividends and emission costs at the firm level. We assume that financial investors currently do not expect the corporate sector to be on track to net zero emissions, taking into account a continuing high demand for fossil fuels, continuing investments in fossil energies[1] and a deep decarbonization lacking behind in most world regions.

Although IAM projections based on climate scenarios are increasingly used in the macroeconomic literature, such projections are less frequently applied at the firm level to date. We propose a novel firm-level approach that combines firm-level dividend expectations from analyst surveys (*IBES*) with actual firm-level emissions (*ISS-ESG*) and long-term IAM projections.[2] The proposed valuation framework is applied to a set of 5,050 listed non-financial stock corporations domiciled in 72 countries. In 2020, these firms accounted for about half of the global equity market capitalization and 8.5 gigatonnes of GHG emissions. Under a *Net Zero 2050* scenario, all firms are projected to reduce their emissions at a Paris-aligned pace – in line with IAM-implied technological progress, energy efficiency gains and shifts in energy mixes. Based on GICS industry classifications, we regroup the firms into 14 sectors, with a special focus on large emitters and fossil energy-based firms. To the extend that *ISS-ESG* provides this information, we also account for their revenue shares by energy carrier: in this case, future dividend flows are projected on the basis of scenario-specific energy production pathways.[3] In other cases, we assume long-term dividends to evolve in line with IAM-implied growth rates of GDP or sector output.

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[1] See International Energy Agency (IEA), 2024a. Global investments in energy amounted to USD 3 tn in 2023, but only USD 1.9 bn has been invested in clean energy. Moreover, according to the IEA, 2024b, oil and gas producers account for only one per cent of global green energy investment.

[2] *IBES* refers to analyst forecasts by the *Institutional Brokers' Estimate System*, data provided by Refinitiv / Thomson Reuters.

[3] Hereby we take into account the substitution of energy carriers which is key in the transition process. Figures A.7a and A.7b illustrate the production trajectories of fossil fuels and alternative energy carriers under the *Current policies* scenario and under the *Net Zero 2050* scenario, respectively.

To discount the future dividend stream net of projected emission costs, we derive and apply an implied expectations-based return on equity for each firm. On this basis, we fill a research gap by quantifying equity price adjustments under the assumption that investors reassess global climate policies and shift their expectations towards a deep transformation of the economy. The indicator we propose combines firm-level data with macroeconomic scenario outcomes from IAMs – including carbon prices, GHG emissions, and output pathways – and translates this back into equity valuations at the firm level. It can be used to improve the assessment of climate transition risk in financial portfolios. As frequently argued, transition risk relates to firm's absolute GHG emissions rather than their emission intensities because the carbon neutrality goal requires absolute emission reductions. This is also reflected in empirical literature where the sensitivity of stock returns to absolute emissions is found to be significant while the sensitivity to emission intensities is not.[4]

To approximate model uncertainty, we display the spectrum of our results across different IAMs. We motivate this exercise with the key role financial markets are expected to play in the process of a low-carbon transition. A strong price differentiation of assets along their - expected - carbon content and associated costs is indispensable to spur transition financing and redirect investments from heavy polluters to low-carbon businesses. To this end, GHG emitters and fossil energy firms need to be subjected to the expected cost of carbon and its economic effects, and asset markets can provide incentives to decarbonize.[5]

As a contribution to this discussion, we suggest that the extent of such a price differentiation will depend on the capacity of firms to bear incremental emission-induced costs along the transition. Here, we claim that dividend expectations of analysts can approximate a firm's financial capacities to bear such unexpected costs.

This boils down to the question of what markets currently expect. While investors are becoming increasingly climate aware and recent studies suggest that carbon risk premia are priced in to some extent, it remains unclear whether these reflections are economically meaningful in terms of supporting a net zero transition. Although firms increasingly express their intentions to better manage climate risks[6] – and despite official pledges to cut emissions –, it remains unanswered whether investors are sufficiently aware of potential transition impacts and what scenario is currently priced into asset markets.[7] Several barriers for a coherent pricing-in are conceivable, and a number of deep uncertainties prevail: what climate policies will be implemented, how steep the rise in carbon prices will be, and what energy sources will be drawn on. The pace and scope of firms' decarbonization efforts will be conditional on expected policies and the availability of substitution technologies. On the financial market side, other obstacles refer to fiduciary duties of investors, an inadequate disclosure of carbon footprints at the issuer level, and regional differences in regulation and reporting standards. Moreover, the pricing-in of a transitioning could

[4] See e.g. Bolton and Kacperczyk (2021a) or Aswani et al. (2024).
[5] See e.g. Karp et al. (2021) for a corresponding analysis with endogenous asset prices.
[6] See ISS-ESG (2022).
[7] See Germanwatch and New Climate Institute (2022). Accordingly, no country performed well enough in all index categories to achieve an overall very high CCPI index rating which would be consistent with the Paris climate goals.

be at stake if high-carbon investments are perceived to imply a favorable risk-return profile: Battiston et al. (2021) warn that in this case, the financial system may impede a low-carbon reallocation of capital, thereby lowering the chances of stabilizing the climate in an orderly way. Against this background, we explore equity price effects under the assumption that global financial markets currently reflect no substantial low-carbon transformation.[8] As a worst case, we assume that investors currently expect a continuation of business-as-usual policies, with firms in many world regions being ill-prepared for a transition. Viewed through this lens of transition risk, a substantial transitioning would yet have to be priced in. However, there is uncertainty about what baseline scenario is currently reflected in market expectations and stock prices. Therefore, we also look at a more optimistic baseline where it is assumed that current national climate pledges are priced in.[9] In both cases, we make the simplifying assumption that a revision towards an ambitious transition policy scenario comes as a shock and for all investors alike.

To measure how such a revision would affect equity prices, we combine an equity valuation approach with firm-level carbon footprint data and the outcome of scenario projections that are run in four different IAMs. The 'flagship' transition scenario we focus on is that of a timely and successful transition to net zero emissions in 2050, as outlined by the NGFS.[10] Using this scenario, the aforementioned IAMs provide a range of projections for a set of variables. We take this range as a proxy for model uncertainty.

As a first result, the majority of stock market capitalization under review is exposed to no more than single digit losses. At the other end of the spectrum, up to 13% of total equity capitalization is exposed to sharp devaluations of more than 50%. Among the latter, a large exposure relates to firms primarily active in fossil fuel sectors or emission-intensive industries.[11] As a result, transition-induced output pathways of fossil fuel-oriented firms suggest that they have limited capabilities to bear incremental emission costs.

Some stock corporations are also exposed to the risk of stranding within the next three decades, defined as a shortfall of expected financial performance[12] relative to incremental carbon costs. Applying this definition to our sample, we find that between 8% and 17% of all stocks (5% to 13% of the capitalization) will get stranded under a zero pass-through of emission costs, and between 4% and 8% of all stocks (2% to 6% of the capitalization) will be subject to stranding under an 80% cost pass-through.

[8] This assumption is corroborated by recent assessments. The International Energy Agency (2021, 2024a) finds that the post-Covid rebound of coal demand in 2021 (beyond 2019 levels) was driven by an increase in coal-fired power generation in Asia, and coal investments have been rising steadily since then. According to McGlade and Ekins (2015) the rapid exploitation of territorial fossil fuels, the resource development in the Arctic and the rise in unconventional oil production are incommensurate with policy commitments to limit average global warming to 2°C. Furthermore, Moody's (2021) warns that there is a lack of preparedness for a net zero transition in emission-intensive sectors.

[9] The scenario of *Nationally Determined Contributions* (*NDCs*) reflects national decarbonization targets and pledges in the wake of the Paris Agreement. See Roelfsema et al. (2020).

[10] This study relies on NGFS Phase III scenarios released in 2022, see DOI: 10.5281/zenodo.7085776. Phase III refers to the third scenario development cycle (REMIND, MESSAGE, GCAM) within the NGFS.

[11] These results refer to stock prices and analyst expectations in 2020. Sensitivity analyses point to somewhat impaired results for 2021.

[12] Here, we approximate financial performance by extrapolating expected dividends (*IBES analyst forecasts*) using scenario-based output projections.

Secondly, price adjustments indicate a high dispersion across sectors: While firms in renewable energy businesses tend to benefit from an ambitious transition, stocks of large emitters and firms active in fossil fuel businesses exhibit highest losses. However, sector averages vary across IAMs, pointing to some degree of model uncertainty. Thirdly, a more granular breakdown suggests that model uncertainty is limited within many region/sector combinations. At the same time, we find that some sectors (chemicals, utilities, other mining and metal processing, transport and infrastructure) are exposed to considerably different price impacts across regions. One reason is that the cost of energy is a function of available resources in the respective region.

The remainder of this paper is structured as follows: Section 2 briefly reviews the literature on scenario-based transition risks and outlines the contribution of this paper. It also sets out how scenario projections of IAMs are taken into account. Section 3 presents our emission-induced price impact indicator. Section 4 proposes an application of this metric to direct GHG emissions and describes the global sample of firm-level data we use. Section 5 presents the results, and Section 6 concludes and sets out avenues for future work.

2 Measuring scenario-based transition risk of equities

While measurement challenges and risk management issues prevail, the financial implications of climate risks have become a focal point for academics as well as for firms, financial markets, financial institutions, supervisory authorities and central banks. Despite a growing awareness of the need to tackle these risks, it remains unclear which climate path societies will ultimately choose as well as the physical versus transition risks that will come as a result. Eventually, both of them are likely to strike down as financial risks – either in the form of revised expectations or in the form of unanticipated shocks. On the one side, minimal mitigation policies paired with business-as-usual emissions will entail unprecedented climate-related damage.[13] On the other side, mitigating climate change will reduce physical damage but mean transitioning to a low-carbon economy with non-negligible, far-reaching implications for economies. While the associated risks comprise a range of economic, legal, reputational, political and technological factors, we focus on potential transition-induced valuation losses of assets.

This study relates to several strands of the literature, including those that deal with the phasing-out of fossil fuels and its implications on stranding – defined as a premature or unexpected writedown of assets.[14] One aspect of the literature has focused on the maximum amount of carbon

[13] At least in the long run, damages are likely to comprise financial effects resulting from food shortages, productivity losses, wealth destruction, new diseases and other impacts on human and physical capital. Unless the rise in atmospheric concentration of carbon dioxide is stopped, the frequency and intensity of climate-related damages to nature and to economies will continue to increase. Dietz et al. (2016) and Rudebusch (2021) state that climate change will entail losses of financial assets for many economic actors. In addition, they claim that the uncertainty about the timing and size of these losses will be a source of risk.

[14] See, for example, Di Virgilio et al. (2024), Cormack et al. (2020) and Vermeulen et al. (2018).

emissions compatible with current global climate objectives, concluding that substantial portions of existing fossil fuel reserves are “unburnable carbon” (see Meinshausen et al., 2009; McGlade and Ekins, 2015; Welsby et al., 2021). Since this would render a substantial proportion of fossil fuel assets worthless, fossil energy industries face the risk of stranding. In their approach to quantifying stranded assets, Semieniuk et al. (2022) estimate lost profits in the upstream oil and gas sector at more than US$1 trillion under a presumed realignment in climate policy expectations.[15] Aside from fossil fuel producers, stranding may also affect other firms and emitters arising from policies to curb GHG emissions, from the breakthrough of new low-carbon technologies or shifts in demand away from fossil fuel-linked products and services.[16]

While the risk of stranding is intensely discussed as a result of climate policies, transition-induced price effects go beyond asset stranding. Empirical studies in this field estimate the asset price response to news or transition-related events, quantify the effects of structural differences between high- and low-carbon assets, or estimate the term structure of carbon risk premia.[17]

A subset of this literature focuses on scenario analysis as a tool to assess the consequences of climate policy choice. Various approaches have been proposed to quantifying the impact of a shift towards a net zero transition scenario on asset values. A commonality of many studies is the use of scenario projections from process-based IAMs, inter alia in macroeconometric and sectoral production network models.[18] Here, a recent strand proposes metrics of asset price impacts that rely on climate scenarios.[19] While a part of the scenario-based literature focuses on fossil fuel assets and their potential stranding, other scenario-based analyses quantify asset price effects for a broader set of firms.

A key motivation to apply forward-looking climate scenarios is rooted in the fact that the data history does not offer transition events in a similar fashion to what might unfold under a transition to a low carbon economy. For example, although recent periods of global energy crisis’ has temporarily driven fossil fuel prices to relatively high levels, the required shift towards renewable energies – including large-scale adjustments in the energy infrastructure – still falls short by factors. For one, since the current rise in fossil-fuel prices is not climate policy-driven, it is uncertain whether energy prices remain at the current level. In addition, changes in energy commodity prices during times of crisis result in changes to both consumer paid and producer

[15] Using a global equity network, Semieniuk et al. (2022) quantify revision-induced losses for 43,439 oil and gas production assets and trace them back to their ultimate shareholders.

[16] Many studies find that the transition towards a low-carbon economy could entail substantial volumes of stranded assets. See, for example, ECB, 2021, Climate change and monetary policy in the euro area, ECB Strategy Review, Occasional Paper No 271, September 2021.

[17] For studies on carbon risk premia, see, e.g., Engle et al. (2020), Xia and Zulaica (2022) or Bolton and Kacperczyk 2021a). Bolton and Kacperczyk conclude that the Paris Accord led investors to update their beliefs about the long-term impact of climate policy tightness. Hengge et al. (2023) analyse how carbon emissions affect the relationship between European stock returns and carbon prices over the period 2011-2021. They conclude that policies which increase carbon prices are effective in raising the cost of capital for high carbon emission firms.

[18] For approaches to estimate sector effects of climate transition policies, see Jorgenson et al. (2018), Frankovic (2022) and Jung et al. (2023). For example, sectoral production network models are applied to derive transition impacts on asset prices. Frankovic (2022) simulates sector impacts of scenario-based future carbon prices in a multi-region production network model. For macroeconomic top-down approaches, see also Vermeulen et al. (2018), Allen et al. (2020), Banque de France (2021) and ECB/ESRB (2021).

[19] see Jebeli et al. (2022).

received prices, which differs from what might unfold as a result of climate policies like carbon taxation. Against this backdrop, the current price increases in energy markets cannot simply be taken as a transition event, and financial markets might even expect fossil fuel prices to return to lower levels.

Contribution: A scenario-based transition risk metric at the firm level

To date, there are still relatively few studies on global asset valuation that apply climate scenario projections at the firm level.[20] The present exercise proposes a granular scenario-based equity valuation approach to transition risk. It consists in a firm-level indicator of emission- and output-induced equity price effects that differs from the existing approaches in several respects. First, we incorporate forward-looking returns on equity for each stock corporation as a reflection of current risk perceptions of investors. To derive it, we rely on survey-based dividend expectations from analyst forecasts. Second, we incorporate revenues from single energy carriers, as far as available. Third, we use firm-level data on initial GHG emissions. Finally, apart from firm-specific data, the indicator incorporates IAM projections. Besides a macroeconomic module and a modeling of the climate system, these IAMs contain a detailed representation of regional energy and land-use systems. By means of such models, globally consistent scenario projections can be derived for the economy and the energy system for a given climate target at the end of the 21st century, including scenario-specific carbon price trajectories at the regional level. To quantify the impact on listed stocks under an expectations shock, we leverage IAM projections of carbon prices, GHG emissions, the supply of energy carriers, GDP and selected sectoral production pathways.

Definition of an expectations shock and scenarios under review

We define the expectations shock as a shift from a baseline scenario to a transition towards carbon neutrality from 2050 onwards. We focus on the *Net Zero 2050* transition scenario designed by a consortium of model developers under the auspices of the NGFS, which includes ambitious carbon pricing policies.[21] When equity investors revise their expectations accordingly, we assume them to expect that stock corporations will curb their GHG emissions at a Paris-aligned pace.[22] That is, a firm is assumed to cut emissions at scenario- and model-implied rates for the region and, where available, the sector to which the firm is attributed. Should this prove true, stock corporations would sustain an incremental cost burden up to the point where the decarbonization effect offsets the carbon price-induced cost push. In the models under review, the decoupling of

[20] In this regard, the Banque de France (2021) proposes an analytical framework to quantify climate transition scenarios and assess the associated financial risks. Battiston et al. (2017) and Roncoroni et al. (2021) examine risk exposures in financial portfolios of institutional investors and explore the question as to how climate policy risks might propagate through the financial system.

[21] The NGFS scenario narratives were co-designed by NGFS members and IAM modelers at PIK, IIASA, and CGS. See https://www.ngfs.net/ngfs-scenarios-portal/ for an explanation of the narratives.

[22] Opposingly, should firms fail to decarbonize or even increase their emissions despite high carbon prices, a higher cost burden would result, followed by significantly higher equity losses. Here, we stick to the IAM output projections and emission reductions. Thereby we implicitly assume that financing costs do not increase in times of economic stress, and we disregard output losses due to a carbon price-induced financial accelerator.

emissions and production is driven by energy efficiency gains and progress in substitution technologies of fossil energy carriers. Within a sector and a region, substitution elasticities are assumed to be identical across firms.[23]

As regards the adequate choice of a baseline scenario, extracting expectations that underlie current asset prices is challenging. Therefore we apply two alternative baseline scenarios and quantify a range of possible outcomes: Besides the *Current Policies* baseline scenario which is geared to a hot-house world – as it assumes the absence of any carbon price policies beyond the status quo, we apply the *Nationally Determined Contributions (NDCs)* scenario as an alternative baseline.[24] Given the uncertainty as to which baseline scenario adequately reflects current market expectations, this study uses both baselines to quantify the range of possible equity price impacts. While the shift from the *Current policies* scenario to *Net Zero 2050* can be regarded as a worst case scenario for large emitters, smaller valuation losses will turn out if emitters are currently expected to decarbonize in line with *NDCs* pledges. While the latter may better reflect market expectations for sectors and regions where investors think that national mitigation pledges are more likely to be implemented.[25]

For each stock corporation in our sample, equity investors are assumed to foresee its future dividends. Dividend projections are made on the basis of two sources: short- to medium-term dividends are available from *IBES* surveys on analyst forecasts at the firm level. In the long-run, nominal dividends are expected to evolve proportionally to regional and sectoral output projections (plus an inflation assumption). To project long-run dividends, we follow Battiston et al. (2021) who approximate future dividends in proportionality to IAM output projections. Moreover, when calculating future carbon costs, we disregard the possibility that firms' emissions deviate from the aggregate decarbonization pathway: at time *t*, equity investors are assumed to start to anticipate that firms will decarbonize their businesses homogenously in line with IAM projections for the region and the sector the firm belongs to.[26] In the case of a net zero transition, we dub this path as being Paris-aligned. At the same time, to the extent that data are available in *ISS-ESG*, we account for individual revenue shares by energy carrier (as of 2019).[27] Here we assume that firms shift their revenues to non-fossil energy income, in line with the model-specific

[23] In the IAMs under review, shifts in the provision of and demand for energy carriers are a function of energy prices and the substitution elasticities by energy carrier. Energy prices are influenced by the carbon price level.

[24] The implementation of the *NDCs* scenario is based on Roelfsema et al. (2020). Compared to the *Current policies* scenario, it is more optimistic because existing national climate policy pledges are put into effect. We follow recent studies and introduce *Current policies* and *NDCs* as alternative baselines scenarios. See, e.g., Roncoroni et al. (2021), Battiston et al. (2021), and Semieniuk et al. (2022). While Semieniuk at al. (2022) who leverage IAM projections for oil and gas prices and corresponding oil and gas demand to measure potential equity losses, our metric traces potential equity losses back to output deviations and the incremental cost of GHG emissions.

[25] While the *Current policies* scenario may be an appropriate baseline scenario for some sectors and world regions, other sectors such as the automotive sector are likely to reflect a pricing of national climate mitigation pledges in a number of countries.

[26] In the absence of projections of greenhouse gas emissions for the sector to which the firm belongs, we apply the rate at which regional aggregate emissions are projected to decline.

[27] We use firm-specific revenue shares and GHG emissions data referring to 2019 (pre-Covid). This allows us to abstract from the subsequent pandemic-driven dip in greenhouse gases.

use of energy carriers.[28] We consider the focus on energy carriers important, because a successful transitioning requires a substantial readjustment of the energy mix at a global scale. To be adequately reflected in asset prices, a prerequisite is that investors have the same views on substitution elasticities as in the IAMs under review, including the response of the energy mix to energy prices and carbon prices.[29]

Purposes of the approach

We use the proposed impact metric to derive a bandwidth of results under alternative sets of baseline scenarios, IAMs, and pass-through assumptions. At the IAM level, a changing carbon price trajectory affect aggregate and sectoral output as well as the supply of energy carriers. At the same time, the sum of factor costs in the production function equals output, which the producer sells. Accordingly, the total amount of factor costs, including the cost of GHG emissions and other energy-related costs net of subsidies, are passed on to the firms' clients – ultimately to the consuming households. While in the IAMs under review, the zero profit condition implies that there is no markup that allows for dividends, our valuation approach allows for capital income in the form of dividends. A second deviation is that we do not assume a complete cost pass-through: instead, we quantify equity price impacts if all or part of these costs are to be borne by the firm – e.g. if its price-setting power is weak.

This serves several purposes. From a macroeconomic angle, the effects of a revision in transition expectations can be gauged in a bottom-up quantification to assess the potential transition-induced sectoral and regional financial market exposure that is induced by emission costs, different energy usage and deviating output pathways under a set of assumptions.[30] Secondly, individual firms may wish to quantify their potential cost burden as a function of own emissions and their fossil fuel dependence on the one side and future transition policies on the other – given a shift towards higher climate policy ambition levels. Thirdly, investors who are engaged in polluting firms may view it through the lens of financial risk: if a firm's carbon emissions are high at given dividend expectations, a steeper path of carbon prices can raise its cost burden and depress its stock value. In this regard, we claim that our firm-level scenario-based metric complements the transition risk indicators investors wish to look at.

[28] Owing to data limitations in *ISS-ESG*, only part of the firms in our sample can be assigned to energy sectors that are modeled in the IAMs under review (coal, oil, gas, wind, solar, geothermal, hydro, biomass, nuclear). Additional firms can be assigned to the steel, cement, transport and chemicals industries that are explicitly modeled in these IAMs too. Instead, if a firm belongs to other sectors, we rely on regional GDP growth. To project nominal long-term dividend growth of a firm, we incorporate an inflation assumption of 2 per cent.

[29] Note that the IAMs under review differ in several dimensions, including substitution elasticities between fossil fuels and climate-friendly energies. We assume that investors expect what is assumed in the respective IAM. For example, in the REMIND model an optimal choice is made between competing technologies to convert primary energy into secondary energy carriers on the basis of investment costs, fixed and variable operation and maintenance costs, fuel costs, emission costs, efficiencies, lifetimes and learning rates. As well, the firms' choice to substitute energy carriers depends, inter alia, on emission costs and thus on the carbon price trajectory that is expected by the agents.

[30] Deviating output pathways comprise all effects we attribute to gross dividends of the stock corporation in the long run (before deduction of incremental emission costs). In the default case, dividends gross of emission costs are assumed to evolve proportionally to GDP in the region where the firm is domiciled. If the energy carrier or the industry sector is modeled explicitly in the IAM under review, we use corresponding production pathways as a proxy for the growth rate of gross dividends.

Looking forward, considerable relative price adjustments appear to be still outstanding at a global level if global warming is to be limited to a mean of 1.5°C. To enter the path of a clean energy transition, the difference between low-carbon and carbon-intensive assets does not yet appear to be sufficiently priced in financial markets. As a consequence, investors would eventually pay a lower price for stocks of large emitters when they revise expected carbon costs upwards, while investments in low-carbon stocks will be encouraged. The structural differentiation along the lines of expected carbon cost is key for the asset management industry to decide on the reallocation of capital into climate-friendly businesses.[31] Carbon costs and financing conditions will then depend on the speed at which carbon prices are expected to increase on the one hand, and the speed at which firms decarbonize on the other. Both determinants are reflected in our metric.

Lastly, as time elapses in the absence of globally effective mitigation policies, societies will increasingly face devastating effects of climate change. Such physiscal risks are likely to entail an additional stranding of assets.[32] The present exercise, however, is limited to transition risks and abstracts from the physical impact of global warming.

3 Approach

We construct a scenario-based, firm-level metric of transition risk by leveraging the outcomes of four large-scale multi-regional IAMs: REMIND (REMIND-MAgPIE[33]), MESSAGE (MESSAGEix-GLOBIOM[34]), GCAM[35], and EPPA[36] (MIT-EPPA). Table 1 lists these models and specifies the variables whose scenario-specific projections are used as inputs in our equity pricing framework: these are regional carbon prices, regional output data and GHG emissions. Based on the firm's sector and region, we map these projections to firm-level information on emissions and analysts' dividend forecasts. That is, investors are assumed to form their firm-level expectations in full consistency with the IAM under review. We start from the assumption that currently the baseline scenario (either *Current Policies* or *Nationally Determined Contributions*) is priced in financial markets rather than a transition to carbon neutrality by 2050.[37]

Imposing a revision in market expectations to a *Net Zero 2050* transition is reflected in strong incremental decarbonization rates. In this setting, stocks are repriced in response to a combination

[31] While capital markets are an important source of finance for climate investments and the build-up of low-carbon structures, credible climate policies are a precondition. This will facilitate a differentiated pricing of assets along their carbon content, including a pricing of the costs and risks associated with carbon-intensive assets. In turn, this requires transparent information on carbon footprints and credible decarbonization pathways of firms.

[32] See the 'Unhedgeable Risk' report by the Institute for Sustainability Leadership, University of Cambridge (2020), for a discussion on scenario triggers in the context of climate change. Alternatively, jurisdictions may also prefer to allocate more resources to climate adaptation and recovery from damages – with fewer resources being left to finance the fight against climate change.

[33] REMIND denotes *Regional Model of Investment and Development*. See Luderer et al. (2015) and Baumstark et al. (2021) who describe the current version 2.1 of the model REMIND-MAgPIE.

[34] The current version of the MESSAGE-GLOBIOM model is described by Huppmann et al. (2019).

[35] See Calvin et al. (2019).

[36] See Chen et al. (2016).

[37] As outlined beforehand, this baseline is either *Current Policies* or the somewhat more optimistic *NDCs* scenario. See NGFS (2022). For the NGFS Climate Scenarios Data Set (Phase III), see doi: 10.5281/zenodo.7085776.

of shifts in projected carbon prices, decarbonization efforts, and output trajectories. While this 'What if' analysis abstracts from assigning probabilities for future climate policies and carbon prices, it highlights potential costs and benefits financial market investors should be prepared for. These effects of an expectation shock can inform policymakers and other economic agents alike.

We leverage projections of IAMs that exhibit several commonalities. All of them feature cost-effectiveness, where a global warming target is defined in the form of a carbon budget. To meet it, these models derive transition pathways to a low-carbon economy at minimum cost. Here, the carbon price trajectory is pivotal to shape the transformation of energy and land-use systems. All models explicitly represent primary energy carriers. In the macroeconomic core of REMIND and MESSAGE, energy is introduced as a separate production factor.[38] All models except GCAM[39] use nested production functions with constant elasticities of substitution. There exist a number of competing energy conversion technologies, all of which are characterised by specific costs (including costs of GHG emissions), degrees of efficiency, and lifetimes.

In MESSAGE and REMIND, savings and investment decisions of the representative agent are based on future economic conditions with perfect foresight. The MESSAGE is a global general equilibrium model with a detailed modeling of the energy system, the land-use system and GHG emissions. Here, the global economy is modeled with 12 regions where aggregate demand is determined, inter alia, as a function of the energy system. Energy demand meets energy supply that is produced at minimal costs. Like MESSAGE, REMIND is a global general equilibrium Ramsey-type growth model with 12 regions. It consists of a macroeconomic core and a process-based modeling of the energy sector with all relevant GHG emissions.[40] The energy module is connected to the macroeconomic core via energy demand and energy costs. Demand for final energy is a function of a nested aggregate CES macroeconomic production function. The production factors are capital, labor, and final energy. Capital and energy are substitutes with an elasticity of 0.5. Output is used for investment in the capital stock, consumption, trade and energy system expenditures. In the optimal solution, investments, consumption, labor, energy demand and trade are chosen such that a Nash equilibrium is set out between welfare-maximizing regions, though the spillover externality for low-carbon technology deployment is internalized in the *Net Zero 2050* transition scenario.

GHG emissions depend on the energy mix and technologies used in energy production. Improvements in energy intensity are calibrated such that baseline final energy demand matches projections from bottom-up models of the industry, transport and buildings sectors.

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[38] GCAM's macro version will only be used in the future – so far it is a partial equilibrium model with an exogeneous GDP.

[39] The first version of GCAM was published in 1983. Calvin et al. (2019) describe the version 5.1 which is very similar to the version 5.3 used in the Phase III scenarios. GCAM uses logit functions for determining technology market shares.

[40] The climate system, including temperature estimation, is not modeled within the REMIND model but in a coupled model. The MAGICC6 model is used here for NGFS scenarios; see Meinshausen et al. (2011).

Table 1: Leveraging projections of selected global multi-regional IAMs

		REMIND-MAgPIE	**MESSAGEix-GLOBIOM**	**GCAM 5.3**	**MIT EPPA**
Equilibrium type		General	General	Partial	General
Modeling approach[41]		Intertemporal optimization	Intertemporal optimization	Recursive dynamic	Recursive dynamic
Number of world regions		12 regions[42]	12 regions[43]	32 regions[44]	18 regions[45]
Modeled period		Up to 2100	Up to 2100	Up to 2100	Up to 2050
Transition scenario	*Net Zero 2050* (NZ) 1.5°C median warming by 2100	✓	✓	✓	✓
Baseline scenarios under review	*Current Policies* (CP) 3.1°C median warming by 2100	✓	✓	✓	✓
	National pledges (NDCs) 2.4°C median warming by 2100	✓	✓	✓	-
Output growth (selected items)	*GDP (regional level)*	✓	✓	✓	✓
	Energy production (regional level)				
	Primary Energy|Coal|w/o CCS	✓	✓	✓	✓
	Primary Energy|Gas|w/o CCS	✓	✓	✓	✓
	Primary Energy|Oil|w/o CCS	✓	✓	✓	✓
	Primary Energy|Nuclear	✓	✓	✓	
	Prim. Energy|Non-Biomass|Wind	✓	✓	✓	(✓)Secondary Energy| Electr. |Wind & Solar
	Prim. Energy|Non-Biomass|Solar	✓	✓	✓	
	Prim. Energy|Biomass| Electricity	✓	✓	✓	✓
	Prim. Energy|Non-Biomass|Hydro	✓	✓	✓	✓
	Prim. Energy|Non-Biomass|Geoth.	✓	✓	✓	-
	Sectoral production (regional level)				
	Production |Steel	✓	✓	✓	(✓) Energy-intensive indu-stry production
	Production |Cement	✓	✓	✓	
	Energy Service |Transportation	✓	✓ Final Energy| Transportation	✓	✓Commercial transportation
	Energy Service|Transportation| Aviatio	✓	-	-	-
Emission growth (selected items)	*CO_2e emissions (regional level)*	✓	✓	✓	✓
	CO_2e emissions by sector (regional level)				
	CO_2|Energy|Demand|Industry|Steel	✓	✓	Kyoto Gases |Steel	-
	CO_2|Energy|Demand|Industry|Cement	✓	✓	Kyoto Gases |Cement	-
	Kyoto Gases |Transportation	✓	CO_2|Energy|De-mand|Transport	✓	-
	CO_2|Energy|Demand|Transportation| Aviation|Passenger	✓	-	-	-

Notes: The scenarios used here are based on the scenario of the shared socio-economic pathway 2 (*SSP2*), which describes a "middle-of-the-road" future. See NGFS (2022), Climate Scenarios Database, Technical Documentation.

[41] See Wilson et al. (2017).

[42] Regions in REMIND-MAgPIE 3.0-4.4: [Canada, Australia, New Zealand], China, EU 28, Non-EU28, India, Japan, Countries from the Reforming Economies of the Former Soviet Union, Sub-saharan Africa, Central Asia, Other Asia, Latin America and the Carribean, USA

[43] Regions in MESSAGEix-GLOBIOM: China, Eastern Europe, Former Soviet Union, Latin America and the Carribean, Middle East and North Africa, North America, Other Pacific Asia, Pacific OECD, Sub-saharan Africa, Rest Centrally Planned Asia, Western Europe.

[44] Regions in GCAM 5.3: Africa (Eastern, Nothern, Southern, Western), Argentina, [Australia, New Zealand], Brazil, Canada, Central America and the Carribean, Central Asia, China, Colombioa, EU12, EU15, Eastern Europe, Non-EU Europe, India, Indonesia, Japan, Mexico, Middle East, Pakistan, Russia, South Africa, South America (Northern, Southern), South Asia, South Korea, Southeast Asia, Taiwan, USA.

[45] Regions in MIT-EPPA6: Africa, Australia, Brazil, Canada, China, East Asia, Eastern Europe and Central Asia, EU+28, India, Indonesia, Japan, Latin America, Mexico, Middle East, New Zealand & Oceania, Rest of Asia, Russian Federation, South Korea, USA. See Chen et al. (2016).

Two types of investment are allowed for: investment in a generic macro-economic capital stock, and investment in specific energy technologies. Endogenous technological change via a global learning curve represents the deployment-dependent cost declines for technologies like solar, wind and batteries. In the model version used here, the REMIND model is linked to the land-use model MAgPIE[46] with a simulation horizon up to 2100, where the time steps 2005 and 2010 are fixed by historical values.
Unlike REMIND and MESSAGE, GCAM and EPPA are recursive dynamic models.[47] EPPA is a computable general equilibrium model with 18 regions, while GCAM is a partial equilibrium model with 32 regions and an adaptive formation of expectations. To conduct analyses of the macroeconomic costs of GHG mitigation policies, recursive dynamic models allow for a large number of sectors to be modeled, and systemic accounting for spillover effects across sectors.[48] In both models, savings and investment decisions are based on current period variables, where saving equals investment in each period. Changing technologies are either modeled as a source of economic growth (EPPA) or can alter regional energy demand and crop production (GCAM).

In our valuation framework, we treat IAM projections as exogenous inputs and abstract from financial accelerator effects.[49] Moreover, we assume that there is consensus in financial markets about future climate policies. While perfect foresight holds within the baseline scenario and within the *Net Zero 2050* scenario, we also assume the transition shock to unfold as a unanimous revision in investor expectations from the baseline scenario to the *Net Zero 2050* scenario under perfect foresight of changes in dividend growth rates and emission cost trajectories. Therefore, while there is no mispricing within one scenario, the assumed expectations shock implies a change in equity prices. Using a dividend discount framework, we capture the emissions- and output-induced change in equity prices on a stock-by-stock basis. For each scenario, we apply IAM projections of carbon prices, emissions and output pathways.[50]

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[46] See Dietrich et al. (2019). Land-use models such as MAgPIE combine economic and biophysical approaches in order to simulate spatially explicit global land-use scenarios (especially pasture, forest and cropland for food and bioenergy purposes) in the 21st century as well as interactions with the environment. In order to identify common transition pathways from energy and land-use systems in connection with the macroeconomic core, the REMIND model is therefore coupled either with land use emulators or, in an iterative process, with the stand-alone MAgPIE land-use model.
[47] The resulting investment pathways of recursive dynamic models can differ from intertemporal optimization models such as MESSAGE and REMIND.
[48] See Wing and Timilsina (2019).
[49] That is, we abstract from financial accelerator mechanisms. Battiston et al. (2021) and Frankovic and Kolb (2023) allow for the possibility of such feedback effects and include a financial accelerator in an E-DSGE framework. Battiston et al. (2021) emphasize the interactions between the perception of climate risks, investor behavior, the feasibility of transition pathways, and the credibility of climate policies. As a result, a macro-financial feedback loop could lead to underinvesting with respect to climate targets. Semieniuk et al. (2021) present a framework that models structural changes in the real economy together with effects on the financial system. Their model includes the drivers, transmission channels, and impacts of a phase-out of carbon-intensive industries on the financial system, as well as the repercussions on the real economy.
[50] Here, output refers to sectoral or energy production, where applicable. Where no sector information is available, we rely on the projected growth rate pf GDP at market exchange rates.

Formalization using the baseline scenario

In a first step, we consider the baseline scenario. Let $V_{i,r,s,t}$ be the time *t* share price of firm *i* assigned to sector *s* and domiciled in region *r*. For each stock i, we use the implied return on equity, $R_{i,m}$, as a forward-looking model-specific discount factor under the baseline. For each firm i and a given model m, $R_{i,m}$ is assumed to be constant over all time horizons. Here, we presume that the risk premium required by investors for holding a given stock remains unchanged from the perspective of today (i.e. at time *t*). To solve for $R_{i,m}$, we set the share price equal to the discounted time *t* expectation of all future dividends-per-share. To project this dividend stream for a given firm, we combine stock-level dividend forecasts from *IBES* analysts for the next four years, $D_{i,r,s,t+\tau}^{IBES}$ (where $1 \leq \tau \leq 4$), with *IBES* forecasts of the three-to-five years earnings-per-share growth rate, g_i^{IBES}, and baseline projections of long-run output growth rates $\hat{Y}_{r,s,t+T}^{IAM,base}$ taken directly from the IAM under review: $\hat{Y}_{r,s,t+\tau}^{REMIND,base}$, $\hat{Y}_{r,s,t+\tau}^{MESSAGE,base}$, $\hat{Y}_{r,s,t+\tau}^{GCAM,base}$ and $\hat{Y}_{r,s,t+\tau}^{EPPA,base}$. According to equation (1), the growth rate g_i^{IBES} is applied to dividends between year 5 and year 12. In this period, expected growth rates are assumed to shift gradually to $\hat{Y}_{r,s,t+12}^{IAM,base}$. For output and emission variables that denote IAM scenario projections, we use the superscript IAM. For all other variables of our own that depend indirectly on these projections, we use the subscript m to refer to the IAM under review.

$$(1) \qquad V_{i,r,s,t} = \sum_{\tau=1}^{T} \frac{D_{i,r,s,t+\tau,m}^{base}}{(1+R_{i,m})^{\tau}} + \frac{D_{i,r,s,t+T,m}^{base}}{R_{i,m} - \hat{Y}_{r,s,t+T}^{IAM,base} - \pi}(1+R_{i,m})^{-T}$$

$where$

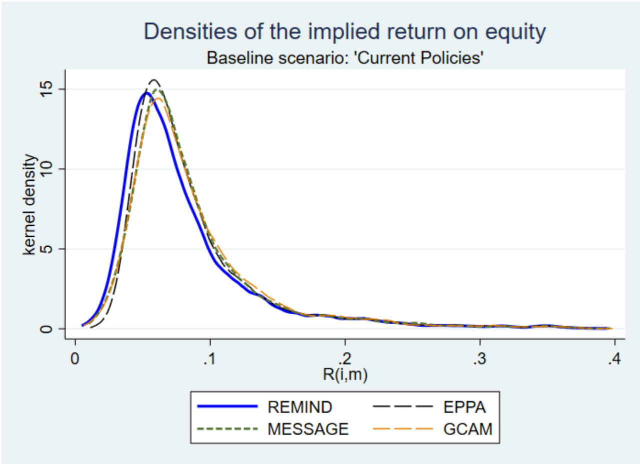
$$D_{i,r,s,t+\tau,m}^{base} = \begin{cases} D_{i,r,s,t+\tau}^{IBES} & \text{for } 1 \leq \tau \leq 4 \\ D_{i,r,s,t+\tau-1,m}^{base} \cdot \left(1 + g_i^{IBES} + \left(\hat{Y}_{r,s,t+12}^{IAM,base} + \pi - g_i^{IBES}\right)\left(1 - \frac{12-\tau}{8}\right)\right) & \text{for } 5 \leq \tau \leq 12 \\ D_{i,r,s,t+\tau-1,m}^{base} \cdot \left(1 + \hat{Y}_{r,s,t+\tau}^{IAM,base} + \pi\right) & \text{for } \tau > 12 \end{cases}$$

The variable $\hat{Y}_{r,s,t+\tau}^{IAM,base}$ denotes the output growth rate in region *r* and sector *s* under the baseline scenario at time $t+\tau$.[51] The superscript IAM denotes that this variable is a direct input from the IAM model. $D_{i,r,s,t+\tau,m}^{base}$ is the projected dividend under the baseline scenario using IAM model *m*. For the initial four years, firm-level dividend expectations are taken from *IBES* analyst surveys ($D_{i,r,s,t+1}^{IBES}, \ldots, D_{i,r,s,t+4}^{IBES}$). This period is followed by an interim period where nominal dividend growth rates gradually adjust from g_i^{IBES} in year $\tau = 5$ to $\hat{Y}_{r,s,t+12}^{IAM,base}$ in year $\tau = 12$, plus an assumed expected inflation rate π of 2 per cent.[52] Thereafter, nominal dividends of firm *i* are assumed to

[51] For firms belonging to sectors *s* that are not explicitly modeled in the IAM under review, dividends are projected to evolve in line with the scenario path of regional GDP in the long-run.
[52] g_i^{IBES} denotes the expected earnings growth rate 3 to 5 years ahead from *IBES* analyst forecasts.

grow proportionally to the macroeconomic projection of the output variable in region *r* and sector *s* to which the firm belongs, plus the inflation rate π.[53]

Figure 1: Densities of implied returns on equity



Two factors affect the equity pricing in a dividend discount framework: dividends net of emission costs, and the discount rate channel.[54] In our model, the latter refers to the return on equity $R_{i,m}$ required by investors as an important determinant. By combining firms' share prices and expected dividends, we obtain a range of implied returns on equity across firms under the baseline scenario. We claim that these discount rates reflect firm-level risk perceptions of investors that correspond to observed share prices. In this regard, our method deviates from other valuation approaches that apply one single discount rate to all assets (Semieniuk et al., 2022, Roncoroni et al., 2021, Schober et al., 2022).[55]

Figure 1 depicts the resulting model-specific densities of the implied return on equity. We see that the densities of the four IAMs under review have similar patterns under the baseline scenario. Turning to a net zero transition scenario in all world regions and an associated shift in expectations, we price stocks against this baseline. Unlike the top-down valuation approaches in the literature, our approach uses scenario-based emission-induced price effects at the firm level a) to quantify individual transition risks and b) to derive average sectoral and regional effects in a bottom-up approach. With respect to the instantaneous change in equity prices, we claim that using the cross-section range of returns on equity as discount rates is a plausible setting.

[53] For stock corporations where no information on revenue shares is available in ISS-ESG, but whose core activities belong to one modeled sector *s*, the sectoral output projections are taken from the IAM under review (i.e. coal, nuclear, oil and gas, biomass, wind energy, solar energy, geothermal power, hydro power, and additionally in REMIND-MAgPIE: steel, cement) and dividends are projected to increase or decrease at the growth rate of production in sector *s* plus an inflation rate π.

[54] See also Bolton and Kacperzcyk (2021a) who refer to the 'cash flow channel' where the numerator in the pricing equation depends on firms' earnings expectations net of the expected cost of decarbonization and capital expenditures needed to switch to renewable energies. They distinguish this channel from the 'discount rate channel' which captures, inter alia, the carbon risk premium required by investors.

[55] For example, Schober at al. (2022) apply the macro-econometric model framework of NiGEM where dividend projections are discounted using a single monetary policy-driven interest rate which is allowed to vary over time.

Table 2: Sector classification of firms and IAM sectors under review

*Classification of firms to sector **s*** *Default:* *Classification according to main sector of activity (GICS industries and sub-industries)*	*Is sector **s** modeled in the IAMs under review?* *No* ($s \notin \Omega_{IAM\ sectors}$)	*Yes* ($s \in \Omega_{IAM\ sectors}$) of which other IAM sectors $s \in \Omega_{IAM\ non-energy}$	of which IAM energy sectors $s \in \Omega_{IAM\ energies}$
Services	×		
Airlines	(partially available)		
Aviation (ex airlines), Aerospace, Defense			
Transport, Automotive industry, Infrastructure		✓ Transportation	
Coal industry (coal mining, power production)[1]			✓ Coal
Oil and Gas industries (extraction, power production)[2]			✓ Oil ✓ Gas
Renewable energies[3]			✓ (Wind, Solar, Hydro, Biomass, Geothermal)
Other/mixed energies/Utilities			✓ Nuclear
Other mining, Metal processing	(partially available)	(partially available)	
Chemicals industry		(partially available)	
Cement industry		✓ Cement	
Steel industry		✓ Steel	
Construction and Engineering	×		
Other manufacturing	×		

See Table 1 for further details on selected sectors that are represented in the IAMs under review. [1]) Attribution to the "Coal industry" sector if the firm's revenue shares in coal-related activities (mining, power generation) exceeds 50%. If no revenue data are available in *ISS-ESG*, a firm is assigned to the Coal sector if its core business is coal mining or coal-fired power generation, or if the GICS sub-industry is "Coal & Consumable Fuels". [2]) Attribution to the "Oil and gas industries" sector if the firm's revenue shares in oil- and gas-related activities (extraction, power generation) exceed 50%. If no revenue data are available in *ISS-ESG*, a firm is assigned to this sector if its core business consists in oil or gas activities (extraction, power generation), or if it is classified in the GICS industry "Oil, Gas & Consumable Fuels", or it is assigned to one of following GICS sub-industries: Oil & Gas Drilling, Exploration & Production, Equipment & Services, Refining, Storage & Transportation, or Integrated Oil & Gas. [3]) Firms are assigned to "Renewable energies" if at least 50% of their revenues come from renewables.

Table 3: Sector classification of firms by revenue share of energy carrier

Energy revenue share $w_{i,r,\theta,t}$ by energy carrier θ (Source: *ISS-ESG*)	*Assignment to sector (s)*
[1]) $w_{i,r,\theta,t}$ (coal mining and coal-fired power production) > 0.5	Coal industry
[2]) $w_{i,r,\theta,t}$ (oil and gas extraction; power production using oil, gas) > 0.5	Oil and gas industries
[3]) $w_{i,r,\theta,t}$ (power production using wind, solar, hydro, biomass, geothermal energies) > 0.5	Renewable energies
[4]) $w_{i,r,\theta,t}$ (power production using nuclear energy) > 0.5	Other/mixed energies
Other constellations where the sum of energy revenue shares > 0.5	Other/mixed energies
Default: Other constellations where revenue shares from energy carriers amount to less than 50%, or when data on corporate revenue shares by energy carrier are not available	Classification by main sector of activity according to GICS industry and GICS sub-industry

We project long-run corporate dividends in proportionality to a proxy output variable drawn from the four IAMs under review. In these models, scenario variables are projected in five-year intervals. For a given scenario j and a future year n within these intervals ($t + \tau < n \leq t + \tau + 5$), we assume firm i's dividends to evolve geometrically with constant growth rates. As shown in equation (2), the model-implied annual rate of output growth, $\hat{Y}^{IAM,j}_{r,s,t+n}$, is defined either as GDP growth in region r (default), or as the sectoral output growth in that region if sector s is modeled explicitly in the IAMs under review (see Table 2).

$$(2) \quad \hat{Y}^{IAM,j}_{r,s,t+n} \equiv \begin{cases} \left(\dfrac{GDP^{IAM,j}_{r,t+\tau+5}}{GDP^{IAM,j}_{r,t+\tau}}\right)^{\frac{1}{5}} - 1 & \text{if } \; s \notin \Omega_{IAM\ sectors} \\ \left(\dfrac{Y^{IAM,j}_{r,s,t+\tau+5}}{Y^{IAM,j}_{r,s,t+\tau}}\right)^{\frac{1}{5}} - 1 & \text{if } \; s \in \Omega_{IAM\ non-energy} \\ \mathrm{f}\left(Y^{IAM,j}_{r,1,t+\tau}, Y^{IAM,j}_{r,2,t+\tau}, \dots, Y^{IAM,j}_{r,1,t+\tau+5}, Y^{IAM,j}_{r,2,t+\tau+5}, \dots\right) & \text{if } \; s \in \Omega_{IAM\ energies} \end{cases}$$

$$\begin{aligned} &where \qquad t + \tau \in [2020, 2025, \dots, 2095] \\ &and \qquad \Omega_{IAM\ sectors} \equiv \Omega_{IAM\ non-energy} \cup \Omega_{IAM\ energies} \end{aligned}$$

For firms with revenue shares from mixed energies, we derive dividend growth as a function of energy production growth of different energy carriers. The derivation of the latter is described in the following. We consider industry-specific output pathways for firms in the following IAM sectors ($\Omega_{IAM\ sectors}$): cement industry, steel industry, transportation, as well as the energy sectors ($\Omega_{IAM\ energies}$) oil, natural gas, coal, and electricity generation using nuclear energy, biomass energy, wind energy, solar energy, hydropower and geothermal power. We benefit from the fact that all IAMs under review contain a detailed modeling of energy sectors. This allows us to treat firms separately if they are active in power production or the extraction of fossil fuels, and incorporate data on their energy-related revenue shares $w_{i,r,\theta,t}$ available for a number of energy carriers θ, with $\theta \in [1,2, \dots, \Theta]$. Here, we rely on information from *ISS-ESG* on energy-related revenues. Rather than simply assigning a firm to one main sector s, we project the dividend paths of these firms as a function of weighted IAM energy production trajectories in the region where the firm resides.[56] According to equation (3), dividends in year $t + \tau$ are set equal to the sum of carrier-specific dividends and a residual component at that time.

[56] The country where a firm has its headquarter is used as a geographical identifier to map regional growth rates of IAM sector output, energy supply as well as regional decarbonisation rates to the firm's dividends and GHG emissions. While we acknowledge that this is a simplification of the effective allocation of the company's activities, we rely on this approximation due to a lack of granular data on the jurisdictions in which firms' GHG emissions are taking place. In support of this, corresponding Bloomberg data suggest that most firms in our sample generate the bulk of their revenues in their headquarters' home region.

Turning to the global aggregates of energy usage under the transition scenario (see Figure A.7b), firms active in the production of renewable energies are projected to grow much faster than fossil fuel producers or refineries. Moreover, the coal industry will be phased out quickly, but oil and gas will be phased down at a considerably lower speed. Starting from near-term dividends, this implies that firms with a high revenue share in coal but a small revenue share in oil and gas will be worse off than firms with a high revenue share in oil and gas but a small revenue share in coal.

At the firm level, the information on the revenue structure by energy carrier is available for a subset of 445 out of 5,050 stock corporations under review (see Table A.1). We use the model- and scenario-implied growth rates of an energy carrier to derive an individual dividend pathway for each firm. This permits us to refine our price impact indicator for firms with diversified businesses in energy carriers. These 445 firms account for 11% of total equity market capitalization under review and emissions of 5.8 gigatonnes of CO_2 equivalents (68% of total emissions under consideration).

In the initial year t, $w_{i,r,\theta,t}$ denotes the revenue share of firm i that is attributable to energy carrier θ. For future years $t+\tau$, we combine this information with the production growth rate of the corresponding energy carrier in the IAM and scenario under review. Let $\hat{Y}^{IAM,base}_{r,\theta,t+n}$ be the annual IAM production growth of energy carrier θ (expressed in exajoules or terawatt per year) in region r in the baseline scenario at time $t+n$. Then the cumulated nominal growth rate until year $t+\tau$ reads $\prod_{n=1}^{\tau}\left(1+\hat{Y}^{IAM,base}_{r,\theta,t+n}+\pi\right)-1$. In the baseline scenario, we assume dividends to evolve proportionally to revenues, and revenues to evolve proportionally to the production of all relevant energy carriers θ, plus an assumed inflation rate π. Starting with expected dividends $D^{IBES}_{i,r,t}$ of firm i in initial year t, we project dividends $D^{base}_{i,r,t+\tau,m}$ in year $t+\tau$ as the sum of carrier-driven dividends $D^{base}_{i,r,\theta,t+\tau,m}$ that are associated with energy carrier θ in IAM model m, plus a residual dividend component $D^{base}_{i,r,residual,t+\tau,m}$ that is assumed to grow at IAM-implied GDP growth rate $\hat{Y}^{IAM,base}_{r,GDP,t+n}$ plus inflation rate π.[57]

(3) $$D^{base}_{i,r,t+\tau,m} = \sum_{\theta=1}^{\Theta} D^{base}_{i,r,\theta,t+\tau,m} + D^{base}_{i,r,residual,t+\tau,m}$$

$$where\ \ D^{base}_{i,r,\theta,t+\tau,m} = D^{IBES}_{i,r,t} \cdot w_{i,r,\theta,t} \cdot \prod_{n=1}^{\tau}\left(1+\hat{Y}^{IAM,base}_{r,\theta,t+n}+\pi\right)$$

$$and\ \ D^{base}_{i,r,residual,t+\tau,m} = D^{IBES}_{i,r,t} \cdot \left(1-\sum_{\theta=1}^{\Theta} w_{i,r,\theta,t}\right) \cdot \prod_{n=1}^{\tau}\left(1+\hat{Y}^{IAM,base}_{r,GDP,t+n}+\pi\right)$$

[57] Depending on the scenario-based IAM projection of energy production, the revenue share of a given energy carrier is projected to change over time.

Accordingly, $D_{i,r,t}^{IBES} \cdot w_{i,r,\theta,t}$ approximates the dividends of firm i attributable to carrier θ in initial year t. This is assumed to hold irrespectively of whether the firm is active in the extraction business or in the power production business. To assign these firms to a main sector, we use the revenue share $w_{i,r,\theta,t}$ in initial year t to determine the sector classification according to Tables 2 and 3. That is, when firms are assigned to the same energy sector, we allow their individual energy-related revenue shares to differ to some degree within this sector.

For all other firms where no information on revenue shares in energy carriers is available, we assign the firm to a sector according to its main business activity (reported in Table 2). To project dividend flows for these firms in a given scenario j, we use IAM-specific output pathways $\hat{Y}_{r,s,t+\tau}^{IAM,j}$ in the sector s to which the firm i is assigned. As a default case, for firms belonging to sectors that are not explicitly modeled in the IAM under review,[58] long-term dividends are projected to evolve in line with GDP in that scenario.

If the firm's core business or its revenues are linked to one or more specific energy carriers (provided this information is available in *ISS-ESG*), the corresponding growth rate of energy output is considered instead of the default GDP projection. As stated beforehand, our data set incorporates production growth rates of fossil and non-fossil energy carriers ($\Omega_{energy\ sectors}$) that are modeled in the IAM under review.

Adjusting the dividend stream for transition-induced output deviations and the cost of emissions

In a next step, we derive gross dividends as well as the cost of GHG emissions under the *Net Zero 2050* transition scenario. For each point in time, we obtain a cross-section distribution of emission costs under the baseline scenario[59] and a corresponding distribution under the transition scenario. Assuming a revision in market expectations from the baseline to the *Net Zero 2050* scenario a trajectory of expected incremental emission costs per share $C_{i,r,s,t+\tau,m}$ is derived for each firm.
The GHG emissions at time t are taken from firm-specific reports and estimates of *ISS-ESG*, respectively. According to equation (4), this cost equals the product of the regional carbon price $p_{r,t+\tau,m}^{NetZero}$ and the firm i's projected per-share GHG emissions $E_{i,r,s,t+\tau,m}^{NetZero}$ (expressed in CO_2e) under the net zero transition, less the corresponding product ($p_{r,t+\tau,m}^{base} \cdot E_{i,r,s,t+\tau,m}^{base}$) under the baseline scenario:

$$(4) \qquad C_{i,r,s,t+\tau,m} = \begin{cases} p_{r,t+\tau,m}^{NetZero} \cdot E_{i,r,s,t+\tau,m}^{NetZero} - p_{r,t+\tau,m}^{base} \cdot E_{i,r,s,t+\tau,m}^{base} & \forall\ E_{i,r,s,t+\tau,m}^{NetZero} > 0 \\ p_{r,t+\tau,m}^{NetZero} \cdot 0 \qquad\qquad\quad - p_{r,t+\tau,m}^{base} \cdot E_{i,r,s,t+\tau,m}^{base} & \forall\ E_{i,r,s,t+\tau,m}^{NetZero} \leq 0 \end{cases}$$

[58] See Table 2.
[59] Under the *Current Policies* scenario, future carbon prices are close to zero in most world regions in the IAMs under review. In Europe, however, positive carbon prices are projected in REMIND, implying non-negligible carbon costs.

Hence, we allow for negative incremental costs at time $t + \tau$ when the expected emission cost under the baseline exceeds the expected cost under the transition, thereby generating incremental dividends. However, we exclude the case of negative emissions at the firm level.

To project a firm's future emissions per share, our assumption is that emissions evolve synchronously across all firms domiciled in region *r* and sector *s*. Thereby we assume identical relative decarbonization efforts within a region – and within a sector – irrespective of whether the firm's initial carbon footprint is high or low. We let current emissions per share[60], $E_{i,r,s,t}$, grow at IAM-implied scenario-specific growth rates of aggregate (i.e. regional and sectoral) emissions:

$$E_{i,r,s,t+\tau,m}^{base} \equiv E_{i,r,s,t} \prod_{n=1}^{\tau} \left(1 + \hat{E}_{r,s,t+n}^{IAM,base}\right)$$

$$E_{i,r,s,t+\tau,m}^{NetZero} \equiv E_{i,r,s,t} \prod_{n=1}^{\tau} \left(1 + \hat{E}_{r,s,t+n}^{IAM,NetZero}\right)$$

Here, the superscripts $^{IAM,\, base}$ and $^{IAM,\, NetZero}$ refer to aggregate emissions trajectories of Kyoto gases (i.e. all greenhouse gases) in the IAM under review under the baseline scenario and the transition scenario, respectively. As outlined in equations (5a) and (5b), the model-implied growth rate $\hat{E}_{r,s,t+n}^{IAM,\dots}$ of emissions in year n is computed from five-year emission projections for region *r* – and, if applicable, sector *s*. Within these five-year intervals, corporate emissions are assumed to evolve geometrically, where the annual emission growth rate in region *r* and, if applicable, in the sector *s* of the firm:

$$(5a) \quad \hat{E}_{r,s,t+n}^{IAM,base} \equiv \left(\frac{E_{r,s,t+\tau+5}^{IAM,base}}{E_{r,s,t+\tau}^{IAM,base}}\right)^{\frac{1}{5}} - 1 \qquad \text{for } \tau < n \leq \tau + 5 \quad and \quad t + \tau \in [2020, 2025, \dots, 2095]$$

$$(5b) \quad \hat{E}_{r,s,t+n}^{IAM,NetZero} \equiv \begin{cases} \left(\frac{E_{r,s,t+\tau+5}^{IAM,NetZero}}{E_{r,s,t+\tau}^{IAM,NetZero}}\right)^{\frac{1}{5}} - 1 & if \ E_{r,s,t+\tau}^{IAM,NetZero} > 0 \ \text{ and } \ \tau < n \leq \tau + 5 \\ -1 & if \ E_{r,s,t+\tau}^{IAM,NetZero} < 0 \ and \ E_{r,s,t+\tau-5}^{IAM,NetZero} > 0 \ \text{ and } \ \tau < n \leq \tau + 5 \end{cases}$$

In equation (5b), $\hat{E}_{r,s,t+n}^{IAM,NetZero}$ accounts for the eventuality that at some point in the future, emissions are projected to turn negative in some regions in an ambitious climate policy scenario ($E_{r,s,t+\tau}^{IAM,NetZero} < 0$). If this happens in year $t + \tau$, emissions will henceforth be set to zero. This is done to rule out negative incremental emission costs that may otherwise result from negative

[60] To derive current emissions per share at the firm level, we use pre-Covid19 emissions of CO_2e that are either reported or estimated by ISS-ESG for 2019, and divide them by the number of shares that are used in the firm's *IBES* dividend forecast.

emissions. Accordingly, equity appreciations resulting from negative emissions are disregarded in our framework.

In the IAMs we consider, the cost of incremental emissions does not monotonously increase over the projected horizon. While GHG emissions are decreasing under ambitious climate policies, the aggregate cost of these emissions exhibits a hump-shaped pattern over time.[61] That is, in a later stage where carbon prices are very high, economies have converted to low-carbon energies to a large degree.

We are now able to derive hypothetical equity prices under the transition scenario. Starting from the assumption that the baseline scenario is currently priced in, a shift in expectations to a stricter carbon pricing policy means to account for and subtract firm-specific incremental emission costs $C_{i,r,s,t+\tau,m}$ from gross dividends. Under the transition scenario, these gross dividends are assumed to grow at the same rate as nominal output, hence at a rate amounting to $\hat{Y}^{IAM,NetZero}_{r,s,t+\tau} + \pi$.

If the firm passes part of its emission costs on to its customers, it merely has to bear a cost share of $\lambda < 1$. We discount the resulting net dividends using the implied return on equity $R_{i,m}$ derived under the baseline scenario.[62] Then the hypothetical equity value is given by:

$$(6) \quad V^{NetZero}_{i,r,s,t,m} = \sum_{\tau=1}^{T} \frac{\max(0, D^{NetZero}_{i,r,s,t+\tau,m} - \lambda C_{i,r,s,t+\tau,m})}{(1 + R_{i,m})^{\tau}}$$

where

$$D^{NetZero}_{i,r,s,t+\tau,m} = \begin{cases} D^{IBES}_{i,r,s,t+\tau} & \text{for } 1 \le \tau \le 4 \\ D^{NetZero}_{i,r,s,t+\tau-1,m} \cdot \left(1 + g^{IBES,NetZero}_{i,m} + \left(\hat{Y}^{IAM,NetZero}_{r,s,t+12} + \pi - g^{IBES}_{i}\right)\left(1 - \frac{12-\tau}{8}\right)\right) & \text{for } 5 \le \tau \le 12 \\ D^{NetZero}_{i,r,s,t+\tau-1,m} \cdot \left(1 + \hat{Y}^{IAM,NetZero}_{r,s,t+\tau} + \pi\right) & \text{for } 12 < \tau \le T \end{cases}$$

As regards expected short-term dividend growth from *IBES* surveys, we assume that g^{IBES}_{i} holds in the baseline scenario, but we assume it to be revised when expectations switch to *Net Zero 2050*. In our approach, we adjust g^{IBES}_{i} by the differential in annual output -growth between the policy scenario and the baseline scenario in the first five-year time interval (2020-2025). Then the adjusted dividend growth rate reads: $g^{IBES,NetZero}_{i,m} = g^{IBES}_{i} + \left(\hat{Y}^{NetZero}_{r,s,2025,m} - \hat{Y}^{base}_{r,s,2025,m}\right)$. That is, if the output growth in the baseline scenario exceeds that of the policy scenario, the short-term dividend growth rate $g^{IBES,NetZero}_{i,m}$ is smaller than g^{IBES}_{i}.

[61] In Europe, for example, REMIND projects an emission reduction in the *Net Zero 2050* scenario implying that from 2045 onwards, aggregate emission costs are lower compared to the emission cost under a scenario of continued current policies.

[62] See equation (1).

Accounting for stranding firms

Equation (6) shows that dividends net of emission costs $\lambda C_{i,r,s,t+\tau,m}$ are taken into account as long as they are positive. Should emission costs that are borne by firm i exceed the dividends at time $t+\tau^{crit}$, we assume that the firm becomes stranded at that time, since it cannot afford to pay this cost out of contemporaneous dividends. As a consequence, net dividends are set to zero henceforth, and the firm's equity value will be equal to the discounted net dividends before that date. That is, a future stranding means that conditional on today's expectations regarding the firm's dividend stream, the equity value of that firm will gradually approach zero up to the point in time $t+\tau^{crit}$.

Assumptions for the 22nd century

No model under review provides projections for the time after 2100. Beyond that date, we assume carbon prices p, GHG emissions E, and the output growth rate $\hat{Y}$ to remain constant at the last projected value in each scenario j and each IAM under review:

$$\hat{E}^{IAM,j}_{r,s,t+\tau} = 0 \qquad for \quad t+\tau > 2100$$
$$\hat{Y}^{IAM,j}_{r,s,t+\tau} = \hat{Y}^{IAM,j}_{r,s,t+\tau-1} \quad for \quad t+\tau > 2100$$
$$p^{IAM,j}_{r,t+\tau} = p^{IAM,j}_{r,t+\tau-1} \quad for \quad t+\tau > 2100$$

Deriving the transition-induced price impact measure

As we have derived a share price implied by a shift in expectations towards a *Net Zero 2050* transition, we compare it to the current share price and quantify the distance between both. Two determinants affect this metric, and their influence differs across firms: a) the incremental cost of emissions and b) the differential between the output trajectory under the baseline scenario and the output trajectory under the transition scenario. At the same time, we assume that the risk perception of investors vis-à-vis firm i remains unchanged when they revise their policy expectations towards a transition scenario. Let x denote the change in the share price. Using macroeconomic projections from the integrated assessment model m under the transition scenario, the equity price deviation from the baseline at the future point in time $t+\kappa$ reads:

$$(7) \qquad x^{base \rightarrow NetZero}_{i,r,s,t+\kappa,m} = \frac{V^{NetZero}_{i,r,s,t+\kappa,m}}{V^{base}_{i,r,s,t+\kappa,m}} - 1$$

Equation (7) defines $x^{base \rightarrow NetZero}_{i,r,s,t+\kappa,m}$ as the deviation of the transition-implied equity value of firm i from its baseline value. It relies on the set of information available at time *t*. For the pricing in the initial year *t* (i.e. $\kappa = 0$), the baseline value is the observed stock price, and $x^{base \rightarrow NetZero}_{i,r,s,t+0,m}$ is the instantaneous price impact of firm i. For any future year $\kappa > 0$, equation (7) describes the deviation of the future equity value under a transition policy, $V^{NetZero}_{i,r,s,t+\kappa,m}$, from its future baseline value, $V^{base}_{i,r,s,t+\kappa,m}$. Future equity values are derived by keeping the expected dividend stream (net of incremental carbon costs) unchanged, but future dividends are discounted less the more distant the year κ of equity valuation is. Note that both equity values, $V^{NetZero}_{i,r,s,t+\kappa,m}$ and $V^{base}_{i,r,s,t+\kappa,m}$, depend on the same firm-specific return on equity $R_{i,m}$.[63] Based on the dividend outlook for a firm at time t and given contemporaneous market conditions R_i, the price impact indicator $x^{base\rightarrow NetZero}_{i,r,s,t+\kappa,m}$ measures its ability to bear incremental transition-induced emission costs, accounting for transition-induced output deviations. Under an ambitious policy scenario of a net zero transition and an incomplete pass-through of emission costs ($\lambda > 0$), we claim that this metric can capture elements of transition risk that investors are exposed to.

The role of firm-specific factors

Beyond the IAM projections of carbon prices, emissions and output under a given scenario, $x^{base\rightarrow NetZero}_{i,r,s,t+\kappa,m}$ is driven by firm-specific factors as well: these include the level of current GHG emissions (which affect equity prices negatively under *Net Zero 2050*), the revenue shares of fossil energy businesses (higher shares reduce the equity price under *Net Zero 2050*), dividend expectations, and the current stock price, which determine the implied return on equity. Additional firm-level determinants are the expected cost pass-through and the degree to which the firm is expected to decarbonize its businesses. Inter alia, the latter relates to its capabilities to substitute fossil fuel-based activities with clean activities.

To summarize, we project incremental costs that are determined by current GHG emission levels in a deterministic way. We thereby make this transition risk metric easy to implement for firms. While adding a stochastic adaptation pattern at the firm level could make aggregate outcomes more accurate, our intention is to keep this approach as simple as possible, by showing that even under a Paris-aligned decarbonization, GHG emissions of some firms will remain considerable along the transition, and their incremental costs can become critical.

We also test whether firms' self-reported GHG emissions make a difference for the implied return on equity at the sector level. This test is motivated by recent discussions in the empirical literature on the role of disclosure in driving stock returns.[64] While we find intra-sectoral differences in the returns on equity between disclosing and non-disclosing firms in 9 out of 14 sectors, the sign of these differences varies across sectors (Table A.6): in six sectors, expected dividends of disclosing firms are discounted at lower rates compared to non-disclosing firms. The opposite holds for the

[63] According to equation (1), the firm-specific implied return on equity $R_{i,m}$ depends on the observed stock price of firm i and a contemporary dividend pathway, which is derived from *IBES* analyst expectations and longer-term output growth projections under the baseline scenario of the IAM m. As outlined in Section 3, we assume that $R_{i,m}$ remains unchanged after a revision in expectations.

[64] See the empirical work on the carbon premium and the role of disclosure by Bolton and Kacperczyk (2021b).

remaining sectors (services, aviation/aerospace/defense, and steel).[65] These mixed results take us to disregard the role of disclosure in the following.

4 An application based on scope 1 greenhouse gas emissions

In principal, the aforementioned valuation framework can be applied to different scopes of greenhouse gas emissions and to different settings for the pass-through of carbon costs. However, this study focuses on equity price impacts for scope 1 emissions of firms.[66] We do so to highlight the size of potential effects induced by emissions for which firms are directly responsible – hence the burden weighing on firms induced by their own emissions. An exclusive focus on scope 1 emissions generates consistent results under the assumption of a zero cost pass-through. In this "no pass-through" setting, no firm passes its emission cost to its customers. Firms do not bear the cost of other emissions in the value chain (upstream emissions, downstream emissions) or emissions from the consumption of heat and electricity. These emissions exhibit the highest level of data reliability – referring either to disclosures by firms or to estimates by *ISS-ESG*.[67] Notwithstanding, as an excursus, we derive the incremental price impact that would result from imposing the full cost of scope 2 emissions on the firm – which mainly relate to a firm's heat and electricity consumption – in addition to the cost of its scope 1 emissions.

In a second, alternative setting, we consider a mild scenario with a high price-setting power of firms. Here, firms are assumed to bear just 20% of their own scope 1 emission costs. Hence they pass on the remainder to their customers as well as all costs of indirect and upstream emissions that are imposed on them. In this setting of an 80% pass-through, the ultimate consumer will be charged with 80% of all carbon costs.

While at the individual firm level, our approach would also be suitable for a consideration of the cost of upstream scope 3 emissions, we disregard this variant to avoid the problem of double counting when it comes to a cost aggregation at the sector or regional level. A clear-cut analysis of scope 3 emission costs would require granular data on firms' value chains and their price-setting power.

[65] In a second analysis, we test whether the size of the implied return on equity depends on the size of firms' GHG emissions. However, in 10 out of 14 sectors we do not find that large emitters exhibit different returns on equity within a sector. See Table A.6.

[66] See World Resources Institute (2004) and https://ghgprotocol.org/. The scope 1, 2 and 3 classification standards used in the *Greenhouse Gas Protocol* constitute an important benchmark. Accordingly, scope 1 emissions refer to the production process or services provided by the company. Scope 2 emissions are indirect emissions due to electricity or heat consumption. Scope 3 emissions are grouped in several sub-categories, originating from upstream and downstream stages along the value chain. Included are emissions attributable to purchased goods and services, upstream transportation and business travel, investment, waste generation, the end use of products sold, and their end-of-life treatment.

[67] Data on corporate greenhouse gas emissions are gleaned from company reports and estimates provided by *ISS-ESG*. Out of the 5,050 firms under review in this exercise, 2,018 firms disclosed their direct GHG emissions in 2019, of which 280 firms took part in emissions trading systems. With 7.3 out of 8.5 Gt CO_2 equivalents, the disclosures of these 2,018 firms represent the major part of all GHG emissions under review.

Role of the cost pass-through

For any $0 \leq \lambda < 1$ (see equation 6), an impact quantification limited to scope 1 emissions may fall short in capturing emission-induced costs, because it neglects part of scope 2 and scope 3 costs incurred by a stricter carbon pricing. Under the assumption of a zero pass-through (λ=1), however, a scope 1-based impact metric consistently captures all emission-induced costs on aggregate.[68] Here, we display the additional burden incurred by emissions in each sector, and relate it to the capacities to bear this cost. We compare this case with a setting where the firm is able to pass on 80% of its scope 1 emission costs to its clients (λ=0.2).

Sample construction

We apply the proposed metric to a global sample of 5,050 listed non-financial stock corporations domiciled in 72 countries. With a capitalization of €43.5 trillion (end of 2020), these firms cover roughly half of global market capitalization of listed equities and 17% of global GHG emissions.[69] Stocks are selected contingent on the availability of *IBES* analyst surveys on dividend forecasts for the next years. Moreover, we take into account share prices from Thomson Reuters as well as *ISS-ESG* data on past GHG emissions and revenue shares by energy carrier. In the following, we use stock price and data on dividend expectations as of end-2020, but also carry out an analysis using 2021 data to test for robustness. We combine this corporate data set with existing macroeconomic IAM scenario projections of GHG emissions, GDP and sectoral production including energy carriers, and the carbon price. As outlined beforehand, we refer to three IAMs on the basis of the NGFS Phase III projections (as of September 2022) and projections from the EPPA model. Firms are assigned to 14 sectors according to Table 2. For each sector, Table A.1 reports aggregate emissions, the equity market capitalization per sector, and the number of firms with a regional breakdown.

Accounting for energy production pathways

To the extent that corresponding data are available, we pay special attention to firms' business models that cover multiple energy carriers and account for the future substitution of fossil fuels in the transition process. Out of the full sample of 5,050 corporations*, ISS-ESG* provides data on energy-related revenue shares for 445 firms.[70] With 6.1 out of 8.8 gigatons of CO_2 equivalents, these firms account for the bulk of current GHG emissions under consideration (Table A.1b). Starting with 2019 revenue shares, we factor in IAM energy production pathways and assume dividends to evolve proportionally to revenues.[71] To project future values, we combine the firm's initial revenue shares (pre-Covid figures as of 2019) with regard to selected energy carriers with

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[68] For a conceptual discussion of risk-factor pathways, incremental indirect emission costs and incremental low-carbon capital expenditure, see UNEP Finance Initiative / Oliver Wyman / Mercer (2018).

[69] See Table A.1. Direct emissions in our sample sum up to 8.5 gigatonnes of CO_2 equivalents, referring to pre-Covid reports and estimates of *ISS-ESG* as of 2019. The equity market capitalization of the stocks under review (end-2020) amounts to €43.5 trillion.

[70] The ESG rating agency *ISS-ESG* provides revenue shares referring to the extraction of energy carriers or its usage for power production.

[71] E.g. gross dividends before deduction of incremental emission costs.

production growth rates for each energy carrier taken from IAM scenario projections. Here, regional scenario-specific projections of the future energy mix are used.[72] For the *Current Policies* scenario and the *Net Zero 2050* scenario, Figures A.7a and A.7b depict the global energy mix in the next decades for all IAMs under review. For firms where *ISS-ESG* does not provide a breakdown of revenues into energy carriers, we approximate future dividends by reference to the IAM-implied output growth in the main sector of business activity in the region where the firm is domiciled. If the production of an energy carrier (coal, oil, gas, nuclear, or renewable energies) constitutes the main business of the firm, we assume that its nominal dividends to evolve in line with the corresponding energy production in the IAM under review, plus an inflation assumption. If the firm's business sector is not explicitly modeled in the IAM, its dividend flow is assumed to evolve in line with the GDP projection (plus an inflation assumption) in the respective region.

Once the future path of nominal dividends is calculated for each firm, we are able to deduct the projected incremental cost of GHG emissions.[73] Starting with the firm's 2019 carbon footprint, emissions evolve according to the emission reduction rates implied by the transition scenario. Individual carbon costs are obtained as a product of remaining emissions with future carbon prices along the scenario-implied trajectory. Put in a nutshell, our equity valuation approach incorporates the following driving factors for the baseline scenario and the transition scenario:

1. the projected cost of GHG emissions, driven by aggregate emissions, firm-level carbon footprints, and projections of the carbon price,
2. the projected energy production trajectories by energy carrier, and
3. the projected output growth by sector (default: GDP), combined with firm-level survey data of analysts on dividend expectations.

5 Results

Our scenario-based valuation framework allows us to derive hypothetical asset price impacts in a setting where investors revise their expectations from a baseline to a transition scenario. As described beforehand, this impact metric aims at capturing the firms' ability to bear unexpected emission costs. As mentioned, we apply this method to a set of 5,050 global non-financial equity corporations and ask what happens to their prices in response to projected changes in output and costs of scope 1 emissions. We structure our findings as follows:
We focus on price impacts across firms under the *Current Policies* baseline scenario using 2020 analyst expectations.[74] As a sensitivity analysis, we also look at the consequences of an update in

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[72] Given that *ISS-ESG* provides firm-level data on revenue shares by energy source, we project future revenue shares for this firm on the basis of IAM scenario production growth rates of the respective energy carriers in the region where the firm is domiciled. For the part of revenues that is not energy-specific, we use IAM output projections for the sector and region to which the firm belongs. As a default, we resort to GDP growth rates.
[73] As outlined in Section 3, we quantify the impact of output growth deviations and emission costs that are incurred *on top of the baseline scenario* in an assumed transition scenario. Deviations in output growth entail an adjustment of the firm's trajectory of gross dividends.
[74] i.e. referring to end-2020 stock prices and *IBES* dividend forecasts of analysts.

the year of analyst expectations and explore the bandwidth of results by a variation in the baseline scenario by applying the *NDCs* scenario instead of *Current Policies* to firms in all world regions. Finally, we explore how differently sectoral and regional averages are affected in the four IAMs under review.

Figure 2: Distribution of price impacts, by IAM and baseline scenario

Figure 2a

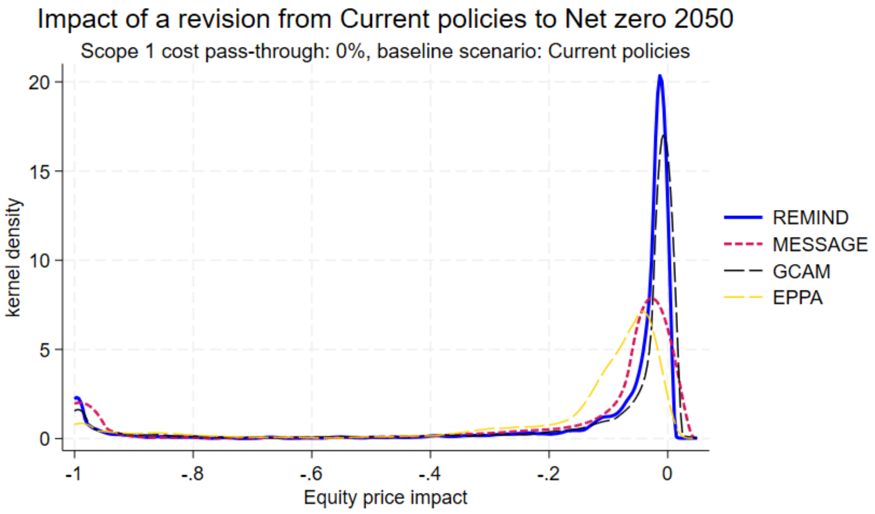
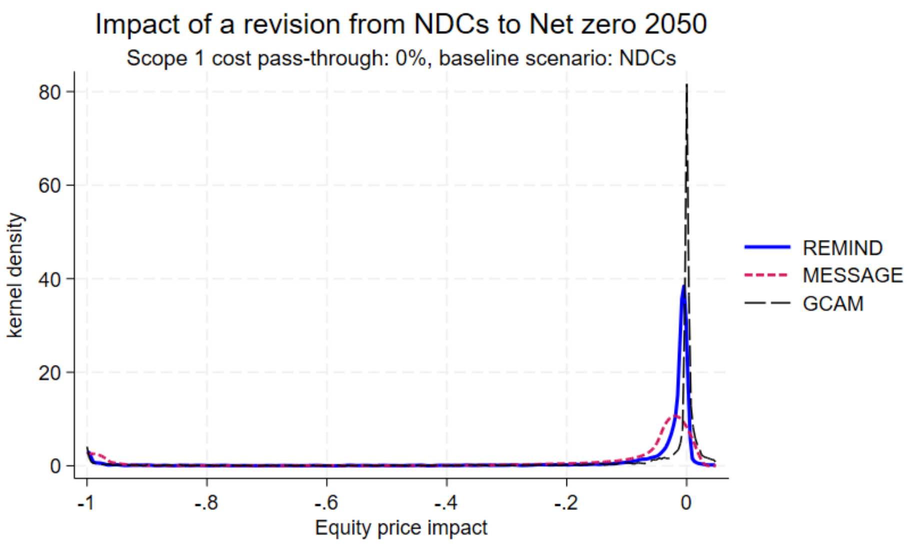


Figure 2b



Notes: Kernel densities are based on NGFS Phase III scenarios (as of October 2022). Equity price impacts refer to deviations from the baseline scenario (*Current Policies* vs. *Nationally Determined Contributions*), assuming a revision in investors' expectations towards a *Net Zero 2050* transition scenario in 2020.

Note that all results we report are conditional on the assumption of Paris-aligned decarbonization trajectories – i.e. high ambition levels – for all stock corporations under review. By construction, we exclude the case that firms fail to curb their emissions when they are exposed to high carbon prices. To display the bandwidth of possible results, we report price impacts under four different IAMs and for two alternative assumptions of the cost pass-through (0% and 80%). Apart from the baseline scenario of continued *Current Policies*, we also report the results under the *NDCs* baseline.[75] While our results primarily refer to dividend expectations from *IBES* analyst surveys as of end-2020, we also carry out a sensitivity analysis using corresponding 2021 data.

Distribution of price impacts under alternative baseline scenarios

For each of the four IAMs, Figure 2 depicts the cross-section distribution of equity price impacts assuming a revision in expectations towards a *Net Zero 2050* transition policy (skipping relatively rare observations of price impacts beyond +0.1%, including renewables). The depicted impacts are derived based on end-2020 *IBES* dividend forecasts under a *Current Policies* baseline (Figure 2a) and an *NDCs* baseline (Figure 2b), respectively. While we do not explore whether the *NDCs* or the *Current Policies* scenario is a better reflection of current expectations for a given stock, we show the bandwidth of outcomes associated with the two alternative assumptions. Figure 2 assumes that all incremental scope 1 emission costs are expected to be borne by the firm.

Under a *Current policies* baseline, there is a (more accentuated) fat tail at the lower end of the distribution, pointing to a more frequent occurrence of severe losses. Even when this tail mass is disregarded, Figure 2 suggests a substantially higher dispersion of price impacts under a *Current Policies* baseline than under an *NDCs* baseline.

Table 4 corroborates these observations. The cross-section range of means, standard deviations and net loss ratios are reported for the two baseline scenarios and both pass-through levels (denoted by *PT*). There is a considerable bandwidth across IAMs, across baseline scenarios and across pass-through levels. Under the *Current Policies* baseline, average (unweighted) price impacts range between 14% and 22% at *PT*=0%, and between 7% and 12% at *PT*=80%. Owing to relatively low equity capitalizations of high emitters and fossil-fuel firms, the capitalization-weighted averages (dubbed 'Net loss ratios') are lower: they range between 10% to 17% at *PT*=0% and between 4% to 9% at *PT* =80%.

Unsurprisingly, price impacts under a revision towards a *Net Zero 2050* transition are more subdued if the baseline scenario is *NDCs* rather than *Current Policies*, as the former implies that more emission costs (but also more benefits from renewables) are already reflected in today's stock prices. Here a future implementation of national climate mitigation pledges is assumed to be priced in all world regions. As a consequence, a shift to a *Net Zero* transition turns out to be less harmful for firms, because their incremental scope 1 cost burden is less elevated than under a *Current Policies* baseline.

[75] Applying the *Current Policies* scenario as a baseline can be motivated by the fact that in many world regions, to date, there is little evidence that markets consistently price in a more ambitious climate scenario, with carbon prices being still relatively close to zero in many countries. However, since in some regions, more ambitious climate policies are likely to be priced in today, including the EU, we also present the results using the *Nationally Determined Contributions* (*NDCs*) scenario as a baseline. Moreover, as regards the EPPA model, projections using the *NDCs* scenario are unavailable for the present study.

Table 4: Aggregate price impacts following a revision in expectations to the *Net Zero 2050* scenario

Price deviation from baseline (Full sample using analyst expectations of end-2020)

	No cost pass-through				80% cost pass-through			
Baseline scenario	REMIND	MESSAGE	GCAM	EPPA	REMIND	MESSAGE	GCAM	EPPA
NDCs				(NA)				(NA)
Mean price impact	-0.099	-0.200	-0.041		-0.053	-0.100	-0.032	
Standard deviation	0.256	0.361	0.496		0.176	0.269	0.190	
Aggregate net loss* (€ bn)	-2813	-6193	-1181		-1585	-3007	-805	
*Net loss ratio***	-0.07	-0.14	-0.03		-0.04	-0.07	-0.02	
Current Policies								
Mean price impact	-0.144	-0.221	-0.146	-0.189	-0.072	-0.120	-0.067	-0.123
Standard deviation	0.294	0.361	0.307	0.276	0.197	0.273	0.221	0.197
Aggregate net loss* (€ bn)	-4468	-7177	-4366	-5912	-2242	-4030	-1619	-3863
*Net loss ratio***	-0.10	-0.17	-0.10	-0.14	-0.05	-0.09	-0.04	-0.09

Notes: Calculations are based on NGFS Phase III scenarios (as of October 2022). Equity price changes in 2020 refer to deviations from the *Current Policies* baseline, assuming a revision in investors' expectations towards a *Net Zero 2050* transition in 2020. *NDCs* denotes the baseline scenario of *Nationally Determined Contributions*.

*) Aggregate net loss denotes the sum of valuation losses less valuation gains in billions of 2020 €.

**) The *net loss ratio* denotes the share of the aggregate net loss in total market capitalization under review (€43.53 trillion as of December 2020, representing 5,050 stock corporations). This definition of the *net loss ratio* corresponds to a capitalization-weighted mean price impact.

Table 5 shows loss frequencies and exposures in two impact categories: cases where losses are -50% and worse, and cases where price impacts remain in a single-digit range or better. For each impact category, we report the loss frequency (number of firms), but also take an investor perspective and report the corresponding exposures in terms of equity capitalization. Under a *Current Policies* baseline and a zero cost pass-through (*PT*=0%), severe equity price losses (beyond 50%) occur for 11% to 18% of all firms, corresponding to 8% to 13% of total equity capitalization under review. Under *PT*=80%, the corresponding frequency ranges are 5% to 9% of all firms and 3% to 7% of total market capitalization.[76] These cross-IAM ranges of the results point to some degree of model uncertainty.

Unsurprisingly, severe price impacts are less frequent if an *NDCs* baseline is applied instead of a *Current Policies* baseline: Referring to projections from REMIND, GCAM and MESSAGE, losses beyond 50% occur for 7% to 17% of all firms and for 5% to 12% of total market capitalization under a zero cost pass-through (*PT*=0%). Under *PT*=80%, the corresponding ranges are 3% to 8% of all firms and 2% to 5% of total market capitalization. These lower impact magnitudes point to additional decarbonization efforts that are already reflected in *NDCs* pledges.[77]

[76] As a sensitivity analysis (not reported here), an update of analyst expectations (i.e. when end-2020 stock prices and *IBES* dividend forecasts are replaced by end-2021) suggests a more frequent occurrence of losses beyond 50%.

[77] See also Table A.1a (REMIND), Table A.1b (MESSAGE) and Table A.1c (GCAM).

Table 5: Frequency of price impacts following a revision in expectations to the *Net Zero 2050* scenario

Full sample (5,050 firms): Number of stock corporations exposed to losses (share in total number of firms)

	Baseline scenario	No cost pass-through				80% cost pass-through			
		REMIND	MESSAGE	GCAM	EPPA	REMIND	MESSAGE	GCAM	EPPA
Size of losses (x)	***NDCs***				(NA)				(NA)
	Frequency of stranding*	0.08	0.17	0.09		0.04	0.07	0.04	
	x ≤ -50%	0.08	0.17	0.07		0.04	0.08	0.03	
	x > -10%	0.85	0.70	0.87		0.91	0.82	0.92	
	Current Policies								
	Frequency of stranding*	0.11	0.17	0.12	0.12	0.04	0.08	0.05	0.05
	x ≤ -50%	0.11	0.18	0.12	0.12	0.05	0.09	0.06	0.05
	x > -10%	0.78	0.67	0.76	0.59	0.88	0.80	0.86	0.69

Full sample (equity market capitalization: €43,531 bn): Capitalization share exposed to losses

	Baseline scenario	No cost pass-through				80% cost pass-through			
		REMIND	MESSAGE	GCAM	EPPA	REMIND	MESSAGE	GCAM	EPPA
Size of losses (x)	***NDCs***				(NA)				(NA)
	Share of stranded equity capital*	0.05	0.11	0.06		0.02	0.04	0.03	
	x ≤ -50%	0.05	0.12	0.05		0.02	0.05	0.02	
	x > -10%	0.90	0.80	0.92		0.93	0.87	0.95	
	Current Policies								
	Share of stranded equity capital*	0.07	0.13	0.08	0.08	0.02	0.06	0.03	0.03
	x ≤ -50%	0.08	0.13	0.09	0.09	0.03	0.07	0.04	0.04
	x > -10%	0.85	0.78	0.83	0.72	0.90	0.85	0.89	0.79

Fossil-fuel and high emissions sectors only (equity capitalization: €2,580 bn): Capitalization share exposed to losses

	Baseline scenario	No cost pass-through				80% cost pass-through			
		REMIND	MESSAGE	GCAM	EPPA	REMIND	MESSAGE	GCAM	EPPA
Size of losses (x)	***NDCs***				(NA)				(NA)
	Share of stranded equity capital*	0.55	0.88	0.53		0.26	0.42	0.27	
	x ≤ -50%	0.57	0.91	0.49		0.26	0.57	0.23	
	x > -10%	0.14	0.03	0.38		0.19	0.09	0.43	
	Current Policies								
	Share of stranded equity capital*	0.64	0.89	0.72	0.72	0.27	0.62	0.34	0.38
	x ≤ -50%	0.64	0.89	0.72	0.72	0.27	0.62	0.34	0.38
	x > -10%	0.08	0.04	0.04	0.02	0.14	0.11	0.10	0.10

Notes: Calculations are based on NGFS Phase III scenarios (October 2022) applied to 5,050 stock corporations globally, using IBES analysts' dividend expectations as of end-2020.

*) Share of firms subject to a 'Future stranding', where a stranding event is defined as an expected shortfall of projected dividends of covering incremental scope 1 emission costs at a point in time between 2020 and 2050. A loss of more than 50% does not necessarily imply that an asset will get stranded at a future point in time. Inversely, stranding at a future point in time does not necessarily imply a loss ratio of more than 50%. The two shares are not mutually exclusive.

However, from an investor's angle devaluations remain still substantial under *NDCs,* and severe downward corrections will affect a number of firms. Table 5 also reports the frequency of stranding, denoting the share of firms where expected dividends will fall short of covering projected incremental emission costs within the next three decades, and the corresponding share of stranded capital. Both ratios correspond closely to the occurrence of severe losses beyond 50%. Unsurprisingly, such events are relatively rare if the cost pass-through is high (*PT*=80%), but occur more often if they have to bear all incremental emission costs (*PT*=0%). This corroborates the role of the price-setting power in sales markets: the higher it is, the more moderate the emission-induced cost burden – to the detriment of the firms' customers.[78]

Finally, the bottom part of Table 5 reports the results for a subsample of fossil fuel firms and large emitters. The loss and stranding frequencies of these 327 firms are markedly different from those of the entire sample: Under a zero cost pass-through, we find a high percentage of stranding capital ranging between 64% and 89% of their equity capitalization under a *Current Policies baseline* and 53% to 88% under an *NDCs* baseline. For *PT*=80%, between 27% and 62% of their equity capital gets stranded under the *Current Policies* baseline. The corresponding values under an *NDCs* baseline scenario range from 26% to 42%.

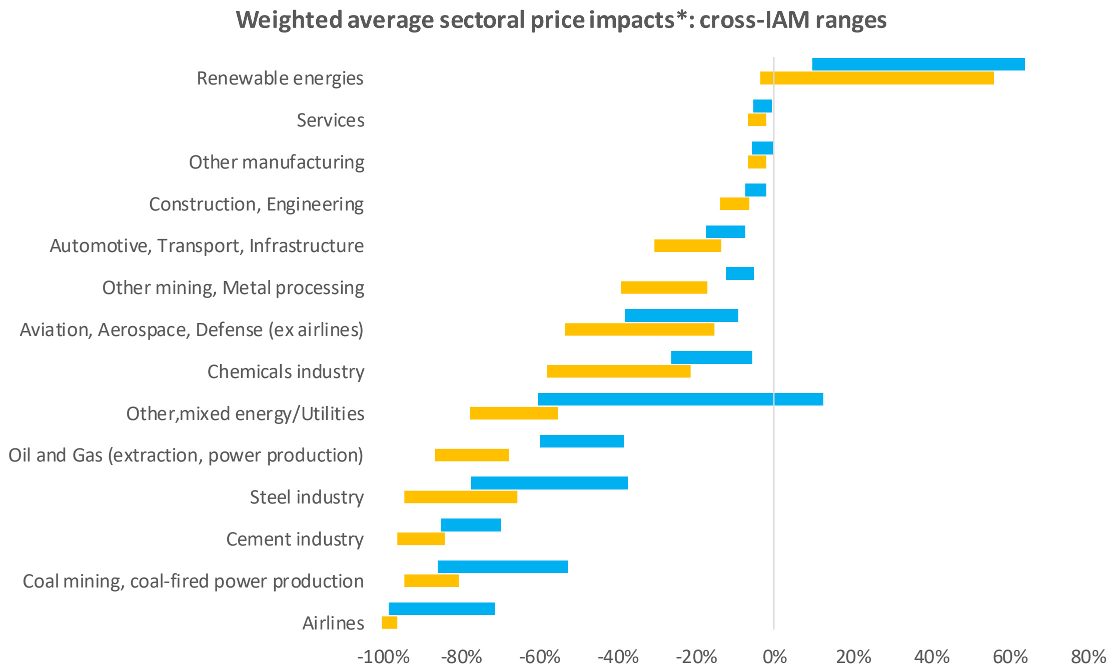
Price impacts at the sector level

Referring to the aforementioned industry classification, we break our results down by economic sectors. As shown in Figure 3, a revision in expectations towards a *Net Zero 2050* transition affects sectors to very different degrees. Based on the *Current Policies* baseline and 2020 analyst expectations, it depicts the cross-IAM range of capitalization-weighted average price impacts for each sector under the two pass-through constellations.

We find that large emitters (airlines, steel and cement producers) as well as fossil-fuel-oriented industries (i.e. firms active in the extraction of coal, oil and gas or in fossil-based electricity generation) exhibit the strongest equity devaluations induced by incremental scope 1 emissions and scenario-implied output changes. This means that equity investors heavily engaged in these sectors are exposed to a relatively high transition risk. Note that these sector risks are in place under the assumed setting that stock corporations will decarbonize their activities at rates that are Paris-aligned. While the magnitude of price impacts is not unexpected for cement, steel and fossil fuel power production sectors, the severe impact on airlines is remarkable. In our setting, the main reason is that analysts expect airlines' dividends to be exceptionally low relative to their direct GHG emissions (scope 1 in 2019). Unlike in other sectors, the maximum CO_2 price affordable by airlines using next year's dividends is as low as 22 € per ton (median value).

[78] In this exercise, further implications of the assumption of a pass-through of scope 1 emission costs are neglected. Here, we disregard that a higher pass-through of scope 1 emission costs implies larger scope 2 and scope 3 emissions for firms in the downstream of the value chain. Depending on the price setting power of these firms, part of these costs would have to be borne by them, with corresponding implications for their equity valuation.

Figure 3: Cross-IAM range of price impacts by sector under a *Current Policies* baseline



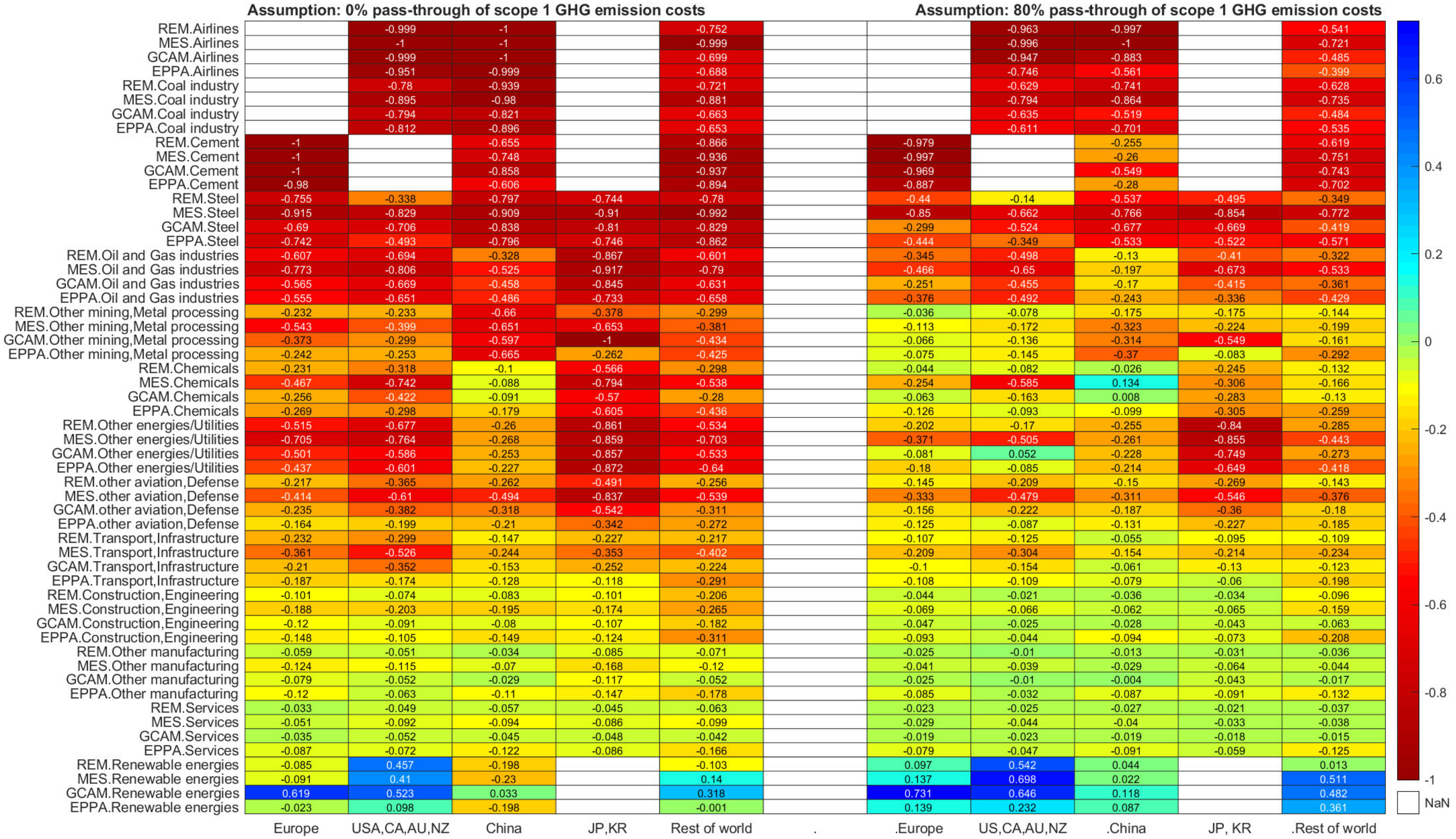
*) using market capitalisation weights of firms in 2020, assuming shift in expectations from *Current policies* to a *Net Zero 2050* scenario.
Cost pass-through: (blue) 80% of scope 1 emission costs is assumed to be passed on to the firms' clients.
(orange) Firms are assumed to bear the total cost of scope 1 greenhouse gas emissions.

Opposed to these sectors, the service sector and low-emission manufacturing stocks are much less affected by a switch to a *Net zero* transition. Even more remarkably, firms with large revenue shares in renewable businesses turn out to be the winners in terms of equity revaluations, with capitalization-weighted average price impacts lying in positive territory. This quantifies by how much firms operating primarily in renewables industries are projected to perform better under an ambitious transition scenario than under the baseline (up to +60% on average).

This outcome for these firms can be traced back not only to relatively muted carbon footprints today, but also to the dynamic evolution of renewable energies that is projected under the transition scenario. In our setting, corresponding production growth rates are taken as proxies to project long-term dividend pathways (see Figures A.7a and A.7b for primary energy production pathways). Nonetheless, owing to heterogeneous IAM-specific projections for renewable energies, we find a considerable span of valuation impacts across IAMs.

Figure 3 displays the range of sector impacts between the extreme case of a zero pass-through of scope 1 emission costs (orange bars) and the case of an 80% pass-through (blue bars). Assuming the latter, the impact metric is more positive, as expected. Furthermore, this constellation implies wider cross-IAM ranges of impacts in most sectors. However, even when a large part of emission costs is pushed to the firms' customers, the coal industry and large emitters (airlines, steel and cement industries) remain predominantly subject to equity price losses of 50% and beyond. The

Figure 4: Instantaneous equity price impact[*] by IAM, sector and domicile region: 2020 revision in expectations from ***Current Policies*** to *Net Zero 2050*



[*]) Unweighted averages. Sector-region combinations covering fewer than 4 firms are faded out for confidentiality reasons (see Table A.1). The transport sector includes automotive industries. *REM* and *MES* refer to projections using REMIND-MAgPIE and MESSAGEix, respectively. Corresponding notations for *GCAM* and *EPPA*.

persistently high magnitudes of negative impacts are remarkable and an 80% pass-through, given the assumption of a Paris-aligned decarbonization, i.e. when fossil fuels are largely and continuously substituted with climate-friendly energies. Yet, should firms decarbonize their activities at a slower pace, they would incur higher emission costs. In Figure 3, correspondingly higher equity devaluations would be reflected in downward shifts in the orange and the blue bars.

Breakdown by region and sector

The heat map in Figure 4 depicts unweighted equity price impacts by sector and region in which the firms are domiciled. Here, a revision of market expectations from the *Current Policies* baseline to *Net Zero 2050* is assumed. In this more granular breakdown we distinguish five world regions.[79] For confidentiality reasons, we omit observations of fewer than four entities per sector and region. For a number of sector-region combinations, Figure 4 indicates a relatively small variation across models, suggesting that model uncertainty is limited at that level. Other sectors, e.g. renewable energies and transport and infrastructure, point to elevated cross-model variations. At the same time, price impacts show similar magnitudes across regions in some sectors. Other sectors, however, exhibit a high cross-regional variation of price impacts – including chemicals, transport and infrastructure, other energy and utilities as well as other mining and metal processing. For example, Chinese companies are exposed to relatively mild equity devaluations in the chemicals sector and other energies/utilities sector, whereas renewable energies tend to underperform in China compared to other regions. The disparities across regions can be traced back, to a certain extent, to regional differences in the trajectories of GHG emissions, carbon prices and sectoral output. Moreover, regional variations in the supply of specific energy carriers, reflecting the relative scarcity of fossil energies in that region, cause differences in the projected dividend growth.[80]

Sensitivity analysis

Next, we test whether sector averages differ significantly when the *Current Policies* baseline scenario is replaced with the *NDCs* baseline. Table A.2 report the corresponding sector impacts of net zero transition as well as the significance of the differential between *NDCs*-based and *Current Policies*-based outcomes.[81]

Furthermore, Figure 5 depicts differentials in price impacts as deviations from the 45° diagonal. The left-hand scatter plots corroborate that sectoral averages tend to shift upwards when an *NDCs* baseline scenario is chosen instead of the *Current Policies* baseline. At the same time, the sectoral structure of the results remains broadly unaffected by a variation in the baseline scenario.

As expected, Table A.2 suggests that in most sectors equity prices perform significantly better under an *NDCs* baseline (lower transition-induced risks), while the contrary is true for renewable energy stocks. This reflects the fact that a considerable part of the *Current Policies*-based appreciation of renewables is already priced in under an *NDCs* baseline. While the differentials

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[79] According to Table A.1, we distinguish five world regions that are represented by the following firms: 1,293 European firms, 885 North American, New Zealand and Australian firms, 589 Chinese firms, 1,075 Japanese and Korean firms, and 1,208 firms in the rest of the world.

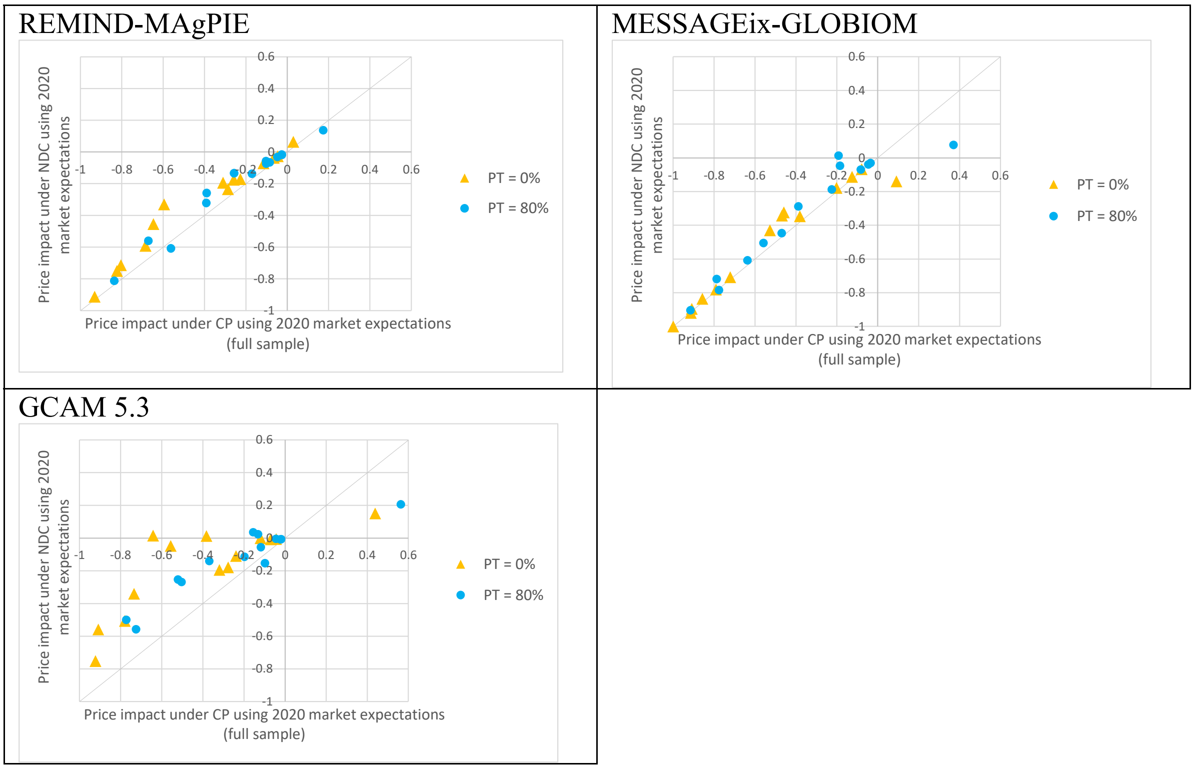
[80] For the 445 firms where information on current revenue shares from energy carriers is available, the share in renewable energies correlates positively with our price impact metric, while the share in fossil fuel energies correlates negatively.

[81] Table A.1 refers to projections from REMIND, MESSAGE and GCAM. Here, EPPA projections are excluded because these are only available for the *Current Policies* baseline scenario.

are rather small when REMIND or MESSAGE projections are used, they are relatively large when GCAM projections are applied.

Figure 5: Sensitivity of price impacts to the choice of the baseline scenario

Sectoral results under the Current Policies baseline compared with sectoral results under the NDCs baseline.



Notes: Unweighted sector averages of 2020 price impacts.

In addition to a variation in the baseline scenario, updates in stock prices and dividend expectations of *IBES* analysts imply some variations in our results. While a replacement of end-2020 stock prices and *IBES* analyst forecasts with corresponding end-2021 data does not significantly affect sectoral averages, the stranding ratios and the frequency of severe devaluations increase to some degree.[82]

Quantifying a stranding of assets

As well, our valuation approach allows us to quantify the stranding of stocks, defined as a future shortfall of expected dividends relative to projected incremental carbon costs. We assume that dividends net of transition-induced incremental emission costs are zero from this point onwards, such that the firm's equity equals the sum of discounted net dividends up to this future point in time. According to Table 5, a zero pass-through of scope 1 emission costs implies a cross-IAM range of 8% to 17% of all stocks getting stranded under *NDCs*, and 11% to 17% of all stocks

[82] For a zero pass through, the 2021 stranding ratios rise from 10% to 13% (REMIND), from 17% to 20% (MESSAGE), from 12% to 14% (GCAM), and from 11% to 14% (EPPA). For an 80% pass through we find an increase from 4% to 6% (REMIND), from 8% to 10% (MESSAGE), and from 5% to 7% (GCAM and EPPA, respectively). This comparison is carried out for a reduced sample of 4604 equity ISINs where data are available in both years.

getting stranded under *Current Policies*. An 80% cost pass-through implies a corresponding range of stranding ratios of 4% to 7% under *NDCs*, and 4% to 8% under *Current Policies*. At the sector level, large emitters (fossil fuel sectors, airlines, cement and steel industries) exhibit the highest exposures to stranding (Table A.4).

Quantifying the incremental impact of scope 2 emissions

As an excursus, we derive the incremental impact of bearing the full cost of scope 2 emissions at the regional and the sectoral level. Here, the only group we allow to pass on their carbon costs are fossil fuel-based power producers – e.g. the cost of emissions by coal- or gas-fired power plants. Hence no emission cost is assumed to remain with these power producers. The remaining sectors are assumed to bear both scope 1 and scope 2 emission costs ("No pass-through" assumption). Using the model REMIND-MAgPIE, Figure A.5a and Figure A.5b report the incremental impacts induced by adding the cost of scope 2 emissions. These additional losses vary across sectors, ranging between 0% and -9% of the initial equity price. Especially high increments turn out for firms who depend on fossil fuel-based heat and electricity – i.e. the chemicals industry, other mining and metal processing, the steel industry as well as automotive, transport and infrastructure. In a regional perspective, the scope 2 -induced losses range between -3.6% for European firms in the sample and -7.0% for Japanese and South Korean firms.

Correlation of the equity price impact metric with existing carbon risk ratings

To test whether our price impact metric provides a value-added relative to existing indicators of transition risk, we compare our results for the equity price impact with the carbon risk ratings of *ISS-ESG*. Out of 5,050 firms under review, *ISS-ESG* provides this information for 2,673 firms in 2019 and for 2,547 firms in 2022. Based the REMIND model and a zero cost pass-through for scope 1 emissions, we find an overall correlation of 28% and 34% using 2019 and 2022 data from *ISS-ESG*, respectively. A sectoral breakdown shows, however, a considerable variation of correlations by sectors: while the correlation is positive in 11 sectors, 3 sectors exhibit negative correlations (airlines, construction and engineering, cement industry). This finding suggests that at least parts of our price impact metric cannot be explained by existing carbon risk ratings provided by data vendors such as *ISS-ESG*. An inclusion of scope 2 emissions changes this pattern only marginally (correlation of 27% and 32% using 2019 and 2022 data, respectively).

6 Conclusion

We develop a firm-level valuation framework to model equity price adjustments induced by greenhouse gas emissions and output deviations as a result of revised transition expectations. To this end, we augment a multi-stage dividend discount framework with carbon footprint data of firms and scenario projections from four large-scale multi-regional process-based IAMs. Firm-specific trajectories of GHG emission costs and gross dividends are derived by combining dividend forecasts from *IBES* analyst surveys and corporate emissions from *ISS-ESG* with scenario projections for carbon prices, GHG emissions, and a set of output variables. First, based on alternative IAM-specific projections, we obtain a cross-model range of price impacts that serves as a proxy for model uncertainty. Secondly, we present results under two alternative assumptions on the pass-through of emission costs. Thirdly, we gauge the bandwidth of potential price adjustments under two alternative baseline scenarios, making reference to the NGFS Phase III *Current Policies* and *Nationally Determined Contributions* scenarios. By doing so we leave open the question to what degree one or the other is currently reflected in financial market prices. Assuming that markets currently believe – and have priced in – that national pledges will be realized in the respective jurisdictions, a transition to *Net Zero 2050* requires smaller price adjustments than under the more pessimistic expectation of a *Current Policies* baseline scenario: Assuming a zero cost pass-through of scope 1 emissions costs, we find that average unweighted impacts range between -4% and -20%, under an *NDCs* baseline, compared to a bandwidth between -14% and -22% under a *Current Policies* baseline.

A key motivation to quantify the transition impact on equity valuations is the pivotal role financial markets are likely to play in the transformation process: if the Paris goal of net zero CO_2 emissions is to be kept in reach, a considerable amount of climate finance will be needed to build clean energy capacities and redirect investments to low-carbon businesses. This requires asset prices to be sufficiently differentiated along their carbon content. At a global scale, such a repricing appears to be still outstanding, conditional on a shift in investor expectations towards globally ambitious climate policies and corresponding carbon prices.

We contribute to the literature by providing a straightforward, consistent approach to quantify potential transition-induced equity price impacts of firms along the lines of their carbon emissions and financial performance. Unlike other studies we rely on firm-specific as discount rates – i.e. returns on equity implied by stock prices, *IBES* analyst dividend forecasts, and IAM scenario projections under the baseline. Thereby we measure the ability of firms to bear incremental emission costs by accounting firm-specific risk perceptions of investors. The resulting repricing of equities can serve as input to assess the financial portfolio exposure to transition-related risks.

Based on a large sample of 5,050 firms, we find fat tails in the distribution of equity price impacts on the way to net zero. A main finding is that present value losses are limited for a majority of firms when CO_2 prices rise strongly. Even under a zero pass-through of emission costs, the major part of the equity market capitalization under review remains exposed to minor losses in a single-digit range, or even benefits from appreciations. At the lower end of the distribution, stock devaluations are most accentuated when incremental emission costs cannot be passed on to the firms' clients. Depending on the IAM projections used, up to 13% of total equity capitalization is exposed to devaluations of more than 50% and the risk of stranding, corresponding to up to 18% of all firms in the sample. Firms primarily active in fossil energy sectors and emission-intensive industries constitute a major part of the firms with a limited ability to bear higher emission costs. Not surprisingly, highest losses turn out under a *Current Policies* baseline with a zero pass-through of emission costs. Impacts are smaller the higher the price setting power of the firm is, and when an *NDCs* baseline is used. A comparison of equity price impacts by region, sector and IAM suggests cross-regional and cross-model heterogeneities that are prevalent in some sectors. Such disparities are particularly accentuated in the sectors of Renewable energies, Mining and Metal processing, Mixed energy/Utilities, and the Chemicals industry.

Some stock corporations are also exposed to the risk of stranding, defined as a shortfall of expected financial performance relative to incremental carbon costs within the next three decades. Following a revision towards net zero transition policies, firms with a bad expected dividend

performance will find it difficult to bear incremental emission-related costs. We find that between 8% and 17% of all stocks (5% to 13% of the capitalization) will get stranded under a zero pass-through of emission costs, and between 4% and 8% of all stocks (2% to 6% of the capitalization) will be subject to stranding under an 80% cost pass-through.
A breakdown of our results by industry sector points to heterogeneous price impacts following a revision in expectations towards a low-carbon transformation: while impacts will be substantial for fossil fuel-based firms and large emitters (coal, oil and gas companies, airlines, steel and cement industries, in particular), other industry sectors (e.g. services) will be much better off. As expected, renewable energy stocks tend to show strong valuation gains.
Under the assumption that fossil-fuel based power producers are able to pass their entire carbon cost on to their customers, we also provide impact estimates for the combined cost of scope 1 and scope 2 emissions. Depending on the sector and the region where the firm resides, the incremental impact varies between 0% and -9% of the initial equity price.

Several caveats apply to the current implementation of our impact metric as a measure of transition risk. First, it cannot be excluded that *IBES* analyst forecasts may overestimate corporate earnings.[83] If the dividend expectations we use are subject to such a bias, this will imply – all else equal – to an overestimation the implied return on equity. As a consequence, correcting this bias in our calculations – e.g. applying lower dividends and a lower return of equity as a discount rate – would lead to a higher weight of the carbon cost component. Since the present value of future carbon costs would be higher in this case, this would create additional downward pressure on the equity value. Hence, should dividend expectations be biased to the upside, our indicator of the equity price impact tends to underestimate valuation losses.
Second, while our indicator accounts for scenario-dependent deviations in output pathways and for incremental costs arising from GHG emissions, it disregards other costs – e.g. changes in capital expenditure for low-carbon investments. Third, the quantitative exercise carried out in this study fades out revised expectations on physical damages and their impact on asset values. Fourth, we disregard potential carbon-related hedging strategies. Moreover, at given expected carbon prices, the optimal decarbonization path of a firm may differ from the aggregate emissions trajectory in the IAM under review, depending on the firm's abatement cost and its transition plan to substitute fossil energies. A final point relates to the nature of investor expectations shock assumed here: we leave open the question of how likely a global inflection point in climate policies is and how likely corresponding revisions of expectations to net zero are. Instead, this paper aims to quantify scenario-implied equity price effects in a what-if setting.

Looking ahead, the proposed indicator will be sensitive to future revisions of the scenarios under review: for example, the 2023 update of the NGFS scenario projections (using Phase IV instead of Phase III data) suggests that every year that goes without the necessary steps towards carbon neutrality implies a worsening of transition-induced asset price effects, as greenhouse gas emissions will remain higher for longer. Using these updates, a delay in the net-zero transition will drive up the overall carbon cost burden that is required over the next decade.

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[83] See, for example, Grinblatt et al. (2023).

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ANNEX

Table A.1: Sample construction – Stock corporations under review

Table A.1a) Full sample *Classification by main sector of activity*	Equity market capitalization (2020), € bn	Aggregate scope 1 emissions*, Mt CO_2e	Average scope 1 emission intensity**	Number of stock corporations under review	of which number of stock corporations domiciled in: Europe	US, CA, AU, NZ	China	Japan, S. Korea
	- all regions -							
Airlines	105	165	1,131	18	3	4	4	2
Aviation (ex airlines), Aerospace, Defense	1026	96	112	104	39	23	16	9
Construction, Engineering	2,247	186	122	550	175	71	63	143
Chemicals industry	1,379	443	342	196	47	34	54	20
Services	11,987	242	53	1471	483	314	104	327
Transport, Automotive industry, Infrastructure	2,182	184	163	326	61	46	37	90
Coal industry (mining, power production)[1]	210	1,780	4,805	43	3	7	17	1
Other mining, Metal processing	945	212	422	89	17	37	11	7
Other manufacturing	19,931	280	42	1,848	381	230	241	440
Oil and Gas industries (extraction, power prod.)[2]	1,760	1,484	815	153	31	56	7	13
Renewable energies[3]	367	84	550	34	11	8	5	1
Other/mixed energy/Utilities	889	1,579	2,435	105	26	40	4	7
Cement industry	198	803	4,147	43	4	1	10	3
Steel industry	305	937	1,542	70	12	14	16	12
Total sample	**43,531**	**8,477**	**259**	**5,050**	**1,293**	**885**	**589**	**1,075**
Table A.1b) Subsample: ***Firms with data on revenue shares by energy carrier*** *(provided by ISS-ESG)*					Average revenue share related to activities in extraction of / power production using: **Coal**	**Oil**	**Gas**	**Renew. energies**
Aviation (ex airlines), …	-	-	-	1	-	-	-	-
Construction, Engineering	228	45	539	41	0.089	0.018	0.002	0.001
Chemicals industry	256	139	544	27	0.018	0.092	0.012	0.000
Services	400	76	446	46	0.043	0.027	0.025	0.012
Transport, Automotive industry, Infrastructure	506	35	447	12	0.053	0.000	0.065	0.001
Coal industry (mining, coal-fired power production)[1]	205	1,779	5,031	41	0.760	0.006	0.038	0.030
Other mining, Metal processing	277	125	712	19	0.041	0.112	0.002	0.001
Other manufacturing	134	14	313	14	0.022	0.000	0.017	0.032
Oil and gas industries (extraction, power prod.)[2]	1,453	1278	1,028	111	0.017	0.487	0.240	0.014
Renewable energies[3]	358	84	591	31	0.024	0.000	0.047	0.652
Other/mixed energy/Utilities	783	1,559	3,105	76	0.124	0.012	0.163	0.072
Cement industry	58	107	3,728	11	0.016	0.000	0.006	0.000
Steel industry	121	561	2,407	15	0.076	0.001	0.004	0.001
Total subsample	**4,780**	**5,803**	**1,646**	**445**	**0.118**	**0.135**	**0.101**	**0.067**

Source: *ISS-ESG*, Thomson Reuters, own classification based on GICS.

*) 2019 GHG emissions in million tonnes of CO_2 equivalents.

**) 2019 GHG emissions in tonnes of CO_2 equivalents per €1 million of revenue.

Table A.2: Sectoral equity price impacts of a *Net Zero 2050* transition: Mean comparison tests of alternative baselines. Significance level of rejecting the equality of means:*** 1%, ** 5%, * 10%

	Price impact after an expectations shock in 2020 using analyst expectations of end-2020	*No pass-through of scope 1 emission costs* Baseline scenario: *Current Policies*	*NDCs*	difference	*80% pass-through of scope 1 emission costs* Baseline scenario: *Current Policies*	*NDCs*	difference
REMIND-MAgPIE	Airlines	-0.931	-0.912	0.019*	-0.836	-0.812	0.025***
	Aviation ex airlines, Aerospace, Defense	-0.287	-0.235	0.052***	-0.17	-0.137	0.033***
	Construction, Engineering	-0.114	-0.072	0.043***	-0.047	-0.032	0.015***
	Chemicals industry	-0.258	-0.174	0.084***	-0.085	-0.065	0.02***
	Services	-0.046	-0.027	0.019***	-0.026	-0.018	0.008***
	Transport, Automotive industry, infrastructure	-0.226	-0.171	0.054***	-0.101	-0.073	0.028***
	Coal industry	-0.823	-0.75	0.073***	-0.671	-0.56	0.111***
	Other mining, metal process.	-0.31	-0.194	0.115***	-0.102	-0.057	0.045***
	Other manufacturing	-0.065	-0.037	0.027***	-0.026	-0.016	0.01***
	Oil and gas industries	-0.646	-0.454	0.193***	-0.39	-0.259	0.131***
	Renewable energies	0.03	0.064	0.034	0.175	0.137	-0.038***
	Other/mixed energy/Utilities	-0.595	-0.33	0.265***	-0.256	-0.133	0.123***
	Cement industry	-0.804	-0.713	0.091**	-0.562	-0.608	-0.046**
	Steel industry	-0.685	-0.591	0.094**	-0.391	-0.321	0.07*
	Total	-0.144	-0.099	0.044***	-0.072	-0.053	0.02***
MESSAGE-GLOBIOM	Airlines	-1	-1	0	-0.915	-0.904	0.011
	Aviation ex airlines, Aerospace, Defense	-0.527	-0.429	0.097***	-0.387	-0.288	0.099***
	Construction, Engineering	-0.201	-0.178	0.023***	-0.083	-0.07	0.013***
	Chemicals industry	-0.459	-0.323	0.135***	-0.192	0.013	0.205***
	Services	-0.079	-0.067	0.011***	-0.036	-0.03	0.006***
	Transport, Automotive industry, infrastructure	-0.38	-0.347	0.034***	-0.224	-0.187	0.038***
	Coal industry	-0.909	-0.895	0.014***	-0.787	-0.719	0.068***
	Other mining, metal process.	-0.468	-0.342	0.126***	-0.184	-0.047	0.137***
	Other manufacturing	-0.125	-0.113	0.012***	-0.046	-0.038	0.008***
	Oil and gas industries	-0.791	-0.781	0.01*	-0.559	-0.505	0.054***
	Renewable energies	0.092	-0.139	-0.231***	0.37	0.078	-0.293***
	Other/mixed energy/Utilities	-0.72	-0.708	0.013	-0.469	-0.446	0.023*
	Cement industry	-0.857	-0.836	0.021	-0.636	-0.608	0.028**
	Steel industry	-0.913	-0.919	-0.006	-0.776	-0.785	-0.009
GCAM	Airlines	-0.909	-0.559	0.35***	-0.772	-0.5	0.272***
	Aviation ex airlines, Aerospace, Defense	-0.319	-0.195	0.125***	-0.197	-0.115	0.082***
	Construction, Engineering	-0.119	-0.001	0.118***	-0.044	-0.005	0.039***
	Chemicals industry	-0.277	-0.18	0.097***	-0.097	-0.154	-0.056***
	Services	-0.043	-0.006	0.037***	-0.019	-0.007	0.013***
	Transport, Automotive industry, infrastructure	-0.239	-0.111	0.128***	-0.118	-0.056s	0.062***
	Coal industry	-0.734	-0.341	0.394***	-0.504	-0.269	0.235***
	Other mining, metal processing	-0.383	0.013	0.396**	-0.155	0.035	0.19***
	Other manufacturing	-0.07	-0.008	0.062***	-0.022	-0.008	0.014***
	Oil and gas industries	-0.642	0.015	0.656***	-0.369	-0.14	0.229***
	Renewable energies	0.438	0.151	-0.288***	0.564	0.206	-0.357***
	Other/mixed energy/Utilities	-0.556	-0.049	0.507***	-0.132	0.023	0.155***
	Cement industry	-0.922	-0.752	0.17***	-0.725	-0.558	0.168***
	Steel industry	-0.779	-0.507	0.272***	-0.521	-0.254	0.267***

Table A.3: Sectoral price impacts of a *Net Zero 2050* transition under alternative baselines

Assumption: No pass-through of scope 1 emission costs	**Baseline scenario: *Current Policies***				**Baseline scenario: *Nationally Determined Contributions***		
	REMIND	MESSAGE	GCAM	EPPA	REMIND	MESSAGE	GCAM
Airlines	-0.931	-1	-0.909	-0.883	-0.912	-1	-0.559
Aviation ex airlines, Aerospace, Defense	-0.287	-0.527	-0.319	-0.212	-0.235	-0.429	-0.195
Construction, Engineering	-0.114	-0.201	-0.119	-0.165	-0.072	-0.178	-0.001
Chemicals industry	-0.258	-0.459	-0.277	-0.318	-0.174	-0.323	-0.18
Services	-0.046	-0.079	-0.043	-0.099	-0.027	-0.067	-0.006
Transport, Automotive industry, infrastructure	-0.226	-0.38	-0.239	-0.189	-0.171	-0.347	-0.111
Coal industry	-0.823	-0.909	-0.734	-0.781	-0.75	-0.895	-0.341
Other mining, metal processing	-0.31	-0.468	-0.383	-0.335	-0.194	-0.342	0.013
Other manufacturing	-0.065	-0.125	-0.07	-0.136	-0.037	-0.113	-0.008
Oil and gas industries	-0.646	-0.791	-0.642	-0.633	-0.454	-0.781	0.015
Renewable energies	0.03	0.092	0.438	-0.005	0.064	-0.139	0.151
Other/mixed energy/Utilities	-0.595	-0.72	-0.556	-0.575	-0.33	-0.708	-0.049
Cement industry	-0.804	-0.857	-0.922	-0.806	-0.713	-0.836	-0.752
Steel industry	-0.685	-0.913	-0.779	-0.733	-0.591	-0.919	-0.507
Total	**-0.144**	**-0.221**	**-0.146**	**-0.189**	**-0.099**	**-0.2**	**-0.041**

Assumption: 80% pass-through of scope 1 emission costs	**Baseline scenario: *Current Policies***				**Baseline scenario: *Nationally Determined Contributions***		
	REMIND	MESSAGE	GCAM	EPPA	REMIND	MESSAGE	GCAM
Airlines	-0.836	-0.915	-0.772	-0.586	-0.812	-0.904	-0.5
Aviation ex airlines, Aerospace, Defense	-0.17	-0.387	-0.197	-0.136	-0.137	-0.288	-0.115
Construction, Engineering	-0.047	-0.083	-0.044	-0.102	-0.032	-0.07	-0.005
Chemicals industry	-0.085	-0.192	-0.097	-0.159	-0.065	0.013	-0.154
Services	-0.026	-0.036	-0.019	-0.076	-0.018	-0.03	-0.007
Transport, Automotive industry, infrastructure	-0.101	-0.224	-0.118	-0.117	-0.073	-0.187	-0.056
Coal industry	-0.671	-0.787	-0.504	-0.613	-0.56	-0.719	-0.269
Other mining, metal processing	-0.102	-0.184	-0.155	-0.183	-0.057	-0.047	0.035
Other manufacturing	-0.026	-0.046	-0.022	-0.094	-0.016	-0.038	-0.008
Oil and gas industries	-0.39	-0.559	-0.369	-0.425	-0.259	-0.505	-0.14
Renewable energies	0.175	0.37	0.564	0.217	0.137	0.078	0.206
Other/mixed energy/Utilities	-0.256	-0.469	-0.132	-0.24	-0.133	-0.446	0.023
Cement industry	-0.562	-0.636	-0.725	-0.603	-0.608	-0.608	-0.558
Steel industry	-0.391	-0.776	-0.521	-0.488	-0.321	-0.785	-0.254
Total	**-0.072**	**-0.12**	**-0.067**	**-0.123**	**-0.053**	**-0.098**	**-0.032**

Table A.4: Projected stranding ratios[*] after an expectations shock to *Net Zero 2050*

Assumption: No pass-through of scope 1 emission costs	**Baseline scenario: *Current policies***				**Baseline scenario: *Nationally Determined Contributions***		
	REMIND	MESSAGE	GCAM	EPPA	REMIND	MESSAGE	GCAM
Airlines	0.89	1	0.89	0.89	0.89	1	0.833
Aviation ex airlines, Aerospace, Defense	0.183	0.308	0.202	0.125	0.144	0.269	0.173
Construction, Engineering	0.071	0.136	0.073	0.087	0.045	0.125	0.038
Chemicals industry	0.173	0.403	0.214	0.204	0.122	0.383	0.327
Services	0.026	0.045	0.027	0.035	0.017	0.041	0.014
Transport, Automotive industry, infrastructure	0.156	0.267	0.193	0.086	0.107	0.255	0.107
Coal industry	0.791	0.884	0.721	0.86	0.767	0.884	0.512
Other mining, metal processing	0.247	0.372	0.361	0.236	0.169	0.337	0.181
Other manufacturing	0.03	0.077	0.04	0.044	0.019	0.075	0.021
Oil and gas industries	0.582	0.765	0.608	0.654	0.379	0.752	0.392
Renewable energies	0.088	0.206	0.059	0.20	0.059	0.206	0.029
Other/mixed energy/Utilities	0.543	0.714	0.543	0.61	0.305	0.695	0.324
Cement industry	0.767	0.837	1	0.791	0.837	0.884	0.977
Steel industry	0.657	0.929	0.814	0.7	0.629	0.929	0.7
Total	**0.106**	**0.172**	**0.12**	**0.117**	**0.078**	**0.166**	**0.086**

Assumption: 80% pass-through of scope 1 emission costs	**Baseline scenario: *Current policies***				**Baseline scenario: *Nationally Determined Contributions***		
	REMIND	MESSAGE	GCAM	EPPA	REMIND	MESSAGE	GCAM
Airlines	0.833	0.889	0.778	0.444	0.833	0.833	0.556
Aviation ex airlines, Aerospace, Defense	0.067	0.125	0.096	0.058	0.067	0.115	0.067
Construction, Engineering	0.02	0.045	0.024	0.029	0.018	0.042	0.013
Chemicals industry	0.031	0.158	0.071	0.056	0.031	0.117	0.27
Services	0.014	0.016	0.014	0.014	0.011	0.016	0.008
Transport, Automotive industry, infrastructure	0.037	0.08	0.055	0.04	0.031	0.08	0.043
Coal industry	0.535	0.698	0.326	0.651	0.419	0.581	0.256
Other mining, metal processing	0.056	0.128	0.111	0.101	0.034	0.116	0.028
Other manufacturing	0.006	0.019	0.01	0.012	0.005	0.017	0.008
Oil and gas industries	0.229	0.464	0.275	0.32	0.137	0.359	0.196
Renewable energies	0	0	0	0	0	0.029	0
Other/mixed energy/Utilities	0.143	0.41	0.162	0.19	0.086	0.381	0.067
Cement industry	0.512	0.628	0.791	0.558	0.791	0.698	0.744
Steel industry	0.3	0.786	0.514	0.443	0.329	0.771	0.371
Total	**0.04**	**0.081**	**0.051**	**0.051**	**0.036**	**0.073**	**0.045**

[*]) Stranding ratios are calculated as the number of firms with a stranding event between 2020 and 2050, divided by the sum of all firms under review. See Table A.1 for the representation of firms per sector.

Figure A.5a: Equity price impact of scope 1 emissions and incremental impact of adding the cost of scope 2 emissions under the *Current Policies* baseline using REMIND-MAgPIE, by region

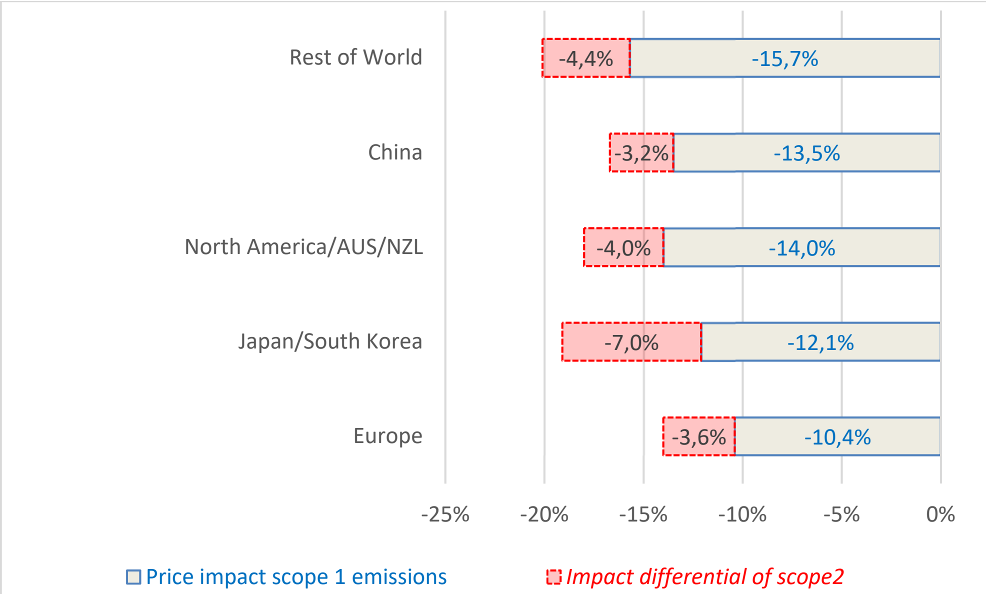
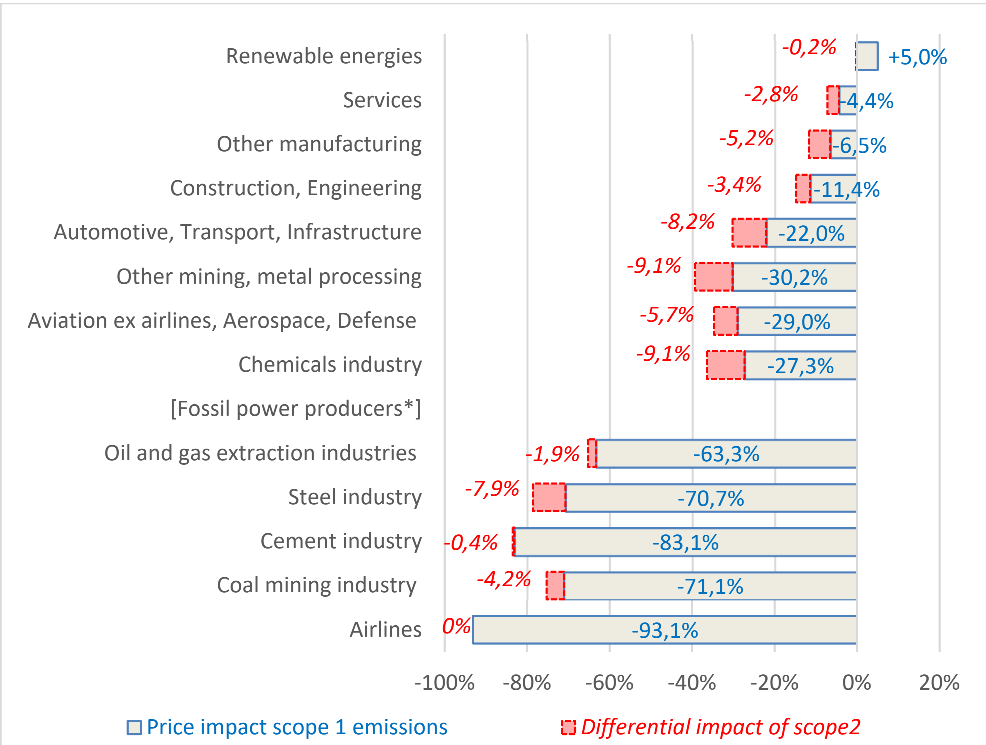


Figure A.5b: Equity price impact of scope 1 emissions and incremental impact of adding the cost of scope 2 emissions under the *Current Policies* baseline using REMIND-MAgPIE, by sector



*) To the extent that the data vendor ISS-ESG provides energy-related revenue data for firms in 2019, firms are classified as "Fossil power producers" if a revenue share of at least 50% stems from power generation and if, within power production, a revenue share of at least 25% stems from fossil fuel-based power production. These fossil fuel-based power producers are assumed to pass on all their scope 1 emission costs, which represent scope 2 emission costs for the remaining sectors. By assumption, no emission costs remain with fossil-fuel based power producers in this setting.

Table A.6: Testing for intra-sectoral differences in implied returns on equity: Do firms' GHG emissions and their disclosure make a difference?

	Testing for the equality of the sector mean (implied return on equity)	*Testing the intra-sectoral equality of RoE means: disclosing firms versus non-disclosing# firms*			*Testing the intra-sectoral equality of RoE means: high emission firms vs. low-emission firms*		
					below/above sector median:		
		No disclosure (sample restricted to firms whose emissions are estimated by ISS-ESG#)	*Disclosure (sample restricted to firms whose where self-reported emission data are available)*	difference	*Low scope1 emissions*	*High scope1 emissions*	difference
REMIND-MAgPIE	Airlines	.117	.102	-.015	.108	.110	-.003
	Aviation ex airlines, Aerospace, Defense	.054	.072	+.018**	.064	.064	-.000
	Construction, Engineering	.086	.080	-.006*	.086	.081	-.006
	Chemicals industry	.094	.079	-.015**	.088	.086	-.002
	Services	.080	.084	+.004**	.080	.083	-.003
	Transport, Automotive industry, infrastructure	.087	.081	-.006	.091	.079	-.012**
	Coal industry	.098	.095	-.003	.086	.106	+.019
	Other mining, metal process.	.088	.089	+.001	.085	.093	+.008
	Other manufacturing	.084	.074	-.010***	.084	.077	-.007***
	Oil and gas industries	.129	.088	-.041**	.111	.091	-.020
	Renewable energies	.075	.092	+.017	.084	.085	+.001
	Other/mixed energy/Utilities	.094	.082	-.012**	.088	.082	-.006
	Cement industry	.131	.066	-.066***	.126	.074	-.053***
	Steel industry	.069	.102	+.034**	.059	.106	+.047***
	Total	**.084**	**.081**	**-.002***	**.083**	**.082**	**-.001**

Notes: Table A.6 reports the results of two intra-sectoral mean comparison tests of implied returns on equity (*ex ante* RoE) which we use as discount rates: Firstly (left-hand columns), we compare the *ex ante* RoE of firms which report their GHG emissions with the *ex ante* RoE of non-disclosing firms (left-hand columns). Secondly, we compare the *ex ante* RoE of large emitters (firms with Scope 1 emissions above sector median) with the *ex ante* RoE of small emitters (firms with Scope 1 emissions below sector median). While the first test shows a weaker discounting of disclosing firms in 6 out of 14 sectors, and 5 sectors with an insignificant role of disclosure, the second test shows that large emitters exhibit significantly higher *ex ante* RoEs than small emitters only in the steel sector. This result for the *ex ante* RoE measure is not supportive to the findings of Atilgan et al. (2023) and Bolton and Kacperczyk (2021a).
Significance level of a rejection of the hypothesis of equal sector means: *** 1%, ** 5%, * 10%. Calculations are based on pre-Covid (2019) data from *ISS-ESG*. #) *ISG-ESG* provides estimated scope 1 emissions of firms where no self-reported emissions data of these firms are available.

Figure A.7a: Primary energy production pathways (rebased to 2020 level of global energy production in Exajoule)

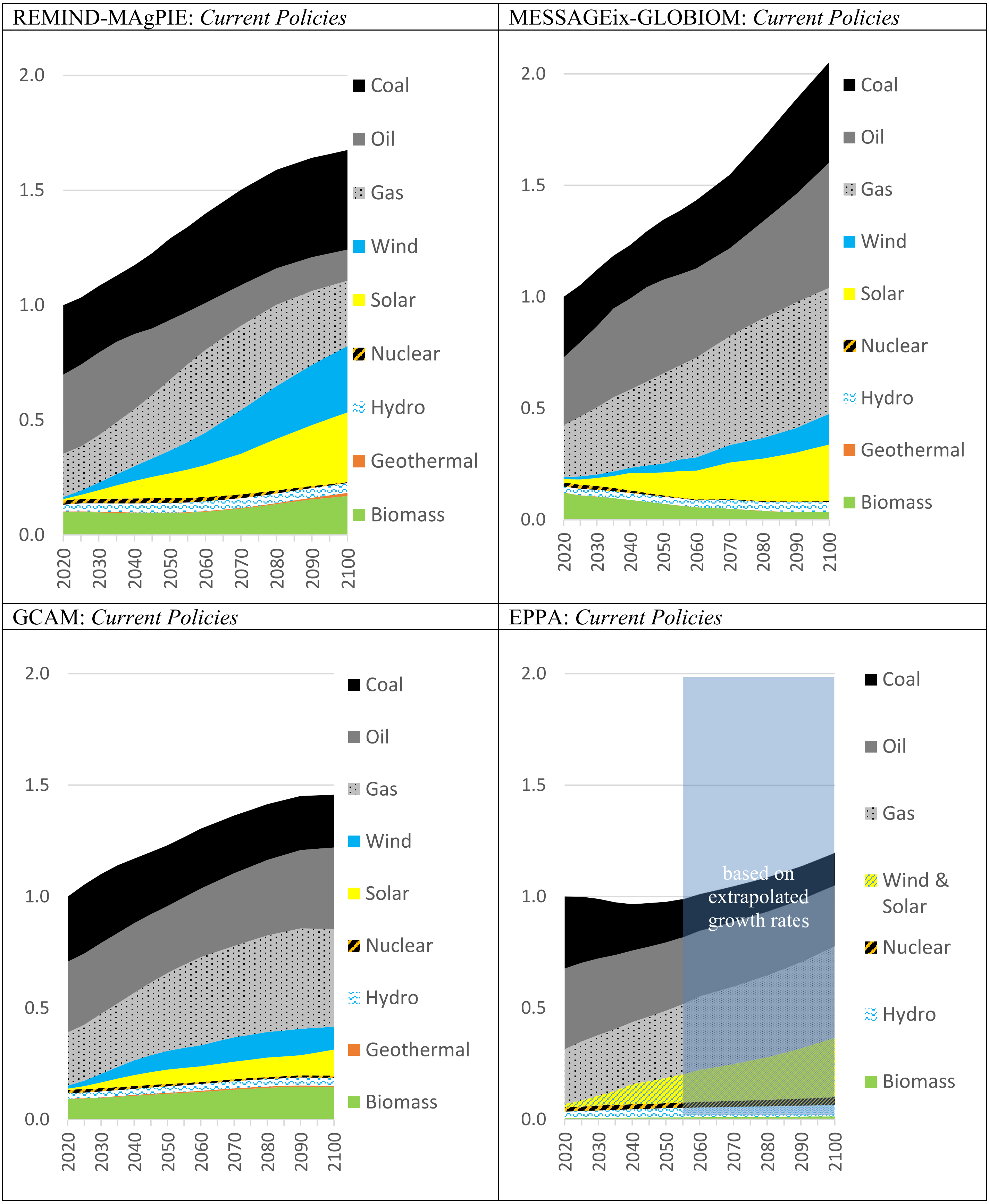


Figure A.7b: Primary energy production pathways (rebased to 2020 level of global energy production in Exajoule)