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Climate-Related Stress-Testing and Net-Zero Valuation: A Case Study for Selected Energy-Intensive Companies

Theo Le Guenedal, Henry Chen, Yassine Derbel, Benjamin Duval, Mathieu Jouanneau, Matthieu Keip, Tegwen Le Berthe, Frederic Lepetit, Rami Mery and Sergey Paltsev

MIT Joint Program on the Science and Policy of Global Change combines cutting-edge scientific research with independent policy analysis to provide a solid foundation for the public and private decisions needed to mitigate and adapt to unavoidable global environmental changes. Being data-driven, the Joint Program uses extensive Earth system and economic data and models to produce quantitative analysis and predictions of the risks of climate change and the challenges of limiting human influence on the environment—essential knowledge for the international dialogue toward a global response to climate change.

To this end, the Joint Program brings together an interdisciplinary group from two established MIT research centers: the **Center for Global Change Science (CGCS)** and the **Center for Energy and Environmental Policy Research (CEEPR)**. These two centers—along with collaborators from the Marine Biology Laboratory (MBL) at Woods Hole and short- and long-term visitors—provide the united vision needed to solve global challenges.

At the heart of much of the program's work lies MIT's Integrated Global System Model. Through this integrated model, the program seeks to discover new interactions among natural and human climate system components; objectively assess uncertainty in economic and climate projections; critically and quantitatively analyze environmental management and policy proposals; understand complex connections among the many forces that will shape our future; and improve methods to model, monitor and verify greenhouse gas emissions and climatic impacts.

This report is intended to communicate research results and improve public understanding of global environment and energy challenges, thereby contributing to informed debate about climate change and the economic and social implications of policy alternatives.

—Ronald G. Prinn,
Joint Program Director

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Climate-Related Stress-Testing and Net-Zero Valuation: A Case Study for Selected Energy-Intensive Companies

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Abstract: This paper proposes a methodology for quantifying the climate-related transition impacts on energy-intensive companies. In this study, we use a publicly available dataset created by the Bank of Canada that combines the scenarios developed by the MIT Economic Projection and Policy Analysis (EPPA) model with the results from two macroeconomic models (ToTEM and BoC-GEM-Fin) to illustrate price and production patterns for 10 emission-intensive sectors across 8 aggregated regions. Our focus lies on mapping the trajectories of future sectoral revenues and operating expenditures (direct and indirect costs) to company-level impacts. We align these indicators with the top-down approach used by the European Central Bank to measure issuer-specific exposure to transition risk. By incorporating company-level data, such as revenues in sub-activities and direct emissions, we are able to compute issuer-level financial statements that are particularly relevant to define scenario- based equity valuation ratio and corporate credit risk. By examining the narrative established by the Network for Greening the Financial System (NGFS) – which includes current policies, nationally determined contributions, net-zero targets, staying below 2°C, and delayed transition – we assess the added value of employing such models for asset allocation. The conclusions drawn from our case study analysis suggest a significant heterogeneity within sectors and demonstrate that the diversification of corporate revenues in sub-activities leads to distinct valuation patterns.

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1. Introduction

Since Mark Carney's landmark speech in 2015 (Carney, 2015), climate-related risks are increasingly considered by the financial community. Regulators and central bankers have explicitly called on financial institutions to establish stress-testing frameworks to measure the extent of their exposure to projected transition and physical risks (ESMA, 2022). This paper focuses on the transition dimension and is particularly suited for estimating transition risk in carbon-intensive sectors at a company level. The main objective is to investigate the value-added from connecting integrated assessment models (IAMs) with the field of asset management, and in particular to provide some illustration of the potential transmission channels to financial statements, relevant in operational valuation models.

Transition risks originate from the shift towards a low-carbon economy, when current activities might be affected by markets and government actions rather than being directly caused by the physical impacts of climate change. These risks arise due to policies aimed at reducing greenhouse gas (GHG) emissions and the corresponding mitigating global warming. For instance, an industrial company that relies on carbon-intensive processes faces risks if regulations become stricter. Changes in consumer demand can also contribute to transition risks. A car manufacturer may experience losses if its products do not align with customers' environmental expectations. Assessments of transition risks typically hinge on a scenario analysis. The initial step involves understanding of the construction of these scenarios, which typically depend on integrated assessment models (IAMs). For suggesting the company-specific emission reduction targets, numerous initiatives use science-based global CO_2 emission trajectories from IAMs (IPCC, 2022) or International Energy Agency (IEA, 2022). While assigning a global emission trajectory to a company level may provide a rough indication of the required mitigation effort, it does not represent heterogeneity of company-specific characteristics. In this paper, we add to the existing literature by providing an example of using the IAMs for transition risk assessment and connecting the results to the impacts at a company level. We rely on the MIT Economic Projection and Policy Analysis (EPPA) model to expand the use of transition scenarios to assess the impact on a representative sample of energy-intensive companies and illustrate the framework with narratives based on mainstream scenarios defined by the Network for Greening the Financial System (NGFS, Boirard *et al.*, 2022).

Addressing the impact of climate-related risks on the real economy and the financial system is essential, given the potential systemic implications. While the direct impact of transition risk on climate-relevant sectors may appear somewhat limited (e.g., 2 Investing Initiative, 2018; Aubert *et al.*, 2019; EIOPA, 2018; Schotten *et al.*, 2016; Vermeulen *et al.*, 2018; Vermeulen *et al.*, 2019; Weyzig *et al.*, 2014 indicate an average exposure of around 10%; see Bouchet *et al.*, 2020), potential cascading effects on the supply chain (Adenot *et al.*, 2022; Cahen-Fourot *et al.*, 2019; Mardones *et al.*, 2020) and financial loss contagion have drawn significant research attention and led to the development of various stress-test methodologies. One of the first climate stress-tests within the banking sector was proposed by Battiston *et al.* (2017) and recently extended by Roncoroni *et al.* (2021).[1] Overall, numerous stress-testing frameworks for the financial and banking system have been proposed (Allen *et al.*, 2020; Alogoskoufis *et al.*, 2021; Dunz *et al.*, 2021; Gourdel *et al.*, 2021; Grippa *et al.*, 2020; Nguyen *et al.*, 2020; Reinders *et al.*, 2020, etc.), differing in the methods, risk scopes or universes considered, that are reviewed and classified in Cartellier (2022). However, these methodologies are better adapted to meet the needs of the banking community than those of asset managers. To introduce a method more suitable for investment portfolios, a systematic stress-testing approach for determining investment portfolio value-at-risk in transition scenarios has been established in Desnos *et al.* (2023). This allows to define a forward-looking portfolio value at risk in the context of deep uncertainty.

In this paper, we introduce a complementary transparent method in line with the methodology developed by the European Central Bank (Alogoskoufis *et al.*, 2021), integrating the trajectories for climate-relevant variables from the Bank of Canada's study[2] on transition risks (Chen *et al.*, 2022b) to derive impact at the issuer level designed for strategic allocation. In general, bottom-up methodologies are privileged in asset management. Although the seminal approach of the central bank is top-down (based on globally fitted exposure), the resolution of the EPPA model (22 sectors in 18 regions) and the introduction of relevant asset level data make this approach impeccably relevant in the context of strategic allocation or stock picking. In this study, we utilize an accessible dataset created by the Bank of Canada that combines the MIT Economic Projection and Policy Analysis (EPPA7) model with two macroeconomic models (ToTEM and BoC-GEM-Fin) to illustrate price and production patterns for 10 emission-intensive sectors across 8 aggregated regions. While our overall goal is to compare transition impacts in numerous sectors of the economy and different regions of the world, in this paper we focus on illustrating our approach by applying it to several energy-intensive companies. It allows us to compare and contrast how different companies might be

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[1] In these papers, authors focus on the financial system interconnectedness rather than on the real economy interdepencies (e.g. materials, resources, chemicals, fuel, etc.).

[2] Bank of Canada's scenario data are available at: https://www.bankofcanada.ca/2022/01/climate-transition-scenario-data/.

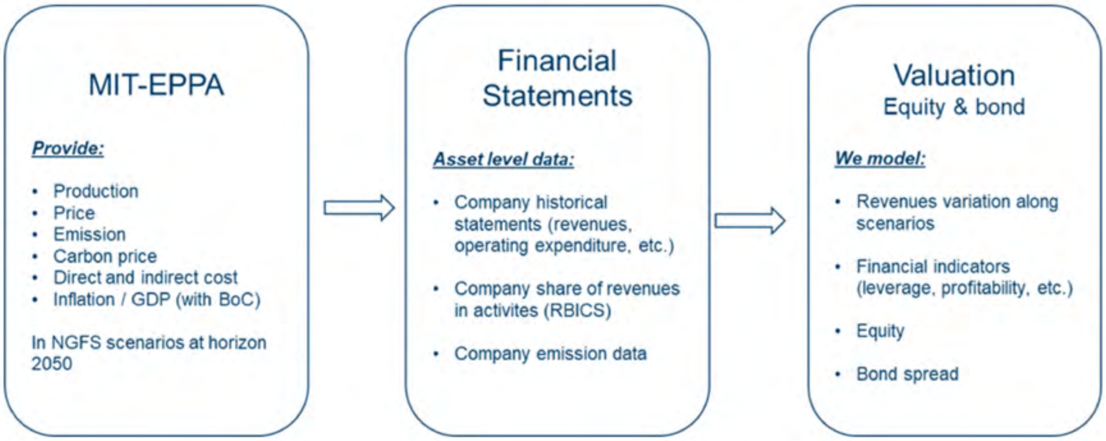

Figure 1. Schematic of the framework

affected by the same conditions of the transition scenario exercise. The Framework is illustrated in **Figure 1**.

Beyond the risk dimension, the top-down modeling of the future cash-flows and profitability presented in this paper, also aims at measuring the potential investment opportunities associated with the NGFS transition scenarios represented by the MIT's general computable equilibrium (GCE) EPPA7 model. For example, we measure the scenario-based equity valuation ratio (relative value of discounted cash flow in a given scenario with respect to the baseline), and show that pure players' value may substantially increase in Net-zero scenarios. In the context of mergers analysis, shareholders would also benefit from merging premia which suggest that there are clear investment opportunities in the clean technology sector.

The paper is organized in the following way. Section 2 explains the construction of scenarios and describes the major features of the EPPA model. Section 3 models the transmission of the shocks on financial variables and estimates the impact on several energy-intensive companies. It also presents the results for our sample of case studies on equity and bonds relative prices. Section 4 provides concluding remarks.

2. Transition scenarios

2.1 Scenario design and integrated assessment models

We use the MIT's Economic Projection and Policy Analysis (EPPA) model (Chen *et al.*, 2016; Chen *et al.*, 2022a; Paltsev *et al.*, 2005) to derive price, production, and emission patterns for 22 sectors in 18 regions to represent the trajectory of future sectoral cash-flows and the required capital expenditure, including issuer specific correction factors. In this exercise, we leverage the dataset (Chen *et al.*, 2022b) produced by the Bank of Canada with inputs from several models (EPPA, ToTEM and BOC-GEM-Fin) to illustrate the value added of the MIT-EPPA framework in the field of asset management. In particular, the EPPA7 framework accounts for global trade effect which allows us to derive impact factors for sectors that are not directly modeled by the framework and to study the breakdown of carbon risk contribution in scenarios based on Phase III of the NGFS climate scenarios released in September 2022 (Richters *et al.*, 2022).

Most studies aiming at measuring transition risks are based on a scenario analysis. Scenarios are derived from deterministic economic modeling of climate risk made by integrated assessment models (IAMs), introducing climate considerations in classic macroeconomic modeling. William Nordhaus' seminal dynamic integrated climate economy (DICE) model (Nordhaus *et al.*, 1992) is one of the first and certainly the most notorious integrated model, and the literature in this domain has been growing ever since (Hourcade *et al.*, 2021; IPCC, 2022).

The integrated models most used by practitioners and public institutions fall in two main categories: cost-benefit and cost-efficiency models. Cost-benefit optimization models, such as the seminal DICE (Nordhaus *et al.*, 1992), essentially allow policy makers to draw a path for the social cost of carbon maximizing the welfare over time balancing the costs of (present and future) climate damage against those of (present and future) mitigation. The optimal GHG emission reduction rate and the corresponding carbon price are directly translated to the social cost of carbon. Although they are popular and widely used in the fields of policy making and energy, cost-benefit models are based on strong functional and parameter assumptions that have relatively weak empirical applications (Kohler *et al.*, 2006) in the field of asset management, requiring much finer sector (and country) granularity.

Conversely, the second category of models typically provides a more detailed representation of sectors, countries, and their interactions, enabling the determination of the optimal (or least costly) pathways to achieve a specified emission scenario without the need to calculate the future climate damages. Notable examples within this category include the Economic Projection and Policy Analysis (EPPA) model (Babiker *et al.*, 2001; Chen *et al.*, 2022a; Paltsev *et al.*, 2005) from the MIT Joint Program on the Science and Policy of Global Change, as well as the IMACLIM-R model (Hourcade *et al.*, 2010) developed by the Centre International de Recherche sur l'Environnement et le D´eveloppement (CIRED). Irrespective of their classification, these models can be organized based on three principal attributes (Hourcade *et al.*, 2021): (i) the degree of technological specificity, (ii) the complexity of macroeconomic feedbacks, and (iii) the realism of agents and markets, as depicted in **Figure 2** from Hourcade *et al.* (2021). For instance, models used by the NGFS (from the REMIND/MERGE/IMAGE/MESSAGE/GCAM families) originally possessed a higher level of technological specificity yet a simpler portrayal of the global economy when compared to EPPA, IMACLIM, or E3ME (Cambridge Econometrics, 2019), which provide enhanced sector granularity and multi-sectoral macroeconomic feedbacks according to Hourcade *et al.* (2021). Lastly, Stock-Flow Consistent (SFC) approaches (e.g., GEMMES, Daumas, 2022; Giraud *et al.*, 2016) endeavor to capture market behavior more accurately by accounting for imbalances and incorporating the financial sector (Dafermos *et al.*, 2017; Godley *et al.*, 2006). The optimal model does not necessarily exhibit superior performance in each attribute but possesses the most suitable configuration to address the question it was designed to tackle.

EPPA7 is particularly advanced in some aspects that are potentially useful for investment portfolio applications (e.g. non-homothetic preferences, explicit representation of international trade in different sectors of economy, capital vintage, endogenous representation of advanced technology deployment, etc.). Moreover, it has recently being used by the Bank of Canada to model climate-related financial risks by the Bank of Canada (Chen *et al.*, 2022b) and border carbon adjustments (Chen *et al.*, 2023). This model facilitates the evaluation of the effects on prices, output, and emissions resulting from various policy initiatives (such as taxes, quotas, or subsidies), potentially distinguishing between sectors and countries. Consequently, it is especially well-suited for examining the cascading consequences on investment portfolios in the face of an uncertain policy environment (c.f. policies 'menue'[3] on **Figure 3**). Indeed, a significant advantage of such models is that they consider differences among sectors and countries, as well as varied responses to the tax environment within investment portfolios. This means that these models acknowledge that the behavior of each issuer may not be a straightforward function of their carbon intensity or regulation level. This complexity requires the use of general equilibrium models, which can account for the diverse, non-linear responses to taxation and regulation. In essence, these models recognize and incorporate the complex interplay of economic and environmental factors across different regions and industries, offering a more accurate and nuanced view of climate-related risks and opportunities.

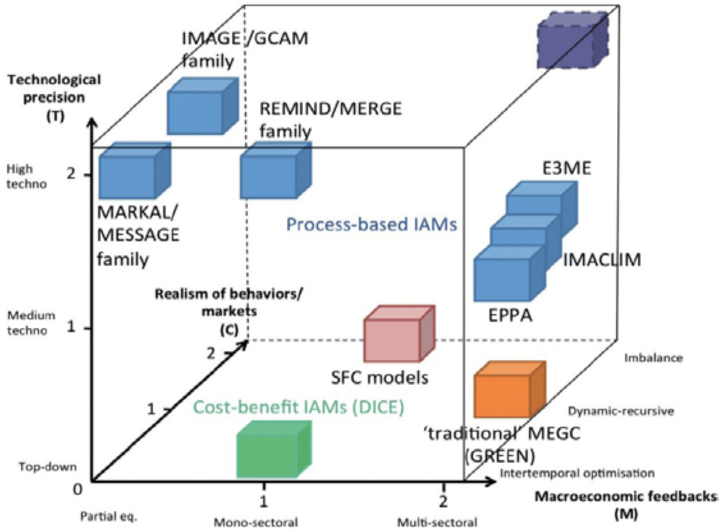

Figure 2. Taxonomy of energy/climate models in terms of three axes of characteristics

Source: Hourcade et al. (2021)

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[3] Fundamentally, this model serves as a tool for assessing different policy mechanisms, thereby enabling the evaluation of a wide range of policy actions. In the context of our current discussion, we primarily emphasize the approach of carbon pricing. Nonetheless, it is crucial to bear in mind that this model allows for the exploration of alternative strategies. Policymakers can opt for various courses of action, which underscores the model's adaptability to diverse policy interventions.

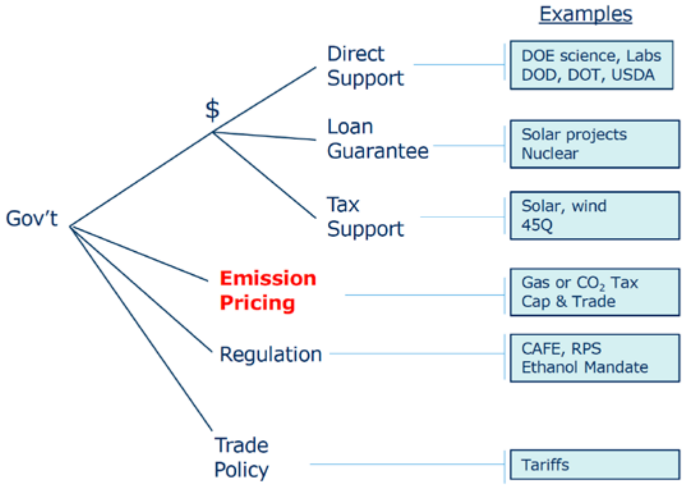

Figure 3. Examples of policy instruments available for an analysis in the EPPA model

Source: MIT Joint Program on the Science and Policy of Global Change

2.2 Transition scenarios narrative

Practitioners commonly use scenarios produced from IAMs to evaluate transition risk (Boirard *et al.*, 2022). Scenarios are derived from a series of assumptions and hypothesis characteristic of a particular storyline. For example, a typical reference for this type of narratives are the shared-socio-economic pathways (SSP) (Van Vuuren *et al.*, 2012) defined concomitantly with Representative concentration pathways (RCPs) (Van Vuuren *et al.*, 2011). The SSPs are five narratives about potential global futures that were developed to inform research in climate change, and to allow for the exploration of different potential ways that the world might develop over the 21st century in relation to challenges in adaptation to and mitigation of climate change. The five SSPs include a sustainable world (SSP1), a middle-of-the-road world (SSP2), a regional rivalry world (SSP3), an inequality world (SSP4), and a fossil-fueled development world (SSP5).[4] Each SSP offers a description of a potential future in terms of its socioeconomic conditions, including aspects like population growth, economic development, education, urbanization, and technological changes. The SSPs are designed to represent different levels of challenges to adaptation to and mitigation of climate change, and offer projection in very long term (2100 and more).

The Network for Greening the Financial System (NGFS, Boirard *et al.*, 2022) extracted and adapted its own scenarios with greater focus on the middle term and the climate-related risk dimensions. The NGFS scenarios are intended to be used by central banks, supervisors and financial institutions to assess climate-related risks to the economy and financial system.

In comparing the SSPs to the NGFS scenarios, it is important to note that both sets of scenarios share a goal of providing useful frameworks for thinking about the future under different conditions. However, the NGFS scenarios are more focused on financial stability and the potential impacts on the financial sector specifically, whereas the SSPs provide a broader view of different potential socioeconomic developments and their implications for climate change adaptation and mitigation. Both sets of scenarios could be used in complementary ways: the SSPs could provide a broad overview of potential socioeconomic futures and climate change challenges, while the NGFS scenarios could provide a more detailed view of potential impacts on the financial system under these different conditions. This combined approach could allow for a more comprehensive understanding of potential future risks and opportunities related to climate change.

In particular, the NGFS scenarios focus on the transition and physical risk dimensions and distinguish several courses of action (**Figure 4**). 'Orderly' scenarios focus on immediate and gradually tightening climate policies to

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[4] These pathways are characterized in terms of their adaptation and mitigation challenges as follows:

- SSP1: Low adaptation and mitigation challenges. This pathway imagines a world moving towards sustainability with reduced resource and energy consumption, lower emissions, and efforts to achieve the Sustainable Development Goals.
- SSP2: Medium adaptation and mitigation challenges. This pathway reflects a "business as usual" scenario where trends follow historical patterns.
- SSP3: High adaptation and high mitigation challenges. This pathway envisions a world with increasing inequality, fragmented regional economies, and slow technological change.
- SSP4: High adaptation challenges and low mitigation challenges. This pathway considers a world with increasing inequality, where the low-income groups are especially vulnerable to climate impacts.
- SSP5: Low adaptation challenges and high mitigation challenges. This pathway envisages a world driven by fossil-fuel dominated growth and innovation, leading to high greenhouse gas emissions and challenges in mitigation.

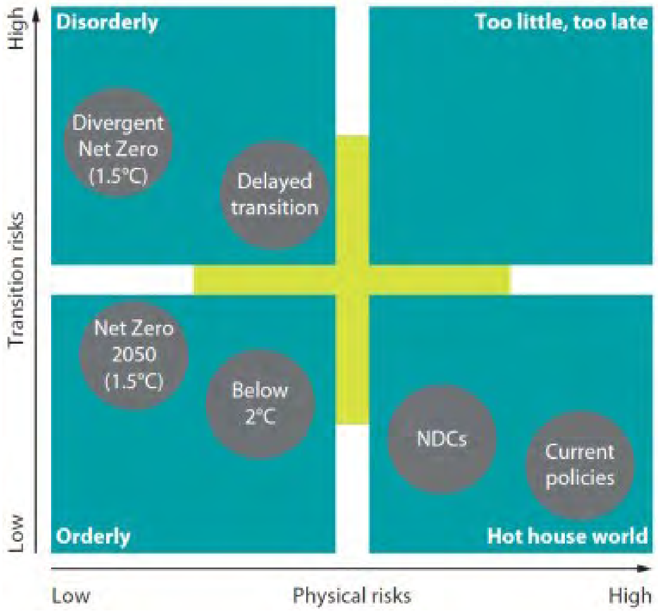

Figure 4. NGFS scenarios Framework

Source: The Network for Greening the Financial System (NGFS)

reduce climate change risks. This includes a plan to reach Net-Zero emissions by 2050 and another to increase climate policy strictness to ensure a high chance of limiting global warming to under 2 degrees Celsius. 'Disorderly' scenarios consider the risks associated with delays or inconsistencies in global climate policy adoption. In these scenarios, one expects to achieve Net-Zero emissions by 2050, albeit with inconsistency, and the other predicts no decrease in yearly emissions until 2030. Lastly, 'Hot house world' scenarios envisage severe global warming due to insufficient global efforts to counter climate change, including one based on already pledged climate goals and another assuming only existing policies continue. We focus on the following categories of the NGFS scenarios: baseline, below 2°, below 2°C delayed and net-zero emissions (NZE).

Baseline. In this scenario, the world follows a trajectory consistent with climate policies established by the end of 2019 (Chen *et al.*, 2022b), which leads to a continued rise in emissions and an increase in average global temperatures in about 3°C by 2100. Forestry maintains a global trend of being a net source of emissions through mid-century. The pace of technological change is slow, and the availability of carbon dioxide removal (CDR) technologies is limited.

Below 2°C immediate. In this scenario, starting in 2020, collective global action is taken to reduce emissions with the goal of keeping temperatures below 2°C by 2100. Early investments, planning, and management enable forests to become a small net sink by mid-century. The pace of technological change is moderate, and the availability of CDR technologies is limited.

Below 2°C delayed. This scenario assumes that, after a decade of adhering to the current policy frameworks, collective global action to align with a 2°C target begins in 2030. A steeper transition is needed to compensate for the additional decade of continued emissions growth. Delayed investments, planning, and management prevent forests from becoming a net sink by mid-century. The pace of technological change is moderate, and the availability of CDR technologies is limited.

Net-Zero 2050 (1.5°C). In this scenario, starting in 2020, collective global action is taken to reduce emissions with the aim of achieving a 1.5°C target by 2050. Current net-zero commitments by some countries are modeled directly in this scenario. Strong early actions enable forests to become a net sink by mid-century. The pace of technological change is fast, and the availability of CDR technologies is moderate, including bioenergy with carbon capture and storage.

2.3 MIT-EPPA model

General description

The MIT Economic Projection and Policy Analysis (EPPA) model is a recursive dynamic computable general equilibrium part of the Integrated Global Systems Modeling (IGSM) framework (Chen *et al.*, 2022a; Paltsev *et al.*, 2005; Sokolov *et al.*, 2005), widely used in energy and climate policy studies (e.g. Garcia-Muros *et al.*, 2022; Gurgel *et al.*, 2023; Octaviano *et al.*, 2016; Paltsev *et al.*, 2018; Paltsev *et al.*, 2022). The human systems are depicted by the interactions within 18 different world regions and 22 sectors between three economic agents (households, firms, and governments).

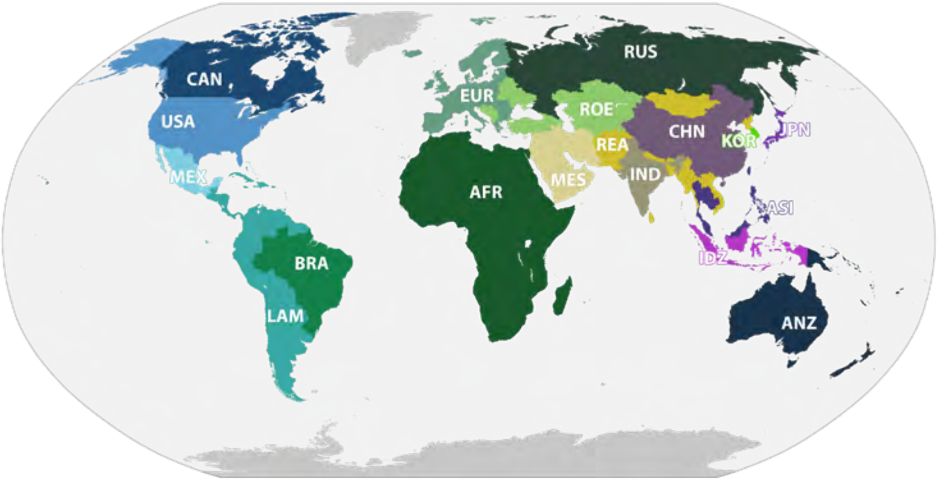

Figure 5. Regions in the MIT's Economic Projection and Policy Analysis (EPPA) model

Source: Gurgel et al. (2023)

The model projects economic variables (GDP, energy use, sectoral output, consumption, prices, etc.) and emissions of greenhouse gases (CO_2, CH_4, N_2O, HFCs, PFCs and SF_6) and other air pollutants (CO, VOC, NO_x, SO_2, NH_3, black carbon, and organic carbon) from combustion of carbon-based fuels, industrial processes, waste handling, agricultural activities and land use change. Key assumptions driving these projections include labor productivity growth, population growth, technology costs, fossil fuel resource availability, elasticities of substitution, energy efficiency improvements and urban pollutant trends.

The EPPA model used in this paper is built on the Global Trade Analysis Project (GTAP) economic dataset (Aguiar *et al.*, 2019) which provides a consistent representation of regional production, bilateral trade flows, and markets. Energy and land markets are supplemented with accounting in physical units. This economic data are augmented with additional information on advanced technologies, greenhouse gases and air pollutants emissions, taxes and details of selected economic sectors. Additional information about the version of the EPPA model used in this study can be found in Chen *et al.* (2022a).

Global results

In this section we summarize the major scenario results from the publicly available report and dataset from the Bank of Canada project (Chen *et al.*, 2022b). **Figure 6** illustrates the global primary energy in different scenarios. From the current dominance of fossil fuels, policy scenarios show an important role that low- and zero-emission alternatives play toward the middle of the century. Wind, solar, and bioenergy are critical for these scenarios. It is also notable that overall energy demand is lower in policy scenarios due to an increased energy efficiency and induced changed in consumer behavior.

As shown in **Figure 7**, policy scenarios lead to an accelerated electrification of the economy. As traditional fossil-fuel technologies are decommissioned, and large investments are made in renewable sources of energy to lower the emissions-intensity of electricity generation, other sectors substitute toward electricity. The net-zero 2050 scenario results in adoption of bioelectricity with CCS, beginning in 2035. It allows for negative emissions.

The dataset also provides output by sector for selected regions (USA, Europe, China, India, Canada, Japan, Africa) and selected sectors (Energy-Intensive Industries, Commercial Transportation, Electricity, Coal, Crude Oil, Refined Liquids, Natural Gas, Crops, Livestock, Forestry, Other industries) for 2020-2050 in different scenarios. In these scenarios, USA and China demonstrate more significant growth in the commercial transportation sector, while Europe and Japan experience relatively slower growth in this sector. China maintains a substantial presence in the coal sector compared to Europe and the United States, with Japan having no presence in the coal sector. Energy-intensive industries and livestock sectors exhibit varying degrees of growth across the regions, with China showing more substantial growth in energy-intensive industries compared to the other regions. The dataset also leverages the coupling with two macroeconomic models of Bank of Canada (Terms-of-Trade Economic Model, ToTEM and Band of Canada's Global Economic Model with Financial Frictions, BoC-GEM-Fin), to provide the Equity value for USA and Canada resulting from the transition scenario.

Focus on power generation in Europe In the realm of asset pricing, the key elements of consideration encompass production output, price, and both direct and indirect costs related to carbon emissions (see Section 3.1 for details). However, the main factor driving transition is the resulting energy and power generating mix modeled by the EPPA model.

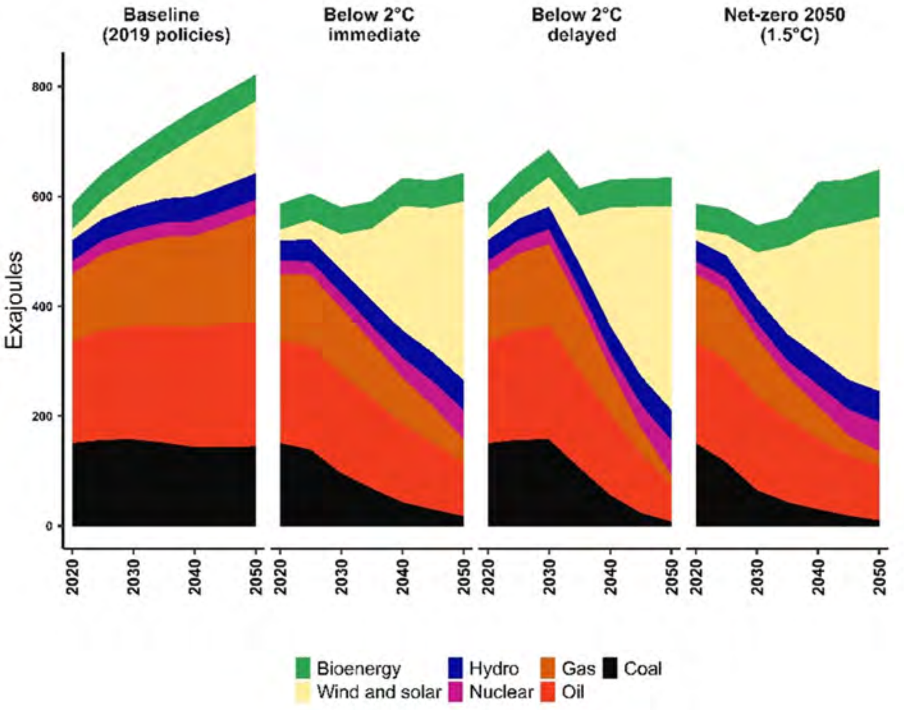

Figure 6. Global primary energy in different scenarios

Source: Chen et al. (2022b)

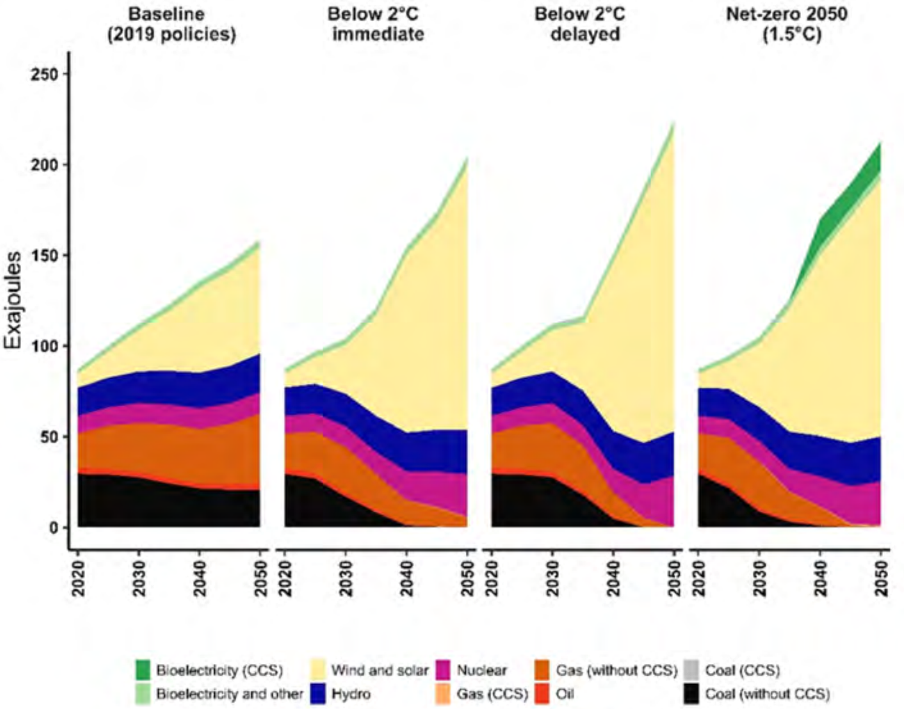

Figure 7. Global electricity generation in different scenarios

Source: Chen et al. (2022b). Note: CCS stands for carbon capture and storage

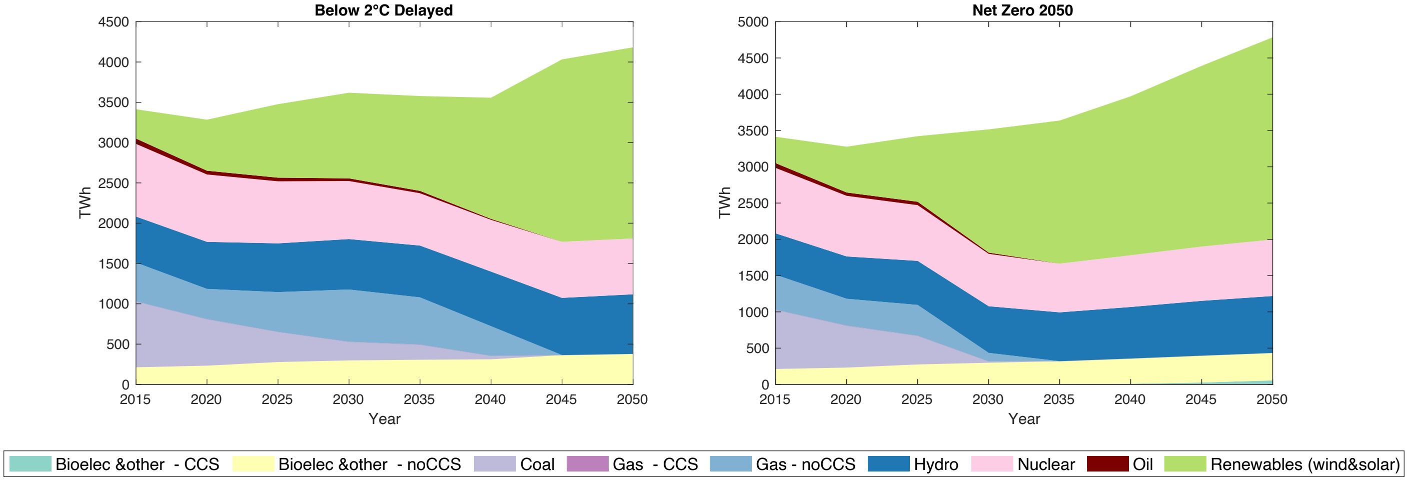

Figure 8. Power generation in Europe in the Below 2°C Delayed and Net-Zero 2050 scenarios

With a particular focus on Europe, the power generation compositions under the delayed 2°C and net-zero scenarios are demonstrated in **Figure 8**. Both scenarios suggest considerable shifts in energy usage. Fossil fuels face dramatic declines, with coal use decreasing about 800 TWh to virtually none by 2050. Oil-based power generation follows a similar trend, with consumption in the 'below 2°C delayed' scenario dropping from about 65 TWh in 2015 to practically zero in 2040. Natural gas usage without carbon capture and storage (CCS) also sees a significant decline, dropping from 500 TWh in 2015 to zero by 2040 in the 'below 2°C delayed' scenario.

Nuclear energy stays relatively consistent, ranging from about 900 TWh in 2015 to approximately 700 TWh by 2050 in the below 2°C delayed scenario. In the Net-Zero 2050 scenario, it even increases to about 800 TWh in 2050. The most substantial growth is seen in renewable energy. Wind and solar jump from about 350 TWh in 2015 to almost 2400 TWh by 2050 in the 'below 2°C delayed' scenario. The 'Net-Zero 2050' scenario shows an even more aggressive increase, with wind and solar reaching 2800 TWh by 2050. In summary, these scenarios depict a considerable shift from traditional fossil fuels towards cleaner energy alternatives, including nuclear, hydro, wind and solar, as well as bioelectricity. This transition will likely influence economic structures, employment, and investment strategies, necessitating adaptive policy measures to support affected regions and industries.

From the EPPA model results we derive the direct and indirect carbon-related costs at the regional level.[5] In the 'Below 2°C Delayed' scenario, power generation emissions in Europe modeled by the EPPA model during 2045-2050 become very small, mostly attributable to bioelectricity without CCS. For direct costs, we consider the payments that are additional to the current EU ETS payments for emission allowances. Starting with the below 2°C delayed scenario, we observe a steady increase in additional direct emission cost value, especially from 2035 to 2050, indicating that the cost or the economic impact associated with this policy is rising over time. The values for this scenario increase slightly until 2035, then jump significantly by 2040 to around USD 15 billion. This suggests a dramatic change or inflection point around that time. We then see a decrease by 2045 to about USD 8 billion, driven by complete elimination of fossil fuels in power generation. Direct carbon costs then see a substantial increase to about USD 40 billion by 2050 driven by the cost of emission reduction in the hard-to-abate sectors.

The resulting pattern for additional direct emission costs in power generation suggests variation over time, but the overall upward trend reflects increasingly challenging and expensive measures to keep global warming below 2°C in a delayed action context. The fluctuations in costs is driven by the interplay between various energy sources. While most of the energy comes from zero-emission technologies like wind, solar, nuclear, and hydroelectric power, there are still notable contributions from biomass and natural gas peaking plants. The associated emissions from these technologies incur certain costs, especially between 2040 and 2050, when we observe a significant increase in costs incurred by these plants that have to pay a carbon price determined by the economy-wide emission cap.

On the other hand, the 'Net-Zero 2050' scenario displays a different pattern for electricity producers and by 2025 the

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[5] In section 2.3.3., we illustrate how we 'downscale' the signal at the company level to perform a discounted cash-flow analysis including projection of revenues and cost per segment of large intensive company activity (section 3.3.3.). The main hypothesis is to assume proportional investment requirement at the company level.

additional direct carbon cost rapidly increases to USD 9.5 billion in Europe. It continues to rise, reaching about USD 17 billion in 2030. Then we see a decrease in 2035 to USD 6.5 billion, and by 2040, the value becomes negative for the first time at around USD -1.07 billion. This negative value is attributed to emission credits earned by Bioenergy with Carbon Capture and Storage (BECCS) technology.[6] By 2045, revenue from emission credits increases dramatically to about -66 billion, and by 2050, it reaches about -440 billion. This suggests that the strategy to reach net-zero greenhouse gas emissions by 2050 may have significant economic benefits in the long run.

This simple illustration calls for a caution when relying on any particular scenario (for example, Net-Zero by 2050 from IEA) or a particular technology assumption (for example, cheap costs for negative emission technologies). While this particular scenario shows that the Net-Zero 2050 scenario can be more economically favorable in the long run despite higher initial costs, it is important to note that such an analysis is highly dependent on many underlying assumptions and models used to derive these numbers. Policymakers and investors would need to consider these along with non-economic factors, like environmental and societal impacts, to make well-informed decisions.

This scenario raises a question about who bears the financial responsibility for operating these peaking plants and their emissions. If peaking plants are needed for electric grid stability in those short time periods when renewables cannot cover the full electricity demand, keeping them operational may require substantial incentives in terms of special revenues, subsidies, or other policy measures. This is a vital factor in assessing the economic feasibility of the energy mix.

As discussed, the Net-Zero 2050 scenario includes Bioenergy with Carbon Capture and Storage (BECCS). Unlike other energy sources, BECCS both generates energy and removes CO_2 from the atmosphere, thus potentially earning revenue from carbon credits. This dual benefit results in the negative values seen in the **Table 1** and the substantial 'profit' increase by 2050. However, these revenues would not be applicable to other types of power generation. In addition, it is crucial to evaluate the technological maturity of BECCS, the potential sustainability impacts of large biomass production or imports, and its impact on biodiversity and food security. The long-term viability of this scenario also hinges on the stability of carbon credit markets and supportive carbon capture policies. We illustrate by this simple example of the electricity sector in Europe that relying on a scenario analysis without a thoughtful exploration of the major assumptions and drivers may lead to a misplaced overconfidence in terms of transitional risk assessments.

Table 1. Additional direct carbon related costs for electricity producers in Europe in billion USD in the Below 2°C delayed and Net-Zero Scenarios

	Below 2°C Delayed	Net-Zero 2050
2020	0.025	0.025
2025	0.02	9.506
2030	0.017	17.098
2035	0.183	6.519
2040	15.016	-1.069
2045	7.473	-66.361
2050	41.452	-441.078

Source: EPPA model

Note: Additional direct carbon costs do not include the current EU ETS payments by electricity producers. Negative costs (i.e., credits) are obtained by electricity producers that employ BECCS and earn credits for the corresponding negative emissions.

Comparison with NGFS

The trajectories of the major variables produced by the EPPA7 model are similar to those generated by integrated assessment models used by the Network for Greening the Financial System (NGFS, Boirard *et al.*, 2022). For example, **Figure 9** provided the projections for the price of carbon in the United States under different scenarios and across several years until 2050. These scenarios, produced by multiple models, include current policies, below 2°C, delayed transition, and Net-Zero 2050.

We compare scenarios from both MIT's model and three downscaled models output of the NGFS database, namely GCAM 5.3+ NGFS, MESSAGEix-GLOBIOM 1.1-M-R12, and REMIND-MAgPIE 3.0-4.4. The data generated by these models vary by scenario, time, and the model itself, but we can see that the patterns are sensibly similar.

For the MIT's EPPA7 model, prices are in 2014 dollars per tonne of CO_2 equivalent. In the current policies scenario, the carbon price starts from USD 4 in 2020, reflecting the current regulations (for a comparison of carbon tax to the current U.S. regulations, see Knittel, 2019) and decreases over time to USD 3 by 2050 because emission mitigation is not strengthened in this scenario but technological advances make emission reductions cheaper. On the contrary, in the 'Below 2°C' scenario, the price starts at the same level in 2020 but then increases considerably to USD 234 by 2050. A similar increasing trend is seen in the Net-Zero 2050 scenario, with a significant jump to USD 422 by 2050. In the delayed transition scenario, the carbon price shows both upward and downward movements over the years, reaching USD 467 by 2050.

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[6] Hence, it is solely the BECCS plants that garner revenue from carbon credits that become substantial in 2050.

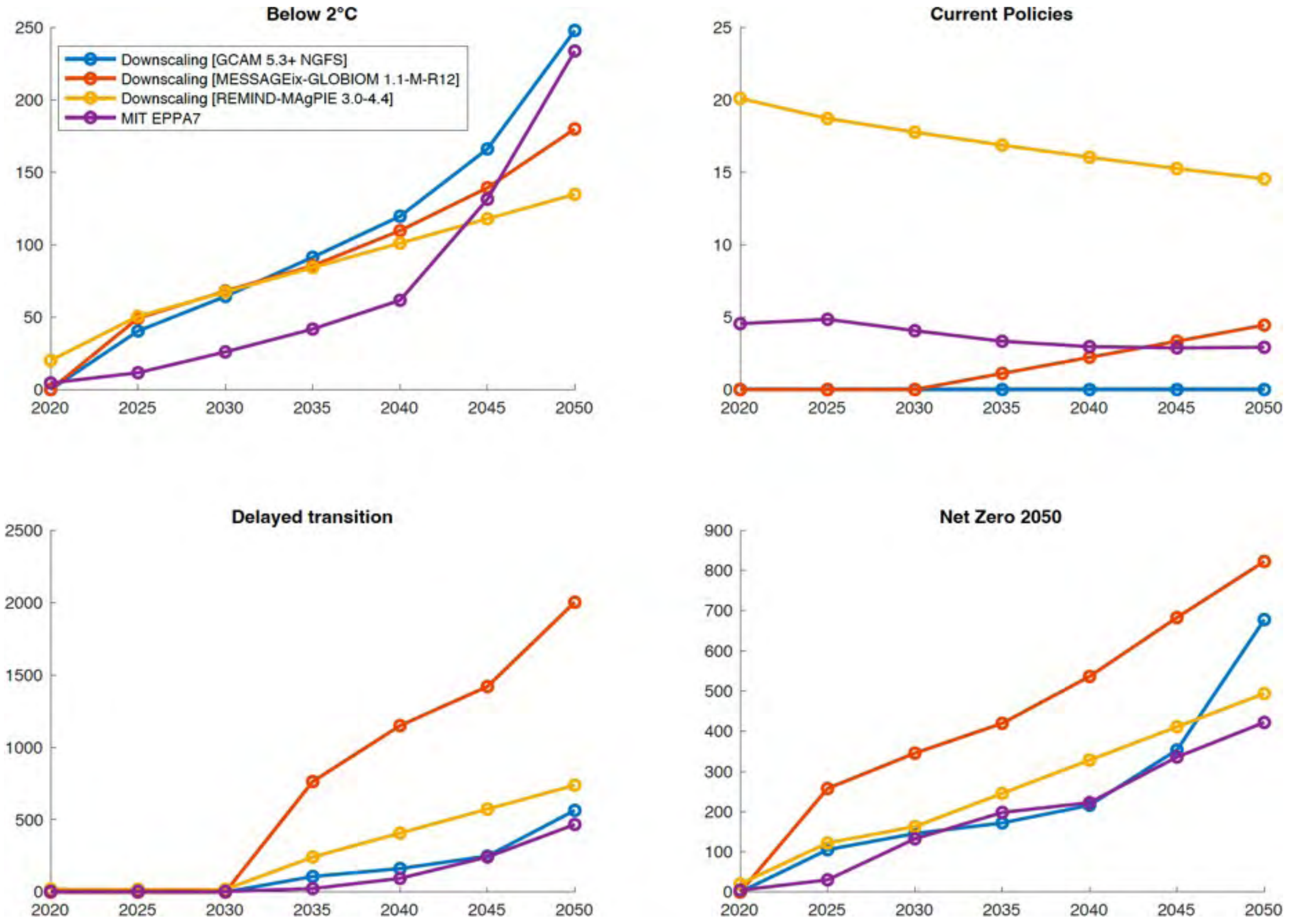

Figure 9. Carbon price value in the United States according to several models

Source: NGFS Phase 3 and the EPPA model

The downscaled models[7] show data in 2010 dollars per tonne of CO_2. The current policies scenario for these models initially has zero carbon price in 2020 for GCAM and MESSAGEix, while REMIND shows a price of USD 20 already. By 2050, GCAM's model still shows a zero price, while MESSAGEix's price rises to USD 137 and REMIND's to USD 15. For the below 2°C scenario, initial prices in 2020 vary from zero (GCAM and MESSAGEix) to USD 20 (REMIND), but by 2050, they increase across all models, with GCAM at USD 199, MESSAGEix at USD 206, and REMIND at USD 233. Similar to the current policies scenario, the delayed transition scenario begins with zero prices in 2020 for GCAM and MESSAGEix, while REMIND shows USD 20. However, by 2050, prices rise dramatically across the models with GCAM at USD 460, MESSAGEix at USD 565, and REMIND at USD 468. For the Net-Zero 2050 scenario, all models show an increasing trend from 2020 to 2050 with GCAM at USD 234, MESSAGEix at USD 697, and REMIND at USD 422 by 2050.

In the 'Below 2°C' scenario, the MIT EPPA7 model projects the price of carbon to increase sharply from USD 4 in 2020 to USD 234 by 2050. This model perceives a steady and robust growth in carbon pricing to reach the target of keeping global warming below 2°C. In contrast to these projections, the downscaled NGFS models present a different perspective, indicating higher prices between 2020 and 2040. This implies that the policy pathway for the 'Below 2°C' scenario, as proposed by EPPA7, seems more deferred in the case of the downscaled NGFS models within the United States. When considering the delayed transition and the Net-Zero 2050 scenarios, the EPPA7 carbon pricing within the United States appears to align with the trajectory suggested by the CGAM model, albeit consistently registering lower overall. We reiterate that in the present work the objective is to analyze the specific response of a company securities valuation under a predetermined scenario; however, to overcome carbon price and scenario uncertainty in both policy making or risk management perspective it is necessary to consider a wide range of scenarios with respective uncertainty (Desnos *et al.*, 2023).

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[7] The downscaling process used by NGFS provide values at the country level.

Application to MSCI world Equity index constituent revenues

Figure 10 highlights the distribution of revenue shares across the FactSet's Revere Business Industry Classification System (RBICS) sectors for MSCI World Index constituents, which is further mapped to sectors used in the MIT's Emissions Prediction and Policy Analysis (EPPA) model. The data reveals a substantial concentration of revenues in the 'other' and 'service' sectors, which together constitute over 67% of total revenues in 2020. This signifies the pronounced role of these sectors in the global economy, and particularly in classical investment universe as illustrated with the MSCI World Index. This index aims at covering approximately 85% of the free float-adjusted market capitalization of the developed countries. For enhanced specificity regarding sub-sectors presently categorized under 'others' and 'services' (which include Health Care, Information Technology, Telecommunications, Consumer Discretionary, among others), one could employ input-output tables. These tables would serve to disaggregate indirect costs with a higher level of detail. Our comprehensive examination of how a shock might disseminate through the value chain is illustrated extensively in Desnos *et al.* (2023) and Adenot *et al.* (2022). These works provide a meticulous analysis of the potential ripple effects a single perturbation can engender across interconnected industrial networks. In the present paper, we focus on energy intensive companies.

In order to compute the fraction of revenues associated with sectoral activity modeled in EPPA7 we introduce the FactSet RBICS dataset. FactSet RBICS is a comprehensive structured taxonomy designed to offer precise classification of global companies and their individual business units. The dataset includes information on the revenue percentages associated to each reported business segment that are standardized into the most granular sectors of the RBICS taxonomy.

Having mapped the revenues share to each RBICS (level 6) activity to EPPA7 sectors, and summing over issuers within the MSCI Index allows us to represent the share of revenues of the companies within the Index. We can see in Figure 10 that sectors such as energy-intensive industries, livestock, and oil & gas also maintain a noteworthy presence. It is interesting to observe the relatively low share held by sectors traditionally associated with high carbon emissions like commercial transportation, electricity, and various fossil fuels. The fossil fuel sectors (oil & gas, refined oil products, gas, coal, and oil) collectively account for roughly 10% of the total revenues. This relatively moderate share indicates a departure from traditional energy-intensive industries, possibly signaling an ongoing transition towards cleaner energy sources or the increasing influence of the technology and service sectors.

3. Financial impact of transition scenarios

3.1 From EPPA7 to financial statements

3.1.1 EPPA7 sectoral impacts

To model the financial impact of the transition scenarios, we start with the dynamics of sectoral revenues, $R^t_{i,\varphi}$ in scenario φ, at time t for sector i. First, as in Chen *et al.* (2022b), we obtain the total sectoral revenues defined as follows:

$$R^t_{i,\varphi} = p^t_{i,\varphi} \times x^t_{i,\varphi} \tag{1}$$

where $p^t_{i,\varphi}$ and $x^t_{i,\varphi}$ are respectively the unitary price of output and the production output of sector i obtained from the EPPA model for a particular scenario. These resulting prices and production outputs account both for direct costs of carbon and indirect production costs in the scenario φ at time t.

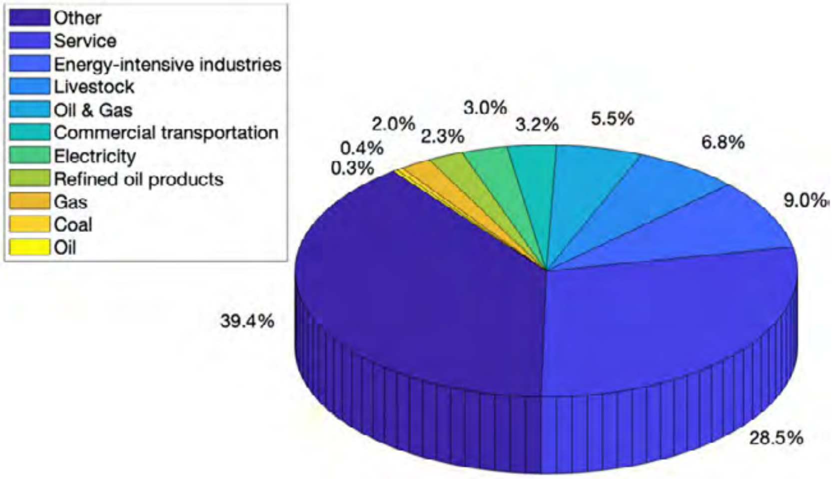

Figure 10. Fraction of revenues of MSCI World Index constituents (~1500 companies), in RBICS lev 6 activities, mapped to EPPA sectoral classification

The EPPA model projects carbon prices and the remaining emissions. Hence, the direct costs of carbon are calculated as:

$$\text{Direct Costs}(t,i,\varphi) = \text{Emissions}(t,i,\varphi) \times \text{Carbon Price}(t,i,\varphi) \qquad (2)$$

The indirect costs reflect all intermediate inputs (i.e., all inputs excluding capital and labor) from supplying sectors j in production of sector i:

$$indirect\ cost(t,i,\varphi) = \sum_j p^t_{j,i,\varphi} \times Z^t_{j,i,\varphi} \qquad (3)$$

where $p^t_{j,i,\varphi}$ denotes the carbon-penalty-inclusive price paid by sector i for goods from sector j at time t in scenario φ and $Z_{i,j,\varphi}$ denotes the amount of transactions between sector j and sector i at time t in scenario φ. These intermediate inputs are calculated by the EPPA model. The computational method outlined in Chen *et al.* (2022b) aligns closely with the approach detailed in Desnos *et al.* (2023), where both the World Input-Output Database (WIOD) and Exiobase are employed. This parallel indicates a consistent methodology across these studies, emphasizing the reliability and reproducibility of these analytical processes in economic research but also the consistency of the two approaches from an operational perspective. The difference between the sectoral revenue and a sum of direct and indirect costs equals to the sectoral value-added, $VA^t_{i,\varphi}$ (which, in turn, equals to earnings of capital and labor):

$$VA^t_{i,\varphi} = p^t_{i,\varphi} \times x^t_{i,\varphi} - \text{Direct Costs}(t,i,\varphi) - \text{Indirect Costs}(t,i,\varphi) \qquad (4)$$

At a country level, the sum of sectoral value-added equals to country-level GDP. We reiterate that the EPPA model explicitly resolves for sectoral and regional emissions, carbon prices, commodity prices, production output levels, and value-added. Thus, utilizing the system outlined in equations (1) through (4) we obtain revenues and operating expenditures to derive sectoral impacts for further downscaling at the firm level. This formulation is also in line with the approach detailed in Desnos *et al.* (2023) to define the climate value at risk at the portfolio level.

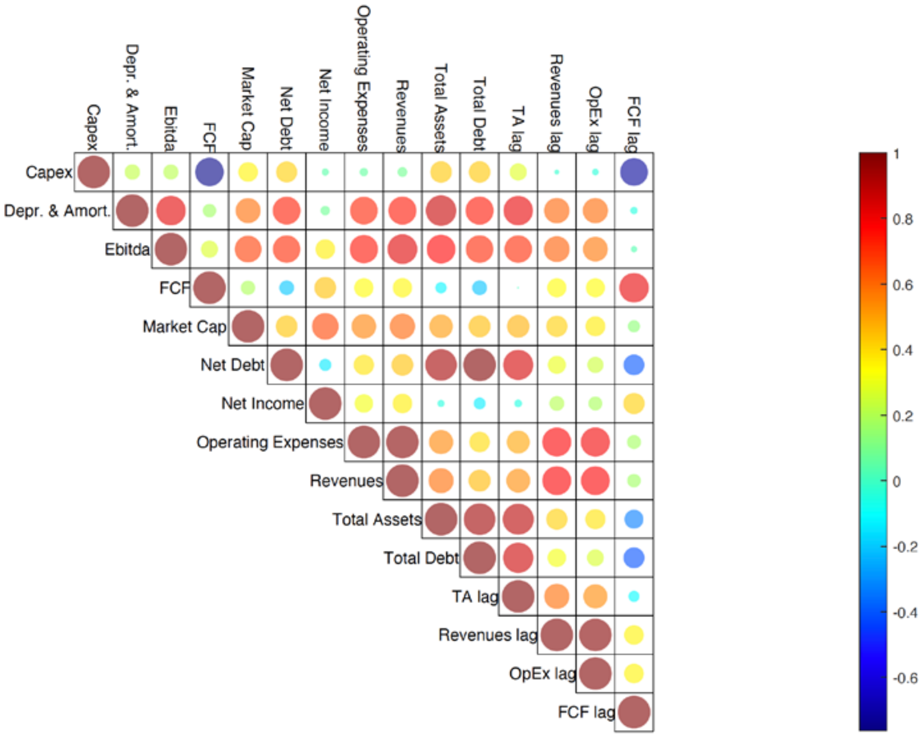

Figure 11. Correlation observed in sample variable on the last 15 years

Table 2. Financial statements modeling based on EPPA variables

Variable	Step	Calculus
Sector Value-added	(*)	Extrapolated with EPPA (Eq. (4))
GDP	(*)	Sum of value-added country wise
Revenues	(a)	EPPA (equilibrium solution, Eq. (1))
Direct Cost / indirect cost	(b)	Extrapolated in EPPA (Eq. (2) and (3))
Gross Profits	(c)	(a) – (b)
Operating expenses*	(d)	
EBITDA	(e)	(c) – (d)
Depreciation and amortization**	(f)	
EBIT	(g)	(e) – (f)
Interest expense	(h)	
Tax expense	(i)	
Net Income	(j)	(g) – (h) – (i)
Total Debt	(k)	Fixed
Total assets	(l)	Equation (5) - Alogoskoufis *et al.* (2021)
Free Cash Flows	(m)	Equation (8)
Discounted cash-flow/Equity value	(o)	Equation (16)
Leverage	(p)	(k) / (l)
Profitability	(q)	(j) / (l)
Probability of Default	(r)	Equation (18) - Alogoskoufis *et al.* (2021)
Bond Spread	(s)	Equation (19)

* Operating expenses excluding depreciation and amortization. The downscaling of this statement is detailed in the next section.

** Change in property land, equipment, and other capital expenditure. also include asset stranding effects (fasting depreciation)

3.1.2 Transmission channels of climate-relevant signals to the financial statements

Numerous studies discuss the theoretical channels through which transition risk might impact financial risk (Colas *et al.*, 2018; Monnin, 2018; TCFD, 2017; Thomae *et al.*, 2019). Transition risk can affect a company's economic and financial performance at various levels. Once the initial transmission channel to financial performance is established, the effects on credit, liquidity, or market risk (Basel Committee on Banking Supervision, 2021, 2022) can be quantified using existing financial models.

Table 2 provides a simplified breakdown of the different mechanisms affecting the income statement of a company. Transition scenario first impact the revenues in line with EPPA variation of output and price per sector. Then, direct and indirect impacts can be derived at the issuer level accounting for GHG emissions and input in production respectively. In this section, we give more details about the modeling of each step. Overall, we focus on the transmission channel of the transition on relative equity value (NZE/baseline) through discounted cash flows and bond spread through changes in profitability.

3.2 Calibration of financial statements at the firm level

The estimation method at the firm level is closely derived from the ECB approach (Alogoskoufis *et al.*, 2021), including the projections of EPPA to model the projected changes in revenues and operating expenditures. The European Central Bank has developed a top-down estimation method (combining issuer specific information and macro variables sensitivity) to derive firm level impacts. In what follows, we reiterate its specification and complement the framework based on the financial variables in our sample of carbon intensive firms.[8]

3.2.1 Top-down approach for financial statements modeling

Macroeconomic effects: ECB economy-wide stress-testing approach for transition risk We first reiterate Alogoskoufis *et al.* (2021) framework for the economy wide stress-test to assess the exposure to transition risks. The total assets value is introduced as a control variable in the specification of the revenues and operating expenditures. The metric is defined with an auto-regressive process calibrated (in logarithm for $t < 2022$) as follows:[9]

$$\text{Total Assets}(k,t) = \alpha_a + \beta_{1a} \cdot \text{Total Assets}(k, t-1) + \beta_{2a} \cdot \text{GDP}(r,t) + \beta_{3a} \cdot \text{Inflation}(r,t) \tag{5}$$

Then, the revenues dynamics were calibrated as follows:

$$\text{Revenues}(k,t) = \alpha r + \beta_{1r} \cdot \text{Revenues}(k, t-1) + \beta_{2r} \cdot \text{Total Assets}(k,t) + \beta_{3r} \cdot \text{VAT}\,(r,t) \tag{6}$$

introducing the sensitivities of revenues to total assets variations, value-added tax VAT(t) along with categorical dummies for size, sector country and time period. This particular equation is adapted to better encompass the revenues variation suggested by EPPA7. However, the original approach including the sensitivities is maintained in our setup. Operating expenditures follows:

$$\text{Opex}(k,\ t) = \alpha_{opex} + \beta_{1opex} \cdot \text{Opex}(k,\ t-1) + \beta_{2opex} \cdot \text{Total Assets}(k,t) \tag{7}$$

Table 3 illustrates the most parsimonious calibration performed by ECB (Alogoskoufis *et al.*, 2021, pp. 84–55, model 4), without dummies.[10] This block allows us to introduce a top-down

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[8] For this exercise, we selected a reduced sub-sample of 12 companies accounting for 17.2% of the scope 1 emissions of the MSCI world for illustrative purpose. With respectively 16.5% of the Utilities, 34.7% of the energy and 14.5% of the materials, and one 'pure player'. We reiterate that the objective is to investigate the feasibility of the downscaling of integrated assessment model at the company level in the perspective of pricing asset under transition scenario uncertainty. For the auto-regressive process defined, we perform a robustness check to insure that the methodology remain consistent for all companies in intensive sectors (c.f. Figure 20 in Appendix).

[9] The authors also added size, sector and region dummies.

[10] This table is provided for illustrative purpose, as the parameters used are calibrated at the company level and some modifications have been brought to their model.

Table 3. Summary table of the sensitivities in ECB calibration without dummies

Variable	R_2	Loading	Value	signif.
Total Asset	99,10%	α_a	0.221	***
		β_{1a}	0.978	***
		$\beta_{\log(GDP)}$	0.01	***
		$\beta_{\text{inflation}}$*	0.00349	***
Revenues	98,20%	α_r	0.312	***
		β_{1r}	0.839	***
		$\beta_{3r(VAT)}$	-0.0012	***
Opex	98,20%	α_{opex}	0.258	***
		β_{1opex}	0.863	***
		β_{2opex}	0.123	***

Source: Alogoskoufis *et al.* (2021)
Note: *** p<0.01, ** p<0.05, * p<0.1

* Inflation is significant only with dummies variable introduced in Alogoskoufis *et al.* (2021) tables.

macroeconomic effect in the stress-testing framework. For instance, in the context of alternative GDP and inflation assumption in response to climate regulation, the consideration of these sensitivities is very important. We made partial updates to this framework in the context of our work that are described in the next sections.

Free-cash flows calibration

Then we introduce the Free-cash flows (FCF) as they are required in the discounted cash-flow approach, which allows us to build synthetic scenariobased transition risk valuation ratio on equity markets. In our sample, we have observed that FCF are positively correlated (45%) with net income,[11] negatively correlated (-72%) with capital expenditures, and strongly positively correlated with its previous value (82%). In the context of integrated assessment models, there is no clear distinction of the capital expenditures (investment, abatement cost, etc.) that would not be represented by the variation of revenues and operating costs. Therefore, we can use an autoregressive formulation, similar to those in Alogoskoufis *et al.* (2021), to further reflecting this relationship:

$$FCF\ (t) = \beta_{1cf} \cdot FCF\ (t-1) + \beta_{2cf} \cdot (\mathrm{Revenues}(t) - \mathrm{Opex}(t)) \tag{8}$$

The fitting procedure are executed both at the global and corporate level. This implies that the betas are calibrated at company level, with no constants or dummy variables involved. This methodology is essential to control if the fit indeed represent company idiosyncratic sensitivities. It also prevents the company-specific financial forecasts from deviating significantly when the unique characteristics of a company are considerably different from the sample's mean.[12]

However, when conducting a comprehensive stress-test on global portfolios, our preference may lean towards projecting financial variables using parameters that have undergone global fitting in a cross-section fashion (c.f. **Table 4**). Additionally, the inclusion of sectoral and country-specific dummy variables is deemed beneficial. This approach allows us to consider broader macroeconomic and sectoral influences, resulting in a more robust and comprehensive stress analysis. Overall, over our sample of companies we illustrate that the sensitivities are aligned with those used in Alogoskoufis *et al.*, (2021) in Table 3. The model suggests for the free-cash flows a relatively conservative result, where the main contributing factor is the free-cash flows of the previous year rather than net incomes.

Regardless the choice of their parametric representation, most financial indicators derived in this exercise are to be interpreted with caution and are not designed to be considered with unconditional trust when considered in isolation. Rather, they serve as instrumental tools in the construction of variables of interest, evaluated relative to other factors. Their significance lies in their capacity to shape and inform these variables, allowing for more nuanced understanding and analysis in the financial domain. Indeed, they are instrumental in the estimation of the relative price of an asset in each scenario versus the baseline.

Table 4. Econometric configuration fitted over the representative sample of intensive companies

Fit over sample Model	Variable	Loading factor	Statistics std. error	statistic	signif.
Total Asset	TA lag	0.81	0.03	24.76	***
	GDP	0.02%	0.00009	2.37	***
	Revenues	0.22	0.05	4.14	***
Revenue	Revenues lag	0.75	0.03	22.88	***
	Total Assets	0.15	0.02	7.74	***
Opex	Opex lag	0.78	0.03	25.35	***
	Total Assets	0.12	0.02	7.41	***
Free-Cash Flows (FCF)	FCF lag	0.7	0.04	16.43	***
	Net Income	0.27	0.05	5.06	***

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[11] In fact, it makes sense that FCF and NI are positively correlated. The difference between the two is mainly related to accruals – revenues earned or expenses incurred that impact a company's net income on the income statement, although cash related to the transaction has not yet changed hands – but also amortizations (that create income or expense) and accounting manipulations. FCF is usually considered more accurate than EPS (or Net Income), as it is less polluted: only cash inflows and outflows are accounted for.

[12] We perform the company level fits on a larger sample to insure the robustness of this method. The distribution of the specific sensitivity estimates for corporate level fits on all the Utilities, Materials and Energy company of the MSCI world with full historical data between 2010 and 2022 (e.g. 251 companies) are provided in Figure 20 in the Appendix. We can see that the at the company level the influence of previous step 'lagged variable' is less strong than on the selected sample. Overall, results are robust, but that the use of specific sensitivities with large universe requires capping the betas to control for outliers.

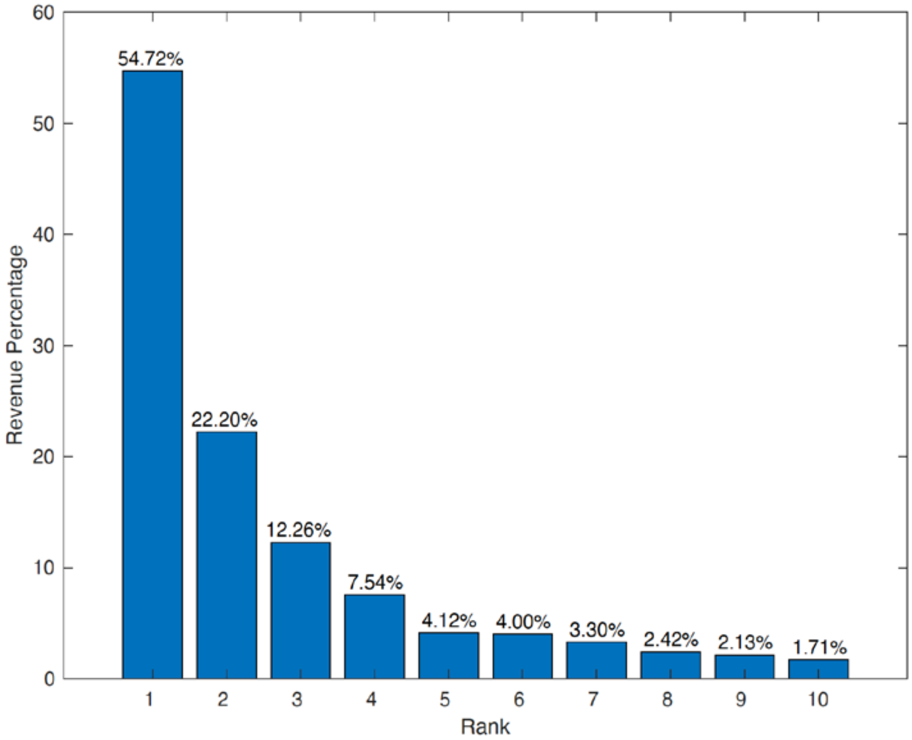

Figure 12. Average share of revenues per ranked activity (MSCI World Index)

3.2.2 Company level activity breakdown

Last reported activity breakdown

In our approach, we introduce the split of the revenues according to the breakdown of corporate activities. Mapping FactSet RBICS level 6 (1886 sub-activities in the whole database) to GTAPs allows us to derive thinner impact ratios at the company level. The fraction of revenues from each activity is initialized according to this share. Introducing this level of granularity is required to meet thus offered by the MIT EPPA model in terms of energy sources. RBICS level 6 allows us to distinguish wind, solar or hydro technologies (which is more complex with other mainstream classifications for example Global Industry Classification Standard (GICS) or Nomenclature of Economic Activities (NACE)). Moreover, large companies have wide range of activities, and the primary activity[13] accounts on average for 54.72% of the MSCI World Index companies' revenues (see **Figure 12**). On the other hand, we see that RBICS level 6 also accounts for regional breakdown within activities (**Figure 13**).

We can see than the revenues are mostly related to the same activities, but in different region of the world. For example, oil and gas companies revenues split of several companies are provided in Figures 13 and 14.[14] We also illustrate the revenues split of utilities; a so-called 'pure player', operating exclusively in green technologies, a provider specialized in renewable energy, and a materials company.

For example, in comparing energy-intensive companies such as Company 8 and 12, and the pure player, Company 10, we can observe significant differences in their revenue composition and business activities. In fact, Company 12 a diversified energy company, derives a substantial portion of its revenue from Europe's petroleum refineries (48.16%) and propane and LPG marketing and distribution (37.10%). This suggests a strong reliance on traditional fossil fuel-based operations. On the other hand, Company 8, a major player in the oil and gas industry, has a significant revenue share from Europe petroleum refineries (49.86%), Americas petroleum refineries (28.93%), and petrochemical manufacturing (7.79%). These figures emphasize the comapny's focus on refining and downstream activities.

In contrast, the leading renewable energy company in the sample, Company 10 demonstrates a different revenue composition. Its revenues percentage is predominantly associated with the United States South Atlantic electric utilities sector (73.82%), with substantial contributions from US natural gas wholesale power (8.81%) and United States wind wholesale power (17.89%). This highlights company's

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[13] Ranking by percentage of revenue for each issuer, then averaging of revenue percentage per rank.

[14] While we use the data for real companies, we do not reveal their names and call them as Company 1, Company 2, etc. in this paper.

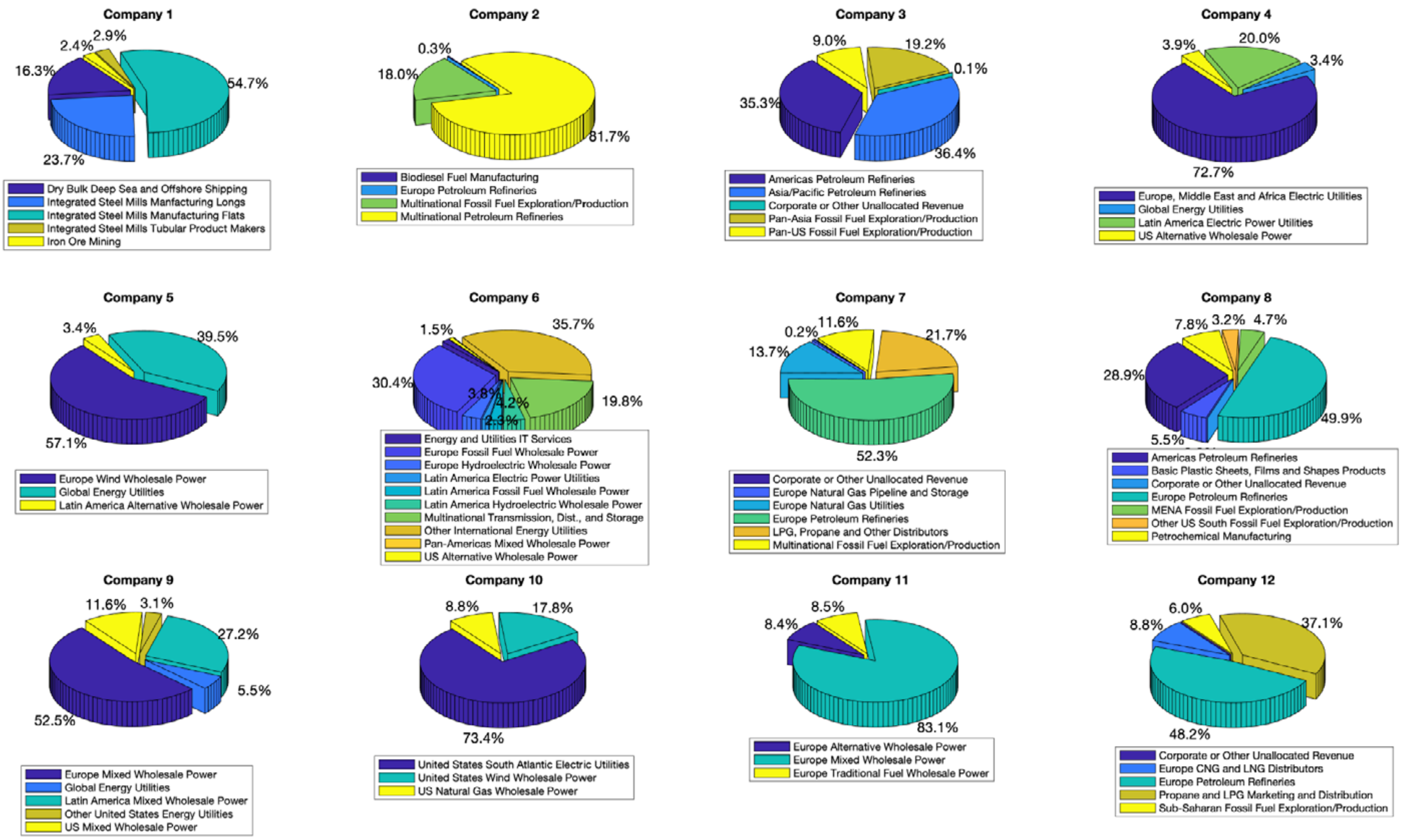

Figure 13. Split of revenues of example companies FACTSET RBICS level 6 taxonomy

strong position in the renewable energy market, particularly wind and natural gas.

The differences in revenue composition among these companies can have, as we will see later, significant consequences for their activities and long-term prospects, particularly in the context of transition scenarios. We can see that the RBICS activities generally map toward two or three EPPA sector activity in the current version. Note that the standard version of the EPPA model offers a wider split in terms of energy mix (wind, solar, hydro presently mapped toward electricity).

Consideration of companies' mitigation plans and M&A effects

It would be imprudent to presuppose that companies' revenue shares will remain static,[15] or that larger corporations will not engage in mergers and acquisitions with smaller entities within the renewable energy sector to diversify their revenue streams. Such actions would align with scenario requirements, demonstrating adaptability to evolving market trends and regulatory conditions. Current forecasts already embody the transition towards renewable energy investments, thereby acknowledging the dynamic nature of industry behaviors and the shift towards sustainable energy sources. For example, it seems that in 2023, 21% of Euro net capital expenditure will be allocated to low carbon solutions, with a focus on integrated power dominated by solar and increasingly offshore wind. Solar capacity is expected to rise from 17GW today to 50GW in 2025 and 150GW by 2030. Wind capacity is also expected to increase from 7GW (largely onshore) to 19GW by 2025, with over 40GW planned by 2030.[16]

Many fossil-fuel companies are planning to diversify their portfolios by investing in solar and wind generation, hydrogen, biofuels, carbon capture and storage. In this study, we deliberately do not dive into detailed modeling of the potential impacts stemming from mergers and acquisitions (M&A) as well as market effects. Instead, our focal point lies on the comparative analysis of equity valuation ratio and bond spreads (i.e., Baseline versus Net-Zero Emissions), grounded on the most recent breakdown of the companies' activities. It is, nonetheless, imperative to highlight that the premiums associated with mergers in the context of M&A, or alterations in equity valuation related to partial acquisitions of a pure player's equity by a larger entity, could yield financial advantages for stakeholders best aligned with Net-Zero Emissions requirements, and thereby, holding their shares.

In general, in the context of transition toward low carbon economy, mergers, characterized by the acquisition of eco-friendly assets, are necessary for fossil fuel companies (coal, refined products, etc.) to align their revenue streams with sustainable objectives. In this transition paradigm, the associated merger premiums become a plausible anticipated return, especially if ambitious scenario becomes more likely. From the perspective of shareholders of green equities, the actual return is constrained by the lower value of the projected augmentation of future cash flows as computed in the scenario valuation ratio (see Section 3.4.1) or the merger premium itself offered by acquired.

If this appear to be an interesting investment opportunity, it must be considered with caution. Indeed, the proliferation of marketing strategies centered around renewables, a phenomenon colloquially referred to as 'greenwashing', can potentially mask true sustainable actions and blur the

Box 1. Shift toward low carbon assets through acquisition in practice

In recent years, some of the power leaders in this GICS Energy sector purchasing wind and solar generating assets include Total, Shell, BP, and Equinor. Biofuels are also an important focus, with Chevron, BP, and ENI leading in bio-diesel/bio-gas production. Acquisitions are driving growth in this area, such as Chevron's acquisition of renewable energy group (2022), Shell's acquisition of Nature Energy (2022), and BP's acquisition of Archaea (2021). Marketing is increasingly prioritizing biofuels as an important aspect of the intensity shift. Hydrogen is another area of focus, with Shell and Equinor appearing to be early movers, and BP also investing in this area. CCUS is largely focused on the US, with Exxon's project capacities leading the way. Retail and end market are key to value capture, but there may be limitations due to their local nature. Other initiatives gaining traction include plastic recycling and circular economy. The merging premia associated with these acquisitions are substantial. For example, BP acquired Archea for 3.3 billion in cash or 26 USD per share, which represent 38% premium compared to its 30-day volume weighted volume average share price andthe transaction price for REG came with a premium of around 57%. Note that such premias are relatively classical in M&A processes and must not be associated with green premium.

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[15] First because companies are constantly adapting their offering to demand, regulatory constraints and emerging trends. It is undeniable that the energy transition fits perfectly under these headings. Then M&A opportunities will emerge and be beneficial for both sides. For example, focusing on the bright side, the acquiring company may green its energy mix, the activity of the purchased company benefit from increasing funding and its shareholders would benefit from a merging premia.

[16] The precise information about capital expenditure in renewable and transition are detailed in Exane report 2023.

distinction between those genuinely offering lower carbon energy and others.[17] This can inadvertently lead to mispricings in the market, subsequently causing a devaluation of genuine green assets, a situation which can be academically characterized as the emergence of 'green bubbles'.

3.2.3 Company level carbon related costs

In our framework, additional costs induced by direct taxes and upstream changes in prices derived from EPPA7 are adding up to corporate operating expenditure.[18] The calibration of fixed expenditure versus carbon related cost is initiated for t=2022, considering that the operating expenditures (excluding amortization and depreciation) already include the current level of carbon related costs.

Direct cost

The direct costs are defined Equation (2) from emissions and carbon price at the sector level. The same formula applies at the company level but it requires the introduction of issuer level emissions trajectory. The main novelty of this framework is the introduction of share of revenues of companies in different activities (c.f. **Figure 14**). Thus, we must compute the carbon emissions per sub-activity of the company. To do so, we introduce the flowing decomposition among EPPA sectors:

$$\text{Scope}_1(k,s) = \text{Revenues Share}(k,s) \times \text{Revenues}(k) \times \text{Carbon Intensity}(s)$$

where:

- Revenue Share(k,s) are the fraction of revenues of company k in EPPA activity s
- revenues(k) are the total revenues from FactSet Fundamentals
- Carbon Intensity(s) is defined as:

$$\text{Carbon Intensity}(s) = \frac{\text{Emission}(s)}{\text{Revenues}(s)}$$

where the values at sector level are defined from the MIT dataset. Then, we sum over EPPA sector for each company k to obtain the total direct costs:

$$\text{Direct cost}(2022, k) = \sum_s \text{Scope}_1(2022, k, s) \times \text{Carbon Price}(2022)$$

Indirect cost

The indirect costs at t=2022, are approximated using the indirect first tier emission from S&P Trucost:

$$\begin{aligned}\text{Indirect Costs}(2022, k) &= \sum_j \theta_j \times \text{Carbon Price}(2022) \times Z(i,j) \\ &\sim \text{GHG Emission Indirect First Tier}(2022, k) \times \text{Carbon Price}(2022)\end{aligned}$$

where θ_j is the fraction of carbon price (modeled with EPPA7) passed from sector j to sector i (therefore to issuer k) relatively to total transition $Z(i,\ j)$. [19]

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[17] We note the emergence of detection processes to overcome this effect (Bingler *et al.*, 2022).

[18] Furthermore, we reiterate that the empirical data on companies in the sample suggest a strong correlation between their revenues and operating expenses due to their inclination to maintain operational equilibrium. Nevertheless, the MIT-EPPA projections, computed at the macroeconomic level, do not consistently account for individual companies' adaptability. Consequently, instances arise where a company's revenues decline while their expenses rise, highlighting the disparity between actual outcomes and projected trends.

[19] The complete methodology explicating carbon pass-through integration in a stress-testing framework is depicted in Desnos *et al.* (2023). Here, we do not include this metric and simply initialize indirect costs with indirect emissions first tiers.

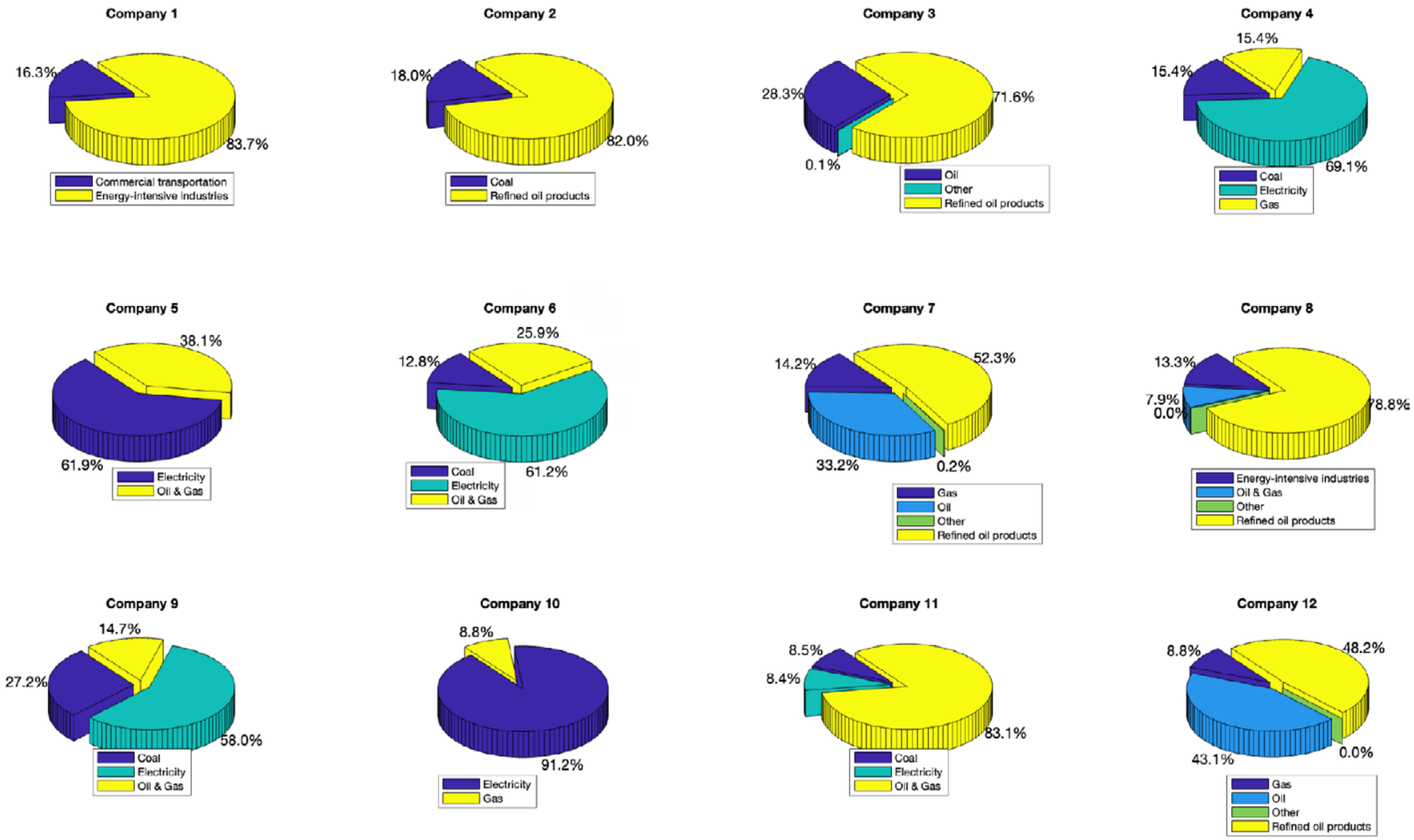

Figure 14. Split of revenues of example companies -MIT EPPA sector taxonomy

Total operating expenditures

The total operating expenditures are initialized as:

$$\text{Opex}(2022,k) = \text{Opex Fixed}(2022,k) + \text{Direct Costs}(2022,k) + \text{Indirect Costs}(2022,k) \quad (9)$$

where we can deduce the fixed operating expenditures that are not related to carbon price (and thus will follow the dynamics Equation (7) if any, see section 3 for projection). In practice, the prices of effective carbon pricing mechanisms observed in Europe (e.g., around EUR 90 for the EU ETS) are much higher than the carbon price proposed by EPPA7 for an economy-wide policy, but are also passed on in the supply chain. To some extent, we can assume that the remaining costs 'borne by the sector/company' are more homogeneous to the price modeled by EPPA7 model than to the effective prices observed in the market.[20]

3.3 Projection of financial statements in transition scenarios

We compute the projections of companies' revenues, operating expenditures, earnings, capital expenditures, leverage, and net income following closely Alogoskoufis *et al.* (2021) and integrating the projections produced by EPPA as well as company specific sensitivities.

3.3.1 Total assets projection

For $t > 2022$, we use EPPA7 projections such as, for a specific company k:

$$\text{Total Assets}(t,k,\varphi) = \beta_{1a} \cdot \text{Total Assets}(t,k,\varphi) + \beta_{2a} \cdot \log(\text{GDP}(t,\varphi)) + \beta_{3a} \cdot \text{inflation}(t,\varphi) \quad (10)$$

where (regional) GDP and inflation rates are retrieved from the EPPA-BoC dataset and initial total assets from FactSet. In this exercise, for simplicity we use the global GDP (without country granularity) and US inflation rate vs. baseline. In this first exercise, we do not introduce the sensitivity to inflation variation in the forecast: $\beta_{3a} = 0$.[21]

The projections are illustrated in **Figure 15**. In all transition scenarios modeled with EPPA, the global GDP keeps increasing until 2050, but with slight varying in growth patterns. Thus, using the auto-regressive Equation (10) with parameters provided in Table 3 and 4 can justify the trajectories Figure 15.[22] In this Figure, we can observe a very slight impact of transition scenarios (through varying changes in

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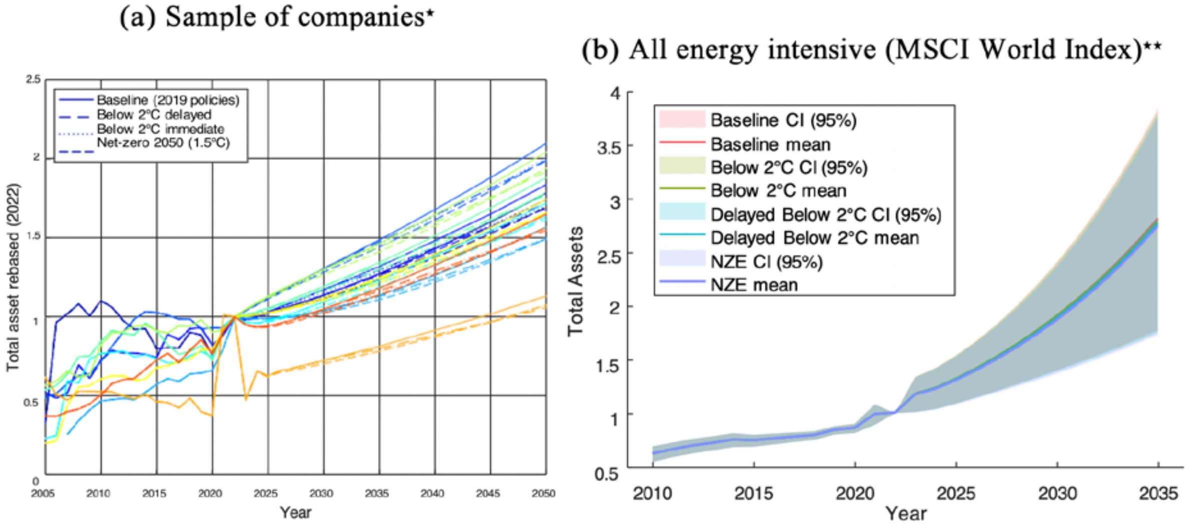
[20] This can be improved at the company level with expert opinion and / or including pass-through rate (Desnos *et al.*, 2023), however, we offer a systematic approach in this paper.

[21] Note that if the projected GDP used is in nominal terms, it would make sense to introduce inflation in the model. If we use the real GDP, there is no need to account for inflation, and therefore there is no need to introduce the variable. The EPPA7 model provides the real GDP, therefore we set the sensitivity β_{3a} to zero.

[22] We reiterate that the objective is not to determine the exact total asset trajectory for each company but rather the sensitivity to transition scenario.


(a) Sample of companies*

(b) All energy intensive (MSCI World Index)**

Figure 15. Total asset projection (auto-regressive with GDP sensibility only)

*Notes: * The line type depends on the scenario and color on the company. Despite relative change depends on the scenario, the GDP growth is positive in all the scenarios.*

*** The large sample contains 106 companies from utilities, Material and Energy GICS sector with full historical total asset data between 2010 and 2022 (out of the 251 with calibrated sensitivities).*

global GDP), on individual companies total assets value (a). However, considering idiosyncratic exposures (e.g. company specific betas) over larger sample of company, the impact of transition scenarios does not significantly shift the distribution of future total assets projections in the medium term (b).[23] Therefore, in absence of inflation or adverse GDP impact scenarios, these sensitivities can be set to [1, 0, 0].

3.3.2 Revenues projection

To estimate the revenues of individual companies, a mapping process is employed to align their activities with the corresponding EPPA sectors. This mapping considers the revenues distribution or percentage per activity within each company, enabling the projection of sectoral revenues onto the company's financial performance. Then, the operating revenues dynamics follows exactly those suggested by the MIT-EPPA7 model[24]

$$\text{Revenues}(t,\ k,\ \varphi) = \text{Revenues}(t-1, k, \varphi) \times (1 + \Delta R^{t}_{i,\varphi}) \quad (11)$$

The projections in our sample are illustrated in **Figure 16**. We note that Energy GICS sector (fossil fuel) are following the same pattern of decreasing revenues. Materials

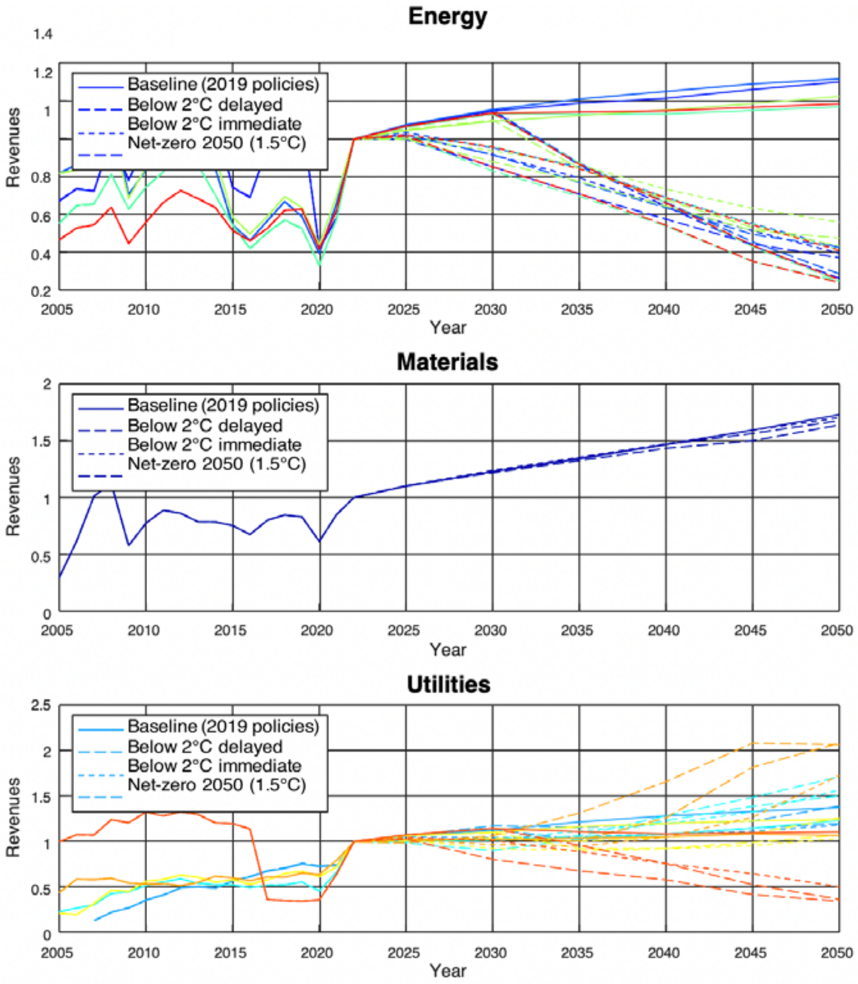


Figure 16. Rebased revenues projections on company sample based on MIT-EPPA7 trajec- tories

Notes: The colors represent different companies (anonymized in the paper). The line type is characteristic of the scenario.

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[23] For instance, in 2050, the sum of the projected total assets of the 106 companies in large sample suggest a loss of 2.6% compared to the baseline value.

[24] The ECB introduced additional sensitivities to total assets. This control can be introduced in a next version with larger samples. Here we focus on the effect of revenues shift induced by the NGFS scenarios applied in the EPPA7 framework only. In the projection of revenues, without the additional controls (sector/ country dummies) or VAT, not available for all regions in current sample of MIT-BoC dataset and β_{1r} can be taken equal to 1, allowing the revenues to fully follow the MIT projections. We can also introduce the sensitivity of companies' revenues to total assets (translating the macroeconomic impact). The fitted contributions are illustrated Table 4. However, we chose to use revenues dynamics from MIT only for these case studies. Note that in the absence of inflation forecasts, total assets have strong positive contribution which would not lead to realistic projections.

companies are less affected in terms of revenues. Finally, utilities companies present the most diverse results in terms of future trajectories depending on their current energy mix and sensitivity to transition scenarios.

3.3.3 Operating expenditures projection

In order to evaluate the direct and indirect costs modeled by the MIT's EPPA model at the sectoral and regional level to companies, we compute the contribution of each company in each sectoral and regional revenues and thus emissions. Then, we affect the costs corresponding to this portion.

Individual contribution in sector activity

In order to scale the direct and indirect emission costs at the issuer level we compute the ratio issuer carbon emissions over the total emissions over each sector. Using revenues split of each company, carbon intensity and revenues we calculate a scaling factor ratio alpha for scope 1 and 2. For an issuer k and sector s we have:

$$\alpha(k, s) = \frac{\text{Issuer Carbon Emissions}(k, s)}{\text{Total Carbon Emissions}_{EPPA}(s)}$$

where α represents the contribution of the issuer k total carbon emissions in an EPPA7 sector. In other words, a company carbon costs will be paid in proportion to its emissions relative to the total emissions of that sector.

For example, in **Table 5**, we sum the downscaled emissions per EPPA7 sector over the company sample. In the left section (EPPA), we can see the total GHG (scope 1 in million tone CO_2-eq) in 2020 suggested by EPPA for some sectors and regions. The section in the middle corresponds to the sum of the companies' sample emission mapped in the matching EPPA7 sector (using the revenues share and implicit carbon intensity in EPPA7). We can see that our sample covers 6.26 $MtCO_2$ out of the 13.4 in total, which represents 47% of the emissions from the coal sector in Europe. Also the sector oil & gas in Europe is well represented with a coverage of 15% with the 12 companies selected. In the last section, we conducted a control downscaling the global direct emission (absolute scope 1 emission in Trucost) of the company according to revenues share only.[25] This control allows to account for specific intensity of the companies; however, it is not always consistent (as the total

Table 5. Total emission covered in company sample with respect to EPPA model in 2020

EPPA			**Total over company sample**		**Control**	
Sector	**Region**	**Emissions**	**Scope 1**	**Contrib. ratio (α)**	**TC Scope 1***	**Spe. CI**
Coal	EUR	13.4	6.26	47%	6.8	1.09
Oil	EUR	22.69	9.56	42%	11.19	1.17
Refined oil products	EUR	584.57	150.61	26%	71.11	0.47
Gas	EUR	31.32	5.9	19%	4.39	0.74
Oil & Gas	EUR	54.01	7.92	15%	42.95	5.42
Oil	CHN	29.14	4.12	14%	10.76	2.62
Refined oil products	USA	390.02	51	13%	49.85	0.98
Coal	ROW	331.37	23.18	7%	3.48	0.15
Oil & Gas	USA	740.95	27.26	4%	9.3	0.34
Electricity	EUR	745.58	21.91	3%	13.68	0.62
Coal	GLB	1065.34	33.36	3%	3.46	0.10
Refined oil products	ROW	1662.32	42.74	3%	20.35	0.48
Oil	AFR	151.4	3.48	2%	1.13	0.33
Refined oil products	GLB	5500.21	89.12	2%	15.7	0.18
Electricity	USA	1770.09	36.57	2%	39.9	1.09
Oil	USA	375.26	9.22	2%	5.06	0.55
Energy-intensive ind.	EUR	1233.64	11.27	1%	103.86	9.22
Electricity	GLB	11073.43	83.95	1%	23.51	0.28
Energy-intensive ind.	USA	714.01	6.26	1%	13.86	2.21
Gas	USA	365.69	3.96	1%	3.79	0.96

Note: *Total Scope 1 in sector country summing over Scope 1 absolute emission in Trucost

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[25] We note that the companies in the sample probably contribute more than 15% to the oil & gas sector as the specific carbon intensity ratio in this sector is 5.42. This means that companies in sample are more intensive than average.

intensity of the company can come from sub-activity with less revenues and inversely).

Operating expenditure dynamics

We compute the operating expenditures at the company level downscaling the MIT EPPA signals through several steps. First, we reiterate that the operating expenditures are not exclusively related to environmental taxations. We split the fixed expenditures (not related to carbon reduction policies) from the operating expenditure related to direct and indirect costs with 2022 values in section 2.3.3). Then, the future operating expenditures following the MIT EPPA signals downscaled at company level can be represented as follows:

$$\begin{aligned}\text{Opex}(t,k,\varphi) &= \text{Opex Fixed}(t,k,\varphi)+\text{Direct Costs}(t-1,k,\varphi) \\ &+ \text{Indirect Costs}(t-1,k,\varphi) + \alpha(k,s) \times [\Delta_s \\ &\text{Direct Costs}(t,k,\varphi) + \Delta_s\text{Indirect Costs}(k,t,\varphi)] \quad (12)\end{aligned}$$

where the direct carbon costs and indirect costs variations Δ_s for sector s (in which belong issuer k)[26] depend on local prices in each region the issuer operates, its direct emissions (scope 1), and other indirect costs from change in input price.[27] These cost dynamics are fully accounted for in the scenarios of interest by the EPPA7 model. Note that the fixed operating expenditures can be projected using an auto-regressive process introduced Equation (7), considering the sensitivities to total assets. In this exercise, we maintain this figure constant (Opex Fixed(t) = cst).

3.3.4 Financial valuation metrics projections

The leverage of a company can be defined as its ratio debt over total asset:

$$\text{Leverage}(t,k,\varphi) = \frac{\text{Total Debt}(t,k,\varphi)}{\text{Total Assets}(t,k,\varphi)}$$

Given the high correlations observed (c.f; **Figure 11**) and in the context of this work (where debt issuance is not modeled), we maintain the leverage level constant for each company k:[28]

$$\text{Leverage}(t,k,\varphi) = \frac{\text{Total Debt}(2022,k)}{\text{Total Assets}(2022,k)} \sim \mathcal{L}(k)$$

in practice the net income does not include the capital expenditures[29] and amortizations. However, we can make a simplifying assumption as the nature of the 'transition costs' are not explicitly in the integrated model.[30] Therefore, the Net Income[31] as follows:

$$EBITDA \sim \text{Net Income}(t,k,\varphi) = \text{Revenues}(t,k,\varphi) - \text{Opex}(t,k,\varphi) \quad (13)$$

And the profitability can be defined as the ratio of the Net Income over Total Assets:

$$P(t,k,\varphi) = \frac{\text{Net Income}(t,k,\varphi)}{\text{Total Assets}(t,k,\varphi)} \quad (14)$$

In practice, net income and free cash flows are both measures of profitability and financial performance. Net income represents the profits of a company from an accounting standpoint and thus includes non-cash expenses such as depreciation and amortization. Free cash flows, on the other hand, measures the actual cash flow that is available to shareholders. It does that by adding back the non-cash expenses to net income, adjusting for changes in working capital, and subtracting out capital expenditures. Therefore, the relationship between the explicitly projected Net income (Equation (13)) and the free cash-flows of the firm is not explicit. In the next step, we introduce an auto-regressive formulation to obtain stable projection of free-cash flows by introducing double dependencies (fitted Equation (8)):

$$FCF(t,k,\varphi) = \beta_{1cf} \cdot FCF(t-1,k,\varphi) + \beta_{2cf} \cdot \text{Net Income}(t,k,\varphi) \quad (15)$$

We do not introduce additional taxes and investments considering that they are only carbon related costs modeled with EPPA7. **Figure 17** illustrates the earnings patterns of companies including the downscaled effects suggested by EPPA7 in the reference scenarios. In accordance with Figure 16, we notice remarkably homogeneous pathways for companies in the Energy sector, as defined by the GICS classification. Upon examining their historical earnings, this sector indeed presents a relatively high correlation within our sample when compared to others, which accounts for the similarity in their projections. Another significant observation is the earnings of the majority of these companies turning negative between 2030 and 2040 in the transition scenarios. This trend aligns with the understanding that

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[26] Note that each company operates in several activity, these computations are performed for each segment and then aggregated at the company level.

[27] requirement coefficient a_{ji} measuring cascading effect through global trade (GTAP, 140 regions x 76 sectors) with input-output and bilateral exchanges.

[28] The other metrics are purely related to macro variables (GDP, inflation, etc.). While the capital structure is more a strategic choice of the management team.

[29] Incompassed in EPPA's through changes in price, quantities, abatement costs, etc. but not explicitly provided in the dataset.

[30] This approximation can be accepted within the framework of projections by 5-year intervals (which is the case in the temporal resolution of EPPA). And, as a result, the capex, which normally impacts the balance sheet and not the income statement (and therefore not the net income), ended up being able to impact it through the annual depreciation of capex (non-cash expenses).

[31] The earnings are attributed to net income.

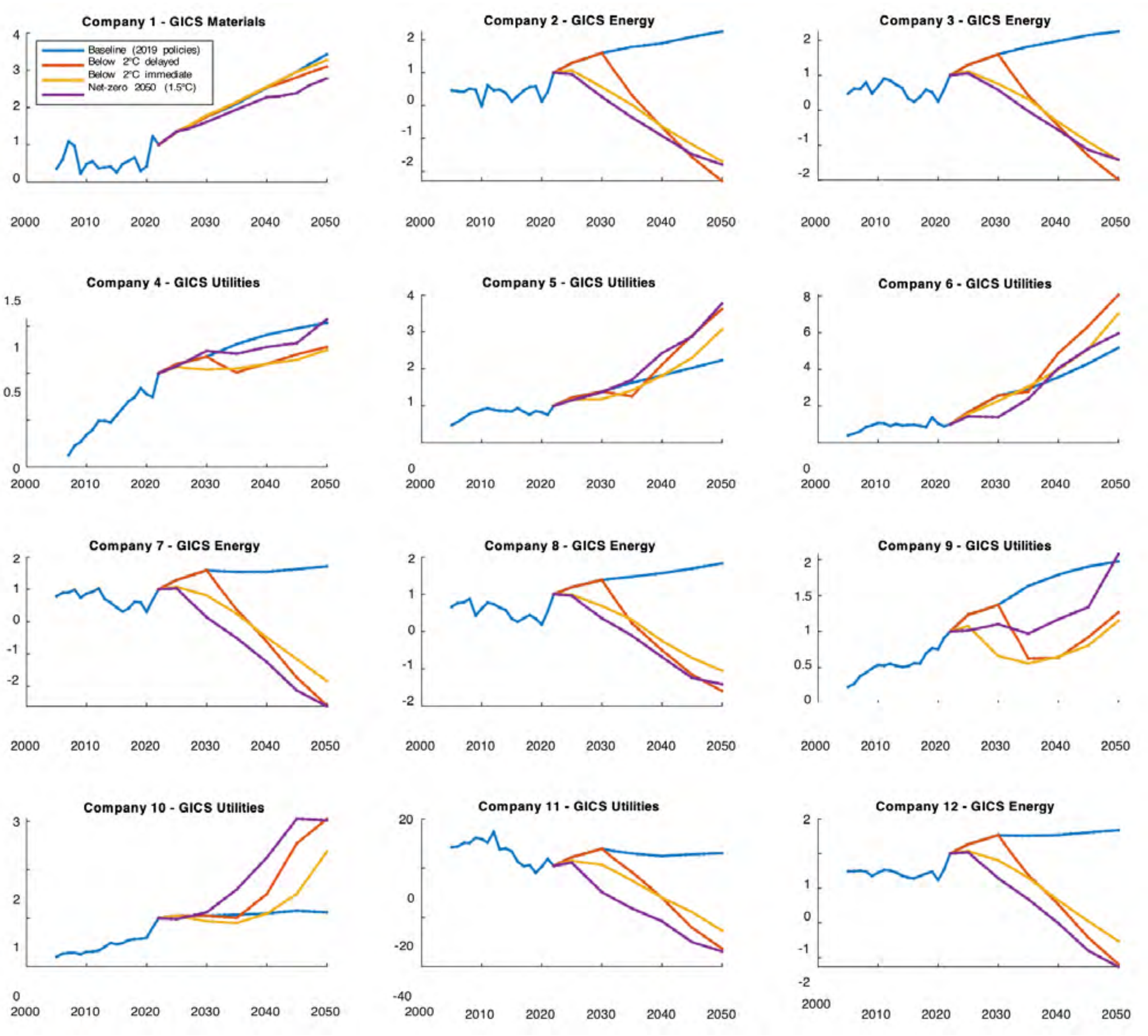

Figure 17. Scenario based projected earnings on companies' samples (rebased in 2022)

their revenues are predominantly tied to fossil fuel-based and intensive activities. However, when applying this framework operationally, one should certainly take into account the diversification efforts these companies have implemented (M&A and others), a topic further discussed in Section 3.2.2. Moreover, our findings reiterate that utilities exhibit intriguingly diversified patterns, heavily influenced by the energy mix that their revenues are associated with.

Concerning free-cash flows we notice in **Figure 18** much more volatile historical variations while the projections reflect those of the earnings with smoother trajectories. These projections are not informative of the future value of the free-cash flows, however, they allow to derive interesting patterns in the context of scenario analysis at the company level.

3.4 Financial security pricing in transition scenarios

In this section, we offer a simple approach to include the forecasted sensitivities in asset pricing following a corporate finance approach. The logic behind this approach is to include additional sensitivities, such as equity risk premiums, cost of debt, corporate tax rate, and local risk-free rate, when incorporating transition risks. The objective is not necessarily to pinpoint the precise value of market securities, but to suggest a method for determining valuation ratios based on refining IAMs projections.

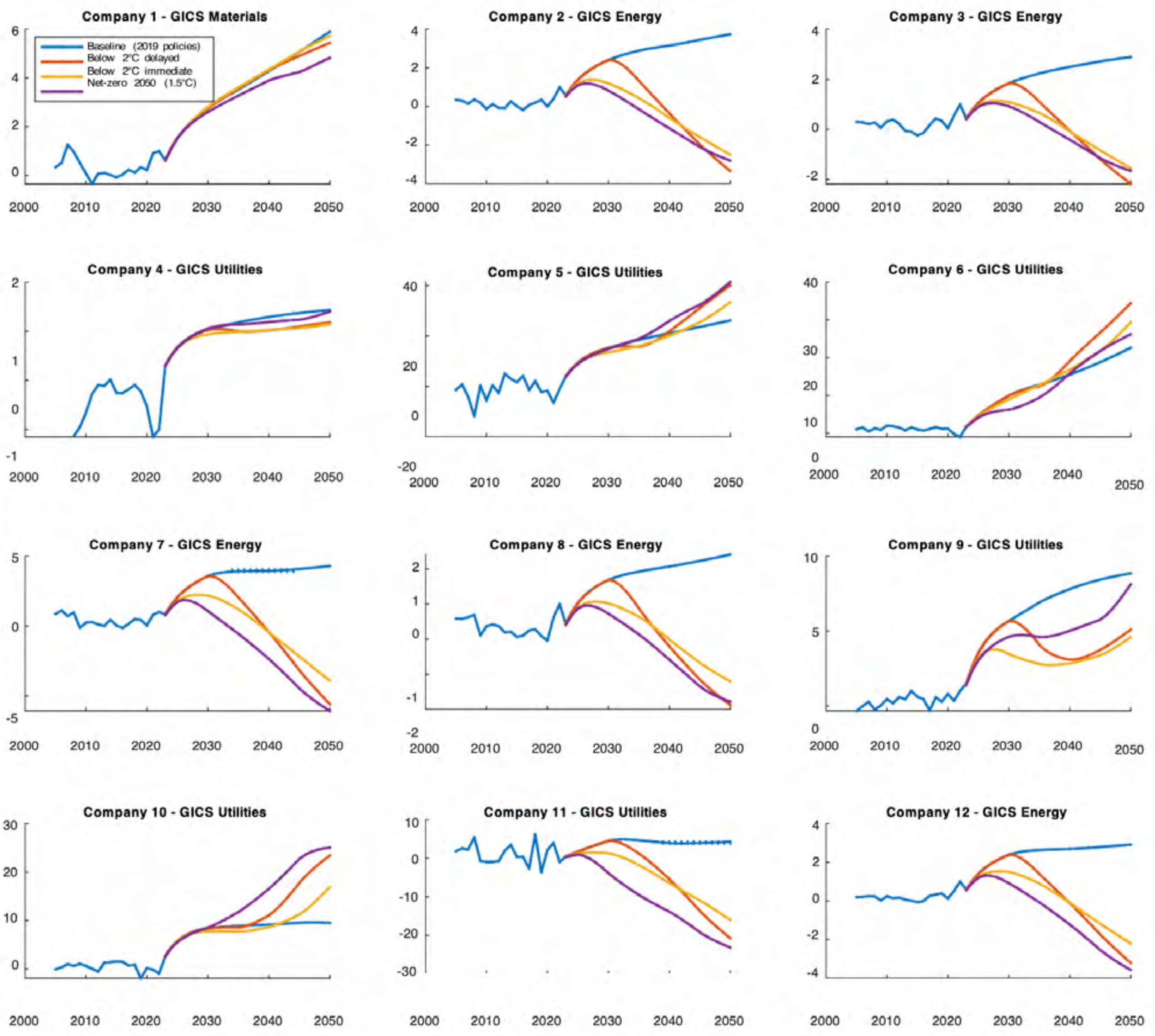

Figure 18. Scenario based shift in free-cash flows on companies' samples (rebased in 2022)

3.4.1 Equity valuation with discounted-cash flows

We define the present value of equity as the sum of the future expected and discounted cash flows:

$$DCF(k,\varphi) = \sum_{t=2023}^{\infty} \frac{FCF(t,k,\varphi)}{(1+WACC)^t} \tag{16}$$

Future cash flows are discounted using the Weighted Cost of Capital (WACC). The rational of this metric is to account for company specific measure of market riskiness. It represents the average rate a company is expected to pay to finance its assets, either through debt or equity. Therefore, this discount rate reflects the level of risk linked to the capital structure of a particular company. It is defined as follows:

where:

$$WACC = \frac{E}{E+D} \times R_E + \frac{D}{E+D} \times R_D \times (1-T) \tag{17}$$

- E is the equity value (last market cap).
- D is the debt (last total debt) retrieved from the financial statement of the company.
- $R_E = R_f + \beta \times ERP$:
  - R_f is the risk free rate. We use the yield of government bonds with maturity of 10 years issued by the country where the company is based or a broader region (Europe).

  - β represents the risk of an investment relative to overall market. The beta is determined by performing a regression on company's stock returns and the local MSCI index or, in the case of European companies, the MSCI EMU, over the 3-year period ending in 2022.
  - *ERP* is the equity risk premia, we use the value from Damodaran website (Damodaran *et al.*, 2013; Damodaran, 2019), and aggregate them for Europe (c.f. **Table 6**)
- R_D is the cost of debt obtained from corporate credit rating.
- T is a corporate tax rate from Damodaran *et al.* (2013) and Damodaran (2019) (c.f Table 6 – we reiterate that, we use country tax rate average over countries for Europe).

It is important to note that the calculation of beta will significantly impact the results when using the CAPM model to calculate the Weighted Average Cost of Capital (WACC) for the selected companies. By calculating the beta based on a three-year time series ending in 2022 and comparing the company's stock price changes to the corresponding market index, we can capture the relative change in risk specific to each company. **Table 7** includes the values of corporate bonds (risk free) and WACC calculated on last year values and 3 year average. It demonstrates that higher discount rate may be applied to account for accrued interest rates.

Table 6. Corporate tax rates and equity risk premium aggregated at region level

Region	Corporate Tax Rate (T)	Equity Risk Premium (ERP)
Africa	26.43%	16.80%
Asia	21.92%	13.47%
Australia & New Zealand	28.81%	8.53%
Caribbean	17.37%	12.68%
Central & South America	28.30%	15.51%
Europe*	17.89%	9.12%
Middle East	11.54%	11.62%
North America	25.00%	5.94%

Source: https://pages.stern.nyu.edu/~adamodar/New Home Page/datafile/ctryprem.html.

* Europe is constructed aggregating all European countries in the database.

Finally, when calculating the WACC, it is preferable to use a regional tax rate for companies operating in Europe rather than relying solely on the tax rate of each individual country. This approach ensures consistency in the tax rate applied to cash flows and accounts for the complex operations and revenues streams that transcend national borders. By using a regional tax rate, the analysis becomes more comparable and reflective of the integrated nature of the markets.

Table 7 illustrates the different WACC ratio of the sample of companies accounting for their specific leverage, corporate taxes and regional specific exposure with respect to ERP. We can note that the actualization factor greatly varies between companies (from 4.6 up to 11.5% using 3 year average risk free and beta). Accounting for these factors is important for possible operational applications of the model. Higher WACC implies that long term cash-flow

Table 7. Summary table illustrating the computation of the Weighted Average Cost of Capital (WACC) for a sample of companies considered in this paper*

Company	Region	Currency	R_D	R_E	β 3Y	T	ERP	R_f last year	WACC last year	R_f 3Y	WACC 3Y
1	Europe	EUR	5,84%	13,7%	1,22	17,9%	9,12%	2,5%	13,19%	0,14%	11,53%
2	Europe	GBP	4,64%	14,9%	1,62	25,0%	6,97%	3,7%	9,92%	1,15%	8,51%
3	North America	USD	4,52%	9,8%	1,00	25,0%	5,94%	3,9%	8,96%	1,76%	7,12%
4	Europe	EUR	0,0%	12,4%	1,08	17,9%	9,12%	2,5%	6,55%	0,14%	4,66%
5	Europe	EUR	4,13%	11,9%	1,03	17,9%	9,12%	2,5%	5,90%	0,14%	4,69%
6	Europe	EUR	4,09%	11,5%	0,99	17,9%	9,12%	2,5%	7,44%	0,14%	6,31%
7	Europe	EUR	3,59%	12,5%	1,10	17,9%	9,12%	2,5%	8,23%	0,14%	6,95%
8	North America	USD	4,55%	9,1%	0,88	25,0%	5,94%	3,9%	8,18%	1,76%	6,41%
9	Europe	EUR	3,14%	8,8%	0,69	17,9%	9,12%	2,5%	6,50%	0,14%	5,03%
10	North America	USD	4,74%	9,6%	0,96	25,0%	5,94%	3,9%	8,06%	1,76%	6,48%
11	Europe	EUR	3,80%	9,5%	0,76	17,9%	9,12%	2,5%	7,48%	0,14%	5,90%
12	Europe	EUR	4,66%	12,9%	1,14	17,9%	9,12%	2,5%	9,89%	0,14%	8,28%

Source: FactSet and author calculations.

* The reference dominated sovereign bonds used for risk free are US, Euro, UK and India Benchmark Bond - 10 Year

(positive or negative) are highly discounted. In general, in the context of positive future cash-flows, higher WACC implies lower discounted present value (at the time of the computation). On the other hand, one can also note that companies with higher WACC, have lower impact on long term cash-flow variation in the DCF thus, their exposure to transition risks may be less priced on their equity.

Looking closely at the table, we can see how each region and currency offers a different financial landscape, as indicated by the weighted average cost of capital (WACC). For instance, the cost of debt, equity, and ultimately, the WACC, is significantly higher in Asia, represented by the Indian Rupee, than in other regions. This suggests a higher risk associated with doing business in this part of the world, or potentially, a macroeconomic climate characterized by higher interest rates. However, without additional context, these numbers are insufficient to provide a comprehensive understanding of the potential challenges or rewards of operating in this region.

On the other hand, Europe has the lowest WACC among the various regions. This lower rate indicates that companies operating in Europe (and using the euro) are likely to face a lower cost of funding their assets and transition. This might be due to the prevailing lower risk-free rates or a more stable business environment reducing the equity risk (EPR). A lower WACC could also mean lower net present value of the future expected returns, and as such, these numbers must always be assessed relative to the potential return on investment.

Contrasting Europe with North America, represented by the US Dollar, we see slightly higher WACCs in North America. Regardless of the region's stability and economic strength make it a prominent player on the global stage. Despite a higher cost of debt, North America manages to balance its overall WACC with a lower equity risk premium. Diving deeper into Europe, it is interesting to see the disparity between operations funded in GBP versus those funded in Euros. This discrepancy may speak to the varying economic and fiscal conditions that differentiate the United Kingdom from the Eurozone.

Finally, it is worth noting the role that corporate tax rates play across the regions. The corporate tax rate in Asia is the highest at 30.0%, compared to Europe's lower rate of 17.9%. This can influence decisions regarding capital structure, as higher corporate tax rates incentivize debt financing due to the associated tax shields.

In conclusion, while these figures offer some valuable insights, they are not a comprehensive representation of the business or economic environment. To gain a holistic understanding, these factors must be interpreted alongside additional elements such as geopolitical stability, currency exchange rate stability, and overall economic growth. Furthermore, industry-specific considerations should also be taken into account when making business decisions.

Then, we compute the equity valuation ratio in scenario φ as:

$$\pi_{E,\varphi} = \frac{DCF(k,\varphi)}{DCF(k,\text{baseline})} \tag{18}$$

That represent the (possibly unpriced) equity return associated to issuers that are better positioned, in terms of revenues share allocated in different activity, to comply with, Below 2°C, Delayed 2°C or NZE requirement. A valuation $\pi_{E,\varphi}$ greater than one implies that the value of the firm's stock is likely to increase in a scenario where the transition regulation is strengthened out, while an valuation smaller than one implies that the company current revenues share does not match the scenario requirement.

In other terms, the equity valuation ratio of a scenario should be interpreted as the return one should expect assuming that the market currently prices the baseline and fully shifts to this scenario (i.e., the market assumes less stringent emission mitigations in the future). For example, the net-zero valuation ratio, is the equity premia associated with sudden pricing of the net zero-scenario.[32] Although these scenario valuation ratios are theoretical, it can provide investment signal. For example, for green stock shareholder, and assuming the market does not currently effectively price transition, the real profit is limited by the smaller of the expected increase in future cash flows as described in this scenario valuation ratio or the merger bonus provided by the acquiring company.[33]

Figure 19 depicts the reaction of various corporations with respect to equity valuation ratios. In the left segment of the figure, businesses are arranged based on their direct (scope 1) carbon intensity. Company 11 is the most intensive with 6169,5 tonnes CO_2e/USD mn in Carbon Intensity-Scope 1 while Company 5 intensity is 1,5 CO_2e/USD mn. It is immediately apparent that there is no correlation between the order of equity valuation ratios and carbon intensity. Moreover, we discern diverse patterns regarding the influence across the varying scenarios. In the right segment, we designate the orderly transition below 2°C as the baseline (represented on the horizontal axis) and portray the valuation ratios for Delayed 2°C and Net-Zero relative to the 2°C premiums. It is unmistakably seen that the responses are not uniform, thereby highlighting the beneficial aspect of incorporating such trajectories into the valuation process.

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[32] In practice, the market price several scenarios with different probabilities but we leave this question requiring more complex Bayesian modeling for further research.

[33] If the '*low-carbon*' company is bought by large fossil fuel player '*greening*' its revenues as discussed in previous section.

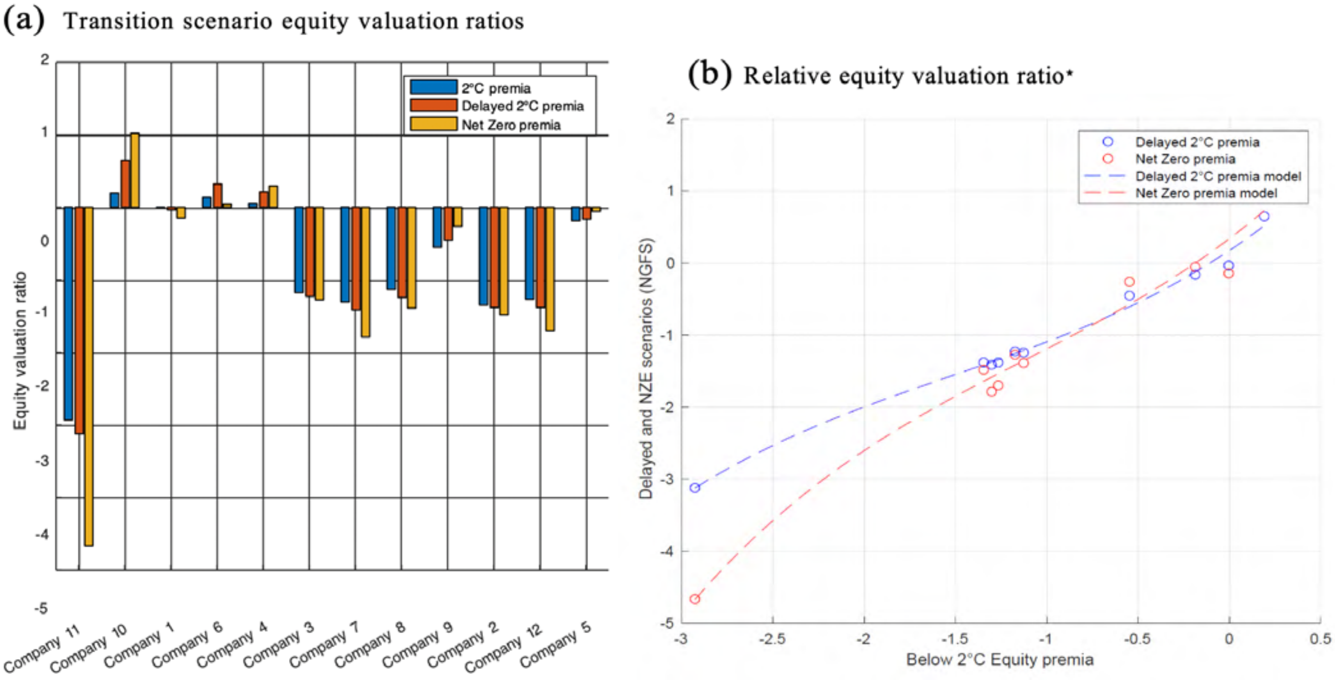

Figure 19. Illustration of the response in terms of equity valuation ratio over the sample of companies

*Note: * relative EVR in delayed (disorderly) and Net-Zero (ambitious) scenarios vs. Below 2°C (orderly transition)*

In Figure 19 (a) we can observe several interesting results. First, we note that all fossil fuel companies (Company 2, 3, 7, 8, 11 and 12), with revenues allocation in coal, refined oil product, oil and gas have ratio smaller than 1. This means that if the market were pricing the future cash flows of these companies in the net-zero scenario (or any other transition scenario), the price of their share should be zero. This is consistent with the idea that there are no fossil fuels in the net zero scenario but it also demonstrates that the market currently gives little weight to this scenario. Note that the extreme values observed on this chart for fossil fuel companies can be explained by the sample of highly intensive companies used. Indeed, we reiterate that these 12 companies account for 17% of the direct emissions of the MSCI World Index, thus they carry much of the transition costs, thus high transition risks.

On the other hand, companies 1, 4, 5, 6, 9 and 10 presents highly heterogeneous valuation ratios, although operating in similar sectors. The material Company 1 has limited impact of transition scenario on its DCF. We note that this company also have relatively high WACC value which can explain the limited influence of future (long-term) change in revenues. Company 4 and 5 (Utilities) present different patterns although relatively similar revenue mix (about 60-70% electricity). Company 4 with higher electricity (69.1%) revenue share presents better valuation ratios in all transition scenarios than Company 5 although is much more carbon intensive. Company 5 also present different pattern with worse ratio in below 2°C and delayed 2°C because it includes gas and the NZE scenario allow some short-term allocation in this resource (in the present configuration presented - cf Figure 8).

Company 10 is a company operating exclusively in low carbon businesses or electricity production or '*pure player*'.[34] Although being second most intensive of the sample, this company presents positive valuation ratio, and even an NZE ratio greater than one. This implied that if the market were to price fully the net-zero scenario, this company share value could theoretically double.

3.4.2 Bonds credit spread

The default probability is defined in Alogoskoufis *et al.*, 2021, as a function of profitability, leverage, GDP and age of the company in a top-down fashion as:

$$PD(t,k,\varphi) = \alpha_{PD} + \beta_{1,PD} \cdot \mathrm{Leverage}(t,k,\varphi) + \beta_{2,PD} \cdot \mathrm{Profitability}(t,k,\varphi) + \beta_{3,PD} \cdot \mathrm{GDP}(t,\varphi) + \beta_{4,PD} \cdot \mathrm{GDP}^2(t,\varphi) + \beta_{5,PD} \cdot \mathrm{age}(t,k) \quad (19)$$

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[34] They are generally characterized by a lower market capitalization and may therefore be the target of global players looking for diversifying energy production toward greener sources. The race for a more virtuous energy mix will lead to an amplification of the equity valuation ratios that we calculate, in line with the M&A premiums that are already taking shape through the acquisitions of certain major players.

This formula straightforwardly shows that a bond's risk is contingent on a company's leverage ratio, which is the proportion of debt to total assets. The higher the leverage, the greater the concern about the company's ability to repay its debt. Profitability plays a crucial role too; a decline in profitability can heighten the likelihood of default. Furthermore, the model adopted by the ECB also factors in macroeconomic influences, including the effects of GDP fluctuations.

The spread is the difference between risk free asset and risky asset. It can also be written as follows:

$$Spread(t,k,\varphi) = PD(t,k,\varphi) \times (1 - \mathcal{R}) \qquad (20)$$

Where $\mathcal{R}$ is the recovery. Similarly, we measure in basis point the transition scenario credit spread as:

$$\pi_{B,\varphi,t} = Spread(k,\varphi,t) - Spread(k,\mathrm{Baseline},t) \qquad (21)$$

As a first proxy, one can note that the change in spread will be mainly sensitive to the change in profitability (Leverage being kept constant). According to Alogoskoufis *et al.* (2021), the sensitivity to profitability, $\beta_{2,PD} \sim -5.3\%$ (see **Table 8**) which allow us to derive the excess spreads for the companies in sample (with recovery rate =50%). Under these assumptions, we find that excess spreads above 50 bps can be observed for the most intense companies in the Net-Zero scenario by 2030 (Company 2, 7, 8 and 12, see **Table 9**).

This indicates that in aggressive transition scenarios, firms that are both capital and carbon-intensive are perceived as less creditworthy. As a result, these companies will need to provide elevated returns to attract investors. Consequently, the higher cost of capital for these firms could mitigate their growth prospects and impact their competitive positioning in the market. Additionally, this may lead to a potential reallocation of investor capital towards firms that are less leveraged or more financially stable, and also those that

Table 8. Estimation of Probabilities of Default ECB stress-test

	Probability of Default		
Leverage	0.0454	(0.000859)	***
Profitability	-0.0533	(0.00165)	***
Ln GDP	-0.00693	(0.00382)	*
Ln GDP sq	0.000113	(6.79e-05)	*
Age	-0.000140	(5.89e-06)	***
Constant	0.105	(0.0537)	*
Observations (ECB)	155,134		
Number of ID	28,167		
R squared	11.9%		

Note: Robust standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1 Source: ECB stress-test - Alogoskoufis *et al.* (2021)

Table 9. Excess spread estimation relative to Baseline (2019 policies) in percentage

Co.	Scenario	Year		
		2030	**2040**	**2050**
Company 1	Below 2°C delayed	0.000	-0.011	0.047
	Below 2°C immediate	-0.013	-0.014	0.015
	Net-zero 2050 (1.5°C)	0.040	0.049	0.110
Company 2	Below 2°C delayed	0.000	0.894	1.326
	Below 2°C immediate	0.452	0.885	1.138
	Net-zero 2050 (1.5°C)	0.586	0.995	1.166
Company 3	Below 2°C delayed	0.000	0.874	1.255
	Below 2°C immediate	0.388	0.836	1.078
	Net-zero 2050 (1.5°C)	0.468	0.925	1.077
Company 4	Below 2°C delayed	0.000	-0.032	-0.138
	Below 2°C immediate	0.035	0.005	-0.081
	Net-zero 2050 (1.5°C)	0.007	-0.072	-0.155
Company 5	Below 2°C delayed	0.000	0.048	0.041
	Below 2°C immediate	0.026	0.047	0.042
	Net-zero 2050 (1.5°C)	-0.004	0.025	0.005
Company 6	Below 2°C delayed	0.000	-0.163	-0.307
	Below 2°C immediate	0.044	-0.054	-0.198
	Net-zero 2050 (1.5°C)	0.181	-0.066	-0.088
Company 7	Below 2°C delayed	0.000	0.683	1.128
	Below 2°C immediate	0.306	0.641	0.920
	Net-zero 2050 (1.5°C)	0.580	0.892	1.124
Company 8	Below 2°C delayed	0.000	0.835	1.149
	Below 2°C immediate	0.352	0.734	0.954
	Net-zero 2050 (1.5°C)	0.522	0.918	1.076
Company 9	Below 2°C delayed	0.000	0.201	0.107
	Below 2°C immediate	0.154	0.198	0.121
	Net-zero 2050 (1.5°C)	0.061	0.110	-0.011
Company 10	Below 2°C delayed	0.000	-0.007	-0.013
	Below 2°C immediate	0.018	0.011	-0.005
	Net-zero 2050 (1.5°C)	0.002	-0.037	-0.018
Company 11	Below 2°C delayed	0.000	0.208	0.398
	Below 2°C immediate	0.098	0.206	0.319
	Net-zero 2050 (1.5°C)	0.267	0.327	0.400
Company 12	Below 2°C delayed	0.000	0.861	1.384
	Below 2°C immediate	0.388	0.810	1.133
	Net-zero 2050 (1.5°C)	0.671	1.107	1.399

Source: Author calculations

have a lower carbon footprint. In the broader economic context and from a policy perspective, such shifts could result in reduced overall investments in sectors with both capital and carbon-intensive firms, potentially leading to job losses and disruptions in supply chains. Consequently, evaluating the effects of climate policies at the corporate level is essential for defining more effective strategies. The downscaling method introduced in this paper offers a path toward that goal.

4. Conclusion

This paper provides a methodology for a transparent stress testing and assessment tool in the context of transition scenarios by focusing on selected energy-intensive companies. While in this paper we rely on one of the most advanced economic models in the integrated assessment modeling community in terms of sectoral and international trade representation, the MIT Economic Projection and Policy Analysis (EPPA7) model, our methodology can be applied to other models and scenarios. We have focused on the NGFS-type of scenarios in this exercise, but other simulations can be realised.

For example, if emission reductions are driven by regulations, such as carbon border adjustment mechanisms like in the EU or the Inflation Reduction Act like in the USA, implications on particular sectors and the overall cost of policies may differ in comparison to economy-wide carbon pricing or emission trading. The menu of regulatory policies that can be represented by the EPPA7 model can have different impacts on financial securities, and thus on investment portfolios. In this paper, we do not conduct a systematic stress test over an investment portfolio, but we first investigate the relevance of integrating IAMs in valuation process on a sample of case studies. The results of this illustrative exercise are promising as they both reveal non-homogenous responses over companies and scenarios, shocks with low correlation with direct Scope 1 emissions, with perfectly clear and transparent processes (i.e. all the instrumental variables trajectories are constructed in the process). Our results support the concerns about practices when the same emission reduction targets (especially if based on the global emission pathways) are applied to individual companies within the economic sector.

The comprehensive nature of the modeling of the economic transition of the framework lies on several aspects. First, it includes an econometric approach - inspired by Alogoskoufis *et al.* (2021) - economy-wide stress test to capture systemic effects with asset exposures to global GDP and other macroeconomic indicators. Although most of these macroeconomic exposures have been neglected in the figures presented in this paper – in order to focus on the sole effect of revenues and operating costs of the transition at the firm level – these features are very important when considering, for example, an inflation scenario or a change in VAT, and are integrated in the stress-test. Second, we included the share of revenues in different activities. As far as we know, our stress testing framework is also the only one that takes into account the fact that large companies are active in several sectors and regions, and thus introduce a precise split of revenues in line with 10-K reports. We then downscaled the variation factors applied to the revenues and costs suggested by EPPA model to the company level (in proportion to each company's contribution to the sector x region activity, i.e. revenues and emissions). Again, applying the results of integrated assessment models at the company level, accounting for its share in sectoral activity, is another novel application in the stress testing landscape. Finally, we reintegrated the results in the comprehensive framework proposed by Alogoskoufis *et al.* (2021), to compute the rest of the financial indicators materials to compute both theoretical bond and equity values.

We illustrate the process with some examples and show that we can measure the ratio of equity value between each scenario and the baseline. For example, the net-zero valuation ratio represents the return on equity if the market starts pricing the net-zero scenario instead of the baseline. We can also use this tool to ask the inverse question: What is the current market sentiment towards the NZE scenario? In theory, the price of equity should reflect discounted cash flows weighted by scenario probabilities (see Le Guenedal *et al.*, 2022), thus reflecting investors' beliefs in each scenario realization. Thus, we can extrapolate the probabilities that investors assign to each transition scenario to form current market cap and stock values. Regarding the bond market, we show on a limited sample that an excess spread above 50 bps in 2030 for the most intense companies in the Net-Zero scenario can be observed based on the impact of the transition on corporate profitability.

Beyond the results, we reiterate that we offer the first framework coupling the science of a technology-based integrated assessment model, econometric sensitivities, advanced corporate level analytic and robust pricing principles to provide an operational answer to the problem of security pricing in the context of transition scenarios. To better account for uncertainties in the scenario, carbon price and pass-through, a stochastic approach is required (for example, as developed in Desnos *et al.*, 2023).

The methodology developed in this paper is generic and can be applied on investment portfolios. The next step of our research will therefore focus on the generalization of this work by expanding the set of scenarios, sectoral and regional coverage, and applications to different investment portfolios.

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Appendix A. Complementary materials

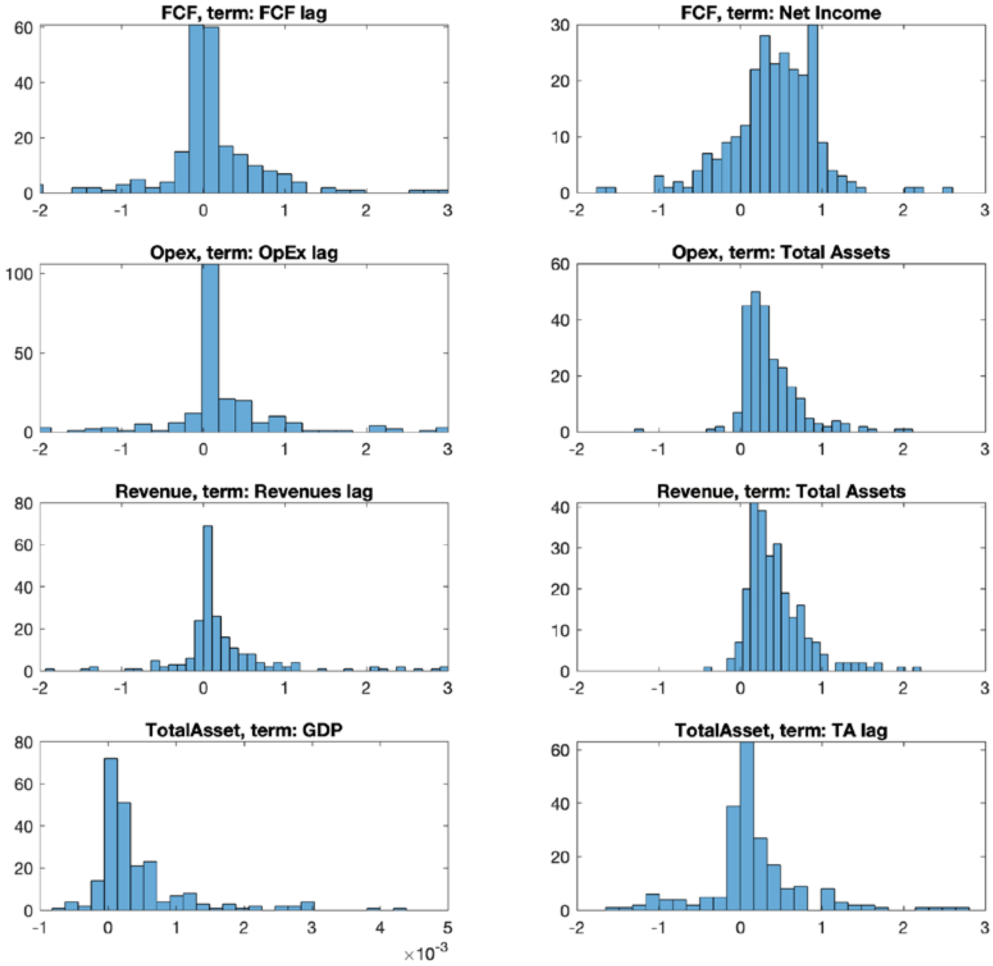

Figure 20. Full sample estimate of sensitivities

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