Region-Sector Heatmaps for Transition and Physical Risks

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Abstract

This paper quantifies the monetary costs of transition and physical climate risks at the region-sector level, based on publicly available data from the Network for Greening the Financial System (NGFS). For transition risks, we rely on the GCAM integrated assessment model, which provides granular regional and sectoral emissions trajectories and carbon price pathways. We develop indicators such as path misalignment, budget overshoot, and abatement share, and translate them into financial costs using discounted carbon price trajectories. Region-sector heatmaps are constructed to highlight heterogeneity across countries and industries, and to illustrate which sectors contribute most to transition misalignment and costs under alternative climate scenarios.

For physical risks, we use NGFS short-term climate scenarios based on physical climate storylines of compound events, including heatwave-drought-wildfire and storm-flood episodes. These scenarios are linked to economic impacts (capital destruction, output losses, productivity shocks), and further mapped into probabilities of default and asset valuations. This provides a consistent macro-financial framework to assess near-term physical risk exposures.

Our results reveal strong heterogeneity across regions and sectors for both transition and physical risks. Energy-intensive industries (such as steel, cement, and electricity) and resource-dependent economies face the largest transition costs, while climate hazards disproportionately increase credit risks in some vulnerable sectors (agriculture and construction) and regions (in South Asia and Latin America). The framework demonstrates the value of NGFS scenarios as a standardized, transparent, and regularly updated basis for climate-related financial risk analysis.

Keywords: Climate financial risk; NGFS scenarios; Region-sector heatmaps

JEL Classification: Q54, Q51

1 Introduction

Given the large uncertainty raised by the climate and environmental crisis on economic perspective, there is a need for financial actors to better understand what could be the implications of a given scenario on asset prices. However, past data are not particularly good at predicting what could happen in a given scenario (?). To address this issue, we need to consider directly a scenario of interest and infer the implications of this scenario on regions and sectors and, ultimately, on firm's prospects. Notably, transition and physical risks are likely to materialize, depending on the selected scenario, and affect the revenues and probability of default of corporates, resulting in different impacts on stock and bond prices. The objective of this research is to quantify the monetary cost of transition and physical risks at the region-sector level, using publicly available data, and to construct heatmaps under different climate scenarios.

Among the available datasets, only the resources provided by the Network of Central Banks and Supervisors for Greening the Financial System (NGFS) allow us to quantify projections of financial losses in a given scenario, while considering both transition and physical risk, at the region and sector levels.[1] This comes, however, at a cost: NGFS scenarios rely on different models, horizons, and levels of detail for transition and physical risks. The transition risk model (NGFS, 2024) typically spans long horizons (2030-2100) and focuses on sectors exposed to rising carbon prices, while the physical risk model (NGFS, 2025) is designed for short horizons (up to 2030) with finer sectoral granularity.

We quantify transition and physical climate risks using publicly available NGFS data at the region-sector level. For transition risks, we construct indicators of emissions misalignment, budget overshoot, and abatement share based on GCAM scenarios, and translate these indicators into normalized financial costs. For physical risks, we rely on NGFS short-term scenarios that combine storyline-driven compound climate events with economic and credit risk models. In both cases, we present region-sector heatmaps that highlight the heterogeneity of exposures across economies and industries.

The heatmaps are based on the principle that we currently face a business-as-usual (BAU) pathway and must evaluate the potential cost of (i) a rapid or delayed transition to net zero and (ii) an acceleration of extreme climate events. The regions and

[1]Other databases, such as those built by the International Energy Agency and the United Nations Principles for Responsible Investment, in the context of the Inevitable Policy Response, either have limited access or lack sufficient sectoral and regional granularity.

sectors considered in both transition and physical risk models developed by NGFS are different. However, we build heatmaps by harmonizing regions and sectors to make them as comparable as possible.

Our results show that transition risks are concentrated in emission-intensive sectors such as electricity, steel, and cement, with strong regional differences depending on the prevailing policy and carbon pricing context. Physical risks, by contrast, disproportionately affect construction, agriculture, and energy supply, with emerging economies particularly exposed due to their vulnerability to climate hazards and weaker adaptive capacity. The comparison of transition and physical risk heatmaps underlines that the two dimensions of climate risk are complementary rather than substitutable: regions with relatively lower transition costs may still face high physical risks, and vice versa.

Importantly, NGFS scenarios are publicly available and free of charge, which ensures that the analysis can be regularly updated as soon as new vintages of scenarios and data become available. This feature makes the methodology particularly relevant for ongoing monitoring of climate-related financial risks.

2 Transition Risk

We focus on the version of the transition risk model based on the GCAM model (one of the three Integrated Assessment Models used by NGFS), which provides the most granular sectoral decomposition. The regions and sectors analyzed in the model are discussed in Section 2.3, while details on the GCAM model are provided in Appendix A. Several NGFS scenarios are of particular interest from the transition perspective, i.e., those implying a positive cost for the economy (Scenarios 1 to 5 in Appendix A.1). The reference document for the transition risk model is NGFS (2024).

Sectors are indexed by $k \in \mathcal{K}$, regions by $r \in \mathcal{R}$, scenarios by $s \in \mathcal{S}$, and years by $t \in \mathcal{T} = \{t_0, \dots, t_1\}$. NGFS provides:

- Sector-region emissions trajectories under scenario s: $E^s_{k,r,t}$
- Carbon prices by region and scenario: $P^s_{r,t}$.

To evaluate the potential financial cost of a shift toward a low-carbon economy, we select a *baseline* scenario $b \in \mathcal{S}$ (the business-as-usual, BAU, scenario). We then define a transition scenario $z \in \mathcal{S}$ (for instance, the Net Zero 2050 scenario).

The excess-emissions gap in scenario b relative to the net-zero (NZ) scenario z is defined as:

$$G_{k,r,t}^{b|z} = \left(E_{k,r,t}^{b} - E_{k,r,t}^{z}\right)_+, \quad \text{with} \quad (x)_+ = \max\{x, 0\}. \tag{1}$$

For firms to be exposed to transition risk, the excess-emissions gap must be positive. Such a gap arises in Scenarios 1 to 5 (orderly or disorderly transitions), so we can choose z among these scenarios. Since $E_{k,r,t}^{b}$ is generally larger than $E_{k,r,t}^{z}$, we omit the max operator in the remainder of the analysis.

Note that we take NGFS scenarios as given and directly evaluates the costs implied by the transition from the BAU to any NZ scenario. In particular, we do *not* optimize abatement strategies or account for stranded-asset effects.

2.1 Sector-level Alignment

Path misalignment. A straightforward way to measure the misalignment of emissions in a given region-sector in the BAU scenario b relative to a NZ scenario z is to compute the *path misalignment*:

$$PM_{k,r}^{b|z} = \sum_{t\in\mathcal{T}} \ln\left(\frac{E_{k,r,t}^{b}}{E_{k,r,t}^{z}}\right). \tag{2}$$

Years can be taken, for example, as 2030, 2040, 2050, etc. Since emissions in the BAU scenario exceed those in the NZ scenario, we generally have $PM_{k,r}^{b|z} > 0$. This measure can be interpreted as the cumulative percentage excess-emissions gap over the horizon $\mathcal{T}$.

Budget overshoot. Alternatively, the *budget overshoot* of b relative to z is defined as:

$$BO_{k,r}^{b|z} = \frac{\sum_{t\in\mathcal{T}} \left[E_{k,r,t}^{b} - E_{k,r,t}^{z}\right]_+}{\sum_{t\in\mathcal{T}} E_{k,r,t}^{z}}. \tag{3}$$

The measure $BO_{k,r}^{b|z} > 0$ captures the ratio of excess emissions relative to the allowed carbon budget ("How many times does the baseline scenario exceed the NZ budget?").

Abatement share (cumulative). We can also compute the required *abatement share* of scenario b relative to scenario z as:

$$AS_{k,r}^{b|z} = \frac{\sum_{t\in\mathcal{T}} \left[E_{k,r,t}^{b} - E_{k,r,t}^{z}\right]_+}{\sum_{t\in\mathcal{T}} E_{k,r,t}^{b}}. \tag{4}$$

Here we normalize by the BAU budget to ensure that the ratio lies between 0 and 1 ("What fraction of BAU emissions must be cut to meet NZ?").

The budget overshoot emphasizes the stringency of the NZ target, whereas the abatement share highlights the scale of the effort required to deviate from BAU.

Sectoral contributions. The budget overshoot and the abatement share can also be aggregated at the regional level, providing a decomposition of how each sector contributes to the overall overshoot or abatement required.

For the budget overshoot, we have:

$$BO_r^{b|z} = \frac{\sum_{k\in\mathcal{K}}\sum_{t\in\mathcal{T}}\left[E^b_{k,r,t} - E^z_{k,r,t}\right]}{\sum_{k\in\mathcal{K}}\sum_{t\in\mathcal{T}} E^z_{k,r,t}} = \frac{\sum_{k\in\mathcal{K}} BO^{b|z}_{k,r}\sum_t E^z_{k,r,t}}{\sum_{k\in\mathcal{K}}\sum_{t\in\mathcal{T}} E^z_{k,r,t}}.$$

This yields

$$BO_r^{b|z} = \sum_{k\in\mathcal{K}} \alpha_{k,r}\, BO^{b|z}_{k,r}, \tag{5}$$

where $\alpha_{k,r} = \frac{\sum_{t\in\mathcal{T}} E^z_{k,r,t}}{\sum_{k'\in\mathcal{K}}\sum_{t\in\mathcal{T}} E^z_{k',r,t}}$ represents the weight of sector k in the regional NZ carbon budget.

Similarly, the regional abatement share required to achieve the NZ scenario can be written as:

$$AS_r^{b|z} = \frac{\sum_{k\in\mathcal{K}}\sum_{t\in\mathcal{T}}\left[E^b_{k,r,t} - E^z_{k,r,t}\right]}{\sum_{k\in\mathcal{K}}\sum_{t\in\mathcal{T}} E^b_{k,r,t}} = \frac{\sum_{k\in\mathcal{K}} AS^{b|z}_{k,r}\sum_{t\in\mathcal{T}} E^b_{k,r,t}}{\sum_{k\in\mathcal{K}}\sum_{t\in\mathcal{T}} E^b_{k,r,t}} = \sum_{k\in\mathcal{K}} \beta_{k,r}\, AS^{b|z}_{k,r}, \tag{6}$$

where $\beta_{k,r} = \frac{\sum_{t\in\mathcal{T}} E^b_{k,r,t}}{\sum_{k'\in\mathcal{K}}\sum_{t\in\mathcal{T}} E^b_{k',r,t}}$ represents the weight of sector k in the regional BAU carbon budget.

2.2 Financial Cost and Normalization

The indicators above account for excess emissions relative to a net-zero scenario, but do not account for the different trajectory of carbon prices across scenarios.

The indicators above measure excess emissions relative to a NZ scenario but do not account for the different trajectories of carbon prices across scenarios.

The present value of the transition cost under the NZ scenario z relative to the

BAU scenario b can be measured at the region-sector level as:

$$C_{k,r}^{b|z} = \sum_{t \in \mathcal{T}} D_t G_{k,r,t}^{b|z} P_{r,t}^{z}, \tag{7}$$

where $D_t = (1+R)^{-(t-t_0)}$ denotes the discount factor, with R the discount rate. Setting $R = 0$ amounts to summing the excess-emission gaps over time.

The transition cost is zero under the NZ scenario and increases with the emission trajectory of the BAU scenario. To make this measure comparable across regions, a normalization is required. One possibility is to scale the financial cost relative to revenues. This approach is consistent with NGFS's treatment of physical risks (see Section 3), where cumulative losses due to carbon costs reduce equity and may ultimately trigger firm defaults. However, NGFS does not provide revenue data at the sector-region level.

Alternatively, we can normalize the financial cost by either (i) the cost under the NZ scenario (analogous to the budget overshoot) or (ii) the cost under the BAU scenario (analogous to the abatement share). Both approaches face limitations. In the BAU scenario, NGFS sets the carbon price to zero, although in practice most regions already apply a positive carbon tax or market price. In the NZ scenario, emissions converge to zero by 2050, making denominators potentially very small in later years.

In practice, we consider two cases. First, normalization by the NZ scenario cost yields:

$$\tilde{C}_{k,r}^{b|z} = \frac{\sum_{t \in \mathcal{T}} D_t P_{r,t}^{z} \left(E_{k,r,t}^{b} - E_{k,r,t}^{z} \right)}{\sum_{t \in \mathcal{T}} D_t P_{r,t}^{z} E_{k,r,t}^{z}}. \tag{8}$$

A drawback of this approach is that $\tilde{C}_{k,r}^{b|z}$ can take very large values as $E_{k,r,t}^{z}$ converges to zero, making cross-region or cross-sector comparisons difficult.

Second, normalization by the BAU scenario cost gives:

$$\tilde{C}_{k,r}^{b|z} = \frac{\sum_{t \in \mathcal{T}} D_t P_{r,t}^{z} \left(E_{k,r,t}^{b} - E_{k,r,t}^{z} \right)}{\sum_{t \in \mathcal{T}} D_t P_{r,t}^{b} E_{k,r,t}^{b}}. \tag{9}$$

In NGFS's BAU scenario, the carbon price is set to zero by assumption. This is not realistic as several countries have imposed a carbon tax for several years.[2] Our approach

[2] Dolphin and Merkle (2024) estimate the average carbon tax, weighted by the share of each country's CO_2 emissions, at \$1.05 per tonne of CO_2 equivalent. Cleary and Willcott (2024) provide a global average carbon price of \$2.79 per tonne for 2022, weighted by each country's share of global emissions. Coverage is limited to countries with carbon pricing policies, representing roughly 15% of global emissions.

is therefore to use a normative value of the carbon price or the current value observed on ETS markets.

Remark 1: Aggregating at the regional level gives:

$$\begin{aligned}\tilde{C}_r^{b|z} &= \frac{\sum_{k\in\mathcal{K}}\sum_{t\in\mathcal{T}} D_t P_{r,t}^z\left(E_{k,r,t}^b - E_{k,r,t}^z\right)}{\sum_{k\in\mathcal{K}}\sum_{t\in\mathcal{T}} D_t P_{r,t}^z E_{k,r,t}^z}\\ &= \frac{\sum_{k\in\mathcal{K}} \tilde{C}_{k,r}^{b|z}\sum_{t\in\mathcal{T}} D_t P_{r,t}^z E_{k,r,t}^z}{\sum_{k\in\mathcal{K}}\sum_{t\in\mathcal{T}} D_t P_{r,t}^z E_{k,r,t}^z}.\end{aligned}$$

This expression simplifies to

$$\tilde{C}_r^{b|z} = \sum_{k\in\mathcal{K}} \beta_{k,r}\,\tilde{C}_{k,r}^{b|z}, \tag{10}$$

where

$$\beta_{k,r} = \frac{\sum_{t\in\mathcal{T}} D_t P_{r,t}^z E_{k,r,t}^z}{\sum_{k'\in\mathcal{K}}\sum_{t\in\mathcal{T}} D_t P_{r,t}^z E_{k',r,t}^z} \tag{11}$$

represents the weight of sector k in the regional NZ carbon budget. This aggregation approach could, in principle, be downscaled to the firm level.

Remark 2: If the cost is computed for a single period (for instance, 2030), the normalization by the BAU scenario cost (Equation (9)) simplifies to:

$$\begin{aligned}\tilde{C}_{k,r,t}^{b|z} &= \frac{P_{r,t}^z\left(E_{k,r,t}^b - E_{k,r,t}^z\right)}{P_{r,t}^b E_{k,r,t}^b}\\ &= \frac{P_{r,t}^z}{P_{r,t}^b}\times\frac{E_{k,r,t}^b - E_{k,r,t}^z}{E_{k,r,t}^b}\\ &= \underbrace{\left(1-\frac{P_{r,t}^b - P_{r,t}^z}{P_{r,t}^b}\right)}_{\text{Price impact }(+)}\times\underbrace{\frac{E_{k,r,t}^b - E_{k,r,t}^z}{E_{k,r,t}^b}}_{\text{Quantity adjustment }(+)}.\end{aligned} \tag{12}$$

This relation can also be written as:

$$\tilde{C}_{k,r,t}^{b|z} \approx \underbrace{\frac{E_{k,r,t}^b - E_{k,r,t}^z}{E_{k,r,t}^b}}_{\text{Quantity adjustment }(+)} - \underbrace{\left(\frac{P_{r,t}^b - P_{r,t}^z}{P_{r,t}^b}\right)\times\left(\frac{E_{k,r,t}^b - E_{k,r,t}^z}{E_{k,r,t}^b}\right)}_{\text{Quantity }\times\text{ Price adjustment }(+)}. \tag{13}$$

This measure defines the financial cost as the potential impact of a sudden scenario shift (transition risk), i.e., moving abruptly from BAU to NZ.

By contrast, normalization by the NZ scenario cost (Equation (8)) directly yields the budget overshoot in period t:

$$\tilde{C}_{k,r,t}^{b|z} = BO_{k,r,t}^{b|z} = \frac{E_{k,r,t}^{b} - E_{k,r,t}^{z}}{E_{k,r,t}^{z}}. \tag{14}$$

Remark 3: In principle, it is also possible to incorporate the idea of partial cost pass-through, i.e., the transmission of carbon tax increases from upstream to downstream sectors. In practice, firms in concentrated industries with high market power may be able to shift a large fraction of the carbon cost to consumers, whereas firms in more competitive markets cannot.

2.3 Data Available in NGFS Database

For the transition risk analysis, we rely on two NGFS-GCAM datasets (https://data.ece.iiasa.ac.at/ngfs-phase-4): sectoral emissions trajectories and regional carbon price pathways.

Sectoral emissions trajectories. The emissions dataset provides values by scenario, region, and sector. Annual emissions are reported in million CO_2-equivalents across Kyoto gases, assuming a uniform carbon price. Importantly, emissions are *production-based (territorial)*, i.e., attributed to the sector where they occur rather than to final consumption.

The full GCAM dataset covers 32 regions, but we restrict our sample to 15 major economies: USA, EU-15, Europe (non-EU), Japan, China, India, South Korea, Canada, Australia-New Zealand, Taiwan, Mexico, Russia, Brazil, South Africa, and Argentina. This restriction ensures both tractability and representativeness of global emissions patterns.

Carbon price pathways. The price dataset reports projected carbon prices by region and sector, with units expressed in constant US$2010 per ton of CO_2. Demand-specific values represent shadow prices in transportation, industry, and residential/commercial building sectors. All series are available in five-year increments from 2020 to 2100.

Model choice. Among the three IAMs employed by NGFS (GCAM, REMIND, MESSAGEix), we rely on GCAM (*Global Change Assessment Model*) because it is the only model with sufficient regional and sectoral granularity for our purposes. GCAM is a recursive-dynamic partial equilibrium model of energy, land, water, and agriculture, coupled with a climate module. It simulates market equilibrium period by period (typically in five-year steps), with agents forming decisions under *myopic expectations*. GCAM provides particularly detailed representations of energy and land systems, with 32 regions and explicit sectoral pathways, making it especially well suited for assessing transition risks. Details on the model are provided in Appendix A.2.

2.4 Some Illustrations

We begin this section with a short description of the technical aspects of dealing with the NGFS database. We then illustrate some data directly provided by NGFS, notably regional emissions and prices in the various scenarios. Last, we present heatmaps for the various indicators of misalignment, overshot, or abatement and normalized financial costs.

2.4.1 Practical Implementation

We use NGFS/GCAM production emissions (*Emissions* | *Kyoto Gases* | ...) at the region × sector × year level. Rows follow the fixed region list introduced in Section 2.3. Columns use the NGFS sector tokens as is: *Supply*, *Other Energy Supply*, *Electricity*, *Steel*, *Cement*, *Chemicals*, *Other Industry*, *Industry*, *Transportation*, *AFOLU*, *Other*. All metrics are reported for horizons $\mathcal{H} \in \{\in\prime\ni\prime, \in\prime\bigtriangledown\prime\}$.

Transition cost (Equation (9), BAU-normalized). For each region r, sector k, and year t, we compute discounted contributions as:

$$\text{Num}_t = D_t \, P^z_{r,t} \left(E^b_{k,r,t} - E^z_{k,r,t} \right)_+, \qquad \text{Den}_t = D_t \, P^{b,\text{fixed}}_r \, E^b_{k,r,t}, \tag{15}$$

with $D_t = (1+R)^{-(t-2020)}$ and $R \in \{2\%, 0\%\}$. The displayed index is then:

$$\widetilde{C}^{z|b}_{k,r} = \frac{\sum_{t \le H} \text{Num}_t}{\sum_{t \le H} \text{Den}_t}. \tag{16}$$

We use the *region-level NGFS carbon price* for $P^z_{r,t}$ and a time-invariant, region-specific BAU price $P^{b,\text{fixed}}_r > 0$. In some cases, the denominator is non-positive, because of net-negative emissions. In these cases, we do not report the normalized cost.

Support of the indicators. All indicators (BO and AS) are computed on the *intersection* of BAU and NZ annual series. As a result, the effective NZ budget used in BO may differ from an NZ-only diagnostic: NZ years without a matching BAU observation are excluded from both numerator and denominator, which can yield fewer grey cells in BO compared to an NZ-only non-positive-budget mask.

Color segmentation and masking. Heatmaps adopt a green-to-red convention where higher values are shown in red. To keep colors informative across heterogeneous scales, each panel uses its own dynamic maximum: the colorbar upper bound $v_{\max}$ is set to the 97th percentile of finite values in that matrix, with larger values clipped to the top color. For AS, although it can exceed 1 when NZ pathways become net-negative, we cap the map at $v_{\max} = 1$ unless otherwise noted (the underlying values remain unchanged). Missing or undefined entries (e.g., BO with non-positive NZ budget, or AS when no year satisfies $E^b > 0$ and $E^z > 0$) are masked and shown in light grey.

Sector handling. Sector names are taken directly from NGFS tokens and are not relabelled. In principle, if a dataset lacked *Supply* but included both *Electricity* and *Other Energy Supply*, we could reconstruct *Supply* as their per-year sum before computing all metrics. This situation did not occur in our analysis.

2.4.2 Regional emissions and prices in NGFS model

Figures 1 to 4 show emissions and carbon prices in the below-2°C scenario and the BAU scenario. Blue and orange circles represent 2020 and 2050 values, respectively. All numbers are drawn directly from the NGFS database. For example, carbon prices in 2020 are reported as zero, even though many countries had already implemented a carbon tax or emissions trading scheme. In each figure, countries are ranked from the most to the least affected.

There is substantial heterogeneity across countries in both emissions reductions and carbon price increases under the below-2°C scenario. By contrast, in the BAU scenario we observe only marginal changes in emissions (aside from a decline in the United States and an increase in India) and no change in carbon prices, consistent with current policy settings.

Figure 1: Emissions in the below-2°C scenario, 2020 vs. 2050

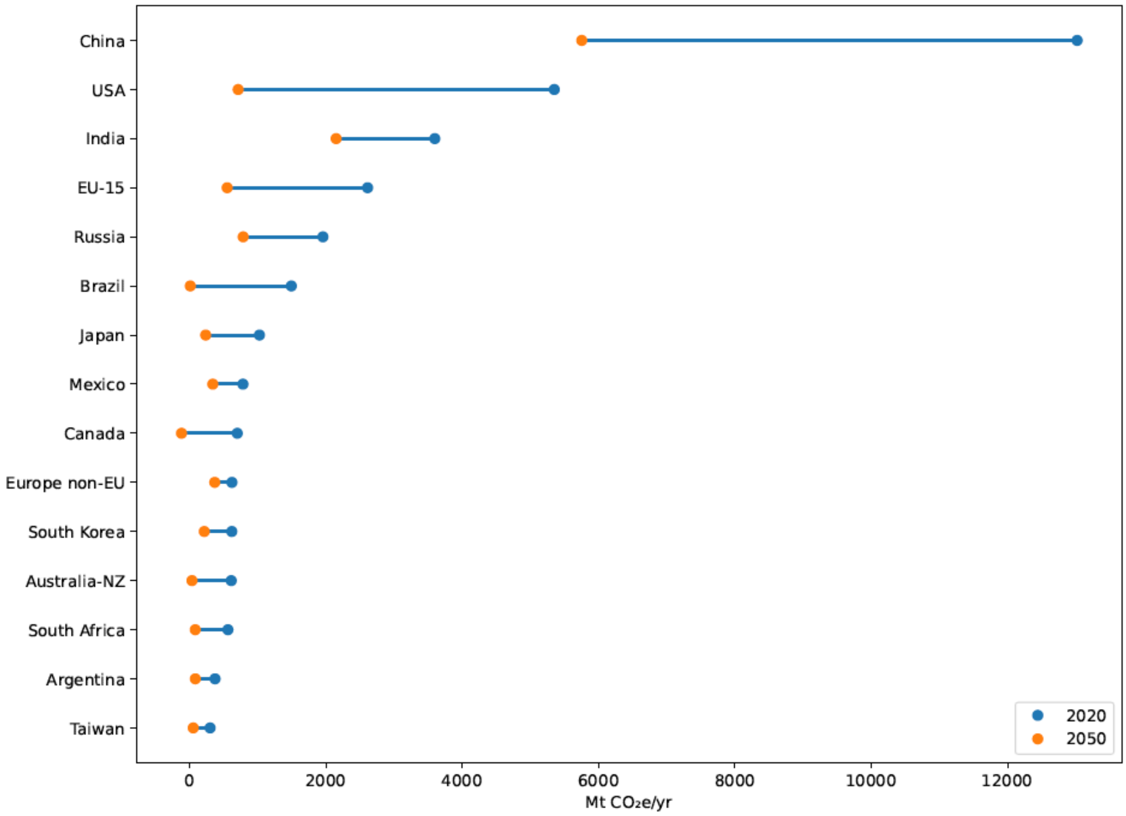


Figure 2: Price in the below-2°C scenario, 2020 vs. 2050

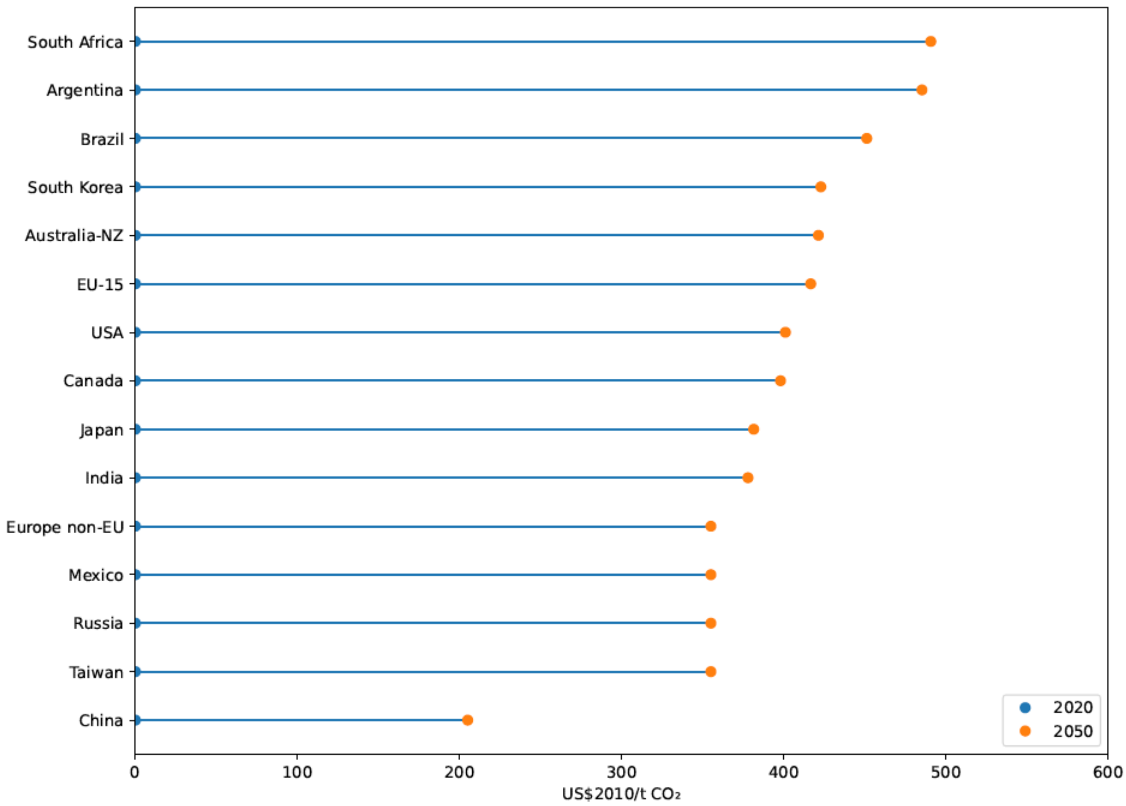


Figure 3: Emissions in the BAU scenario, 2020 vs. 2050

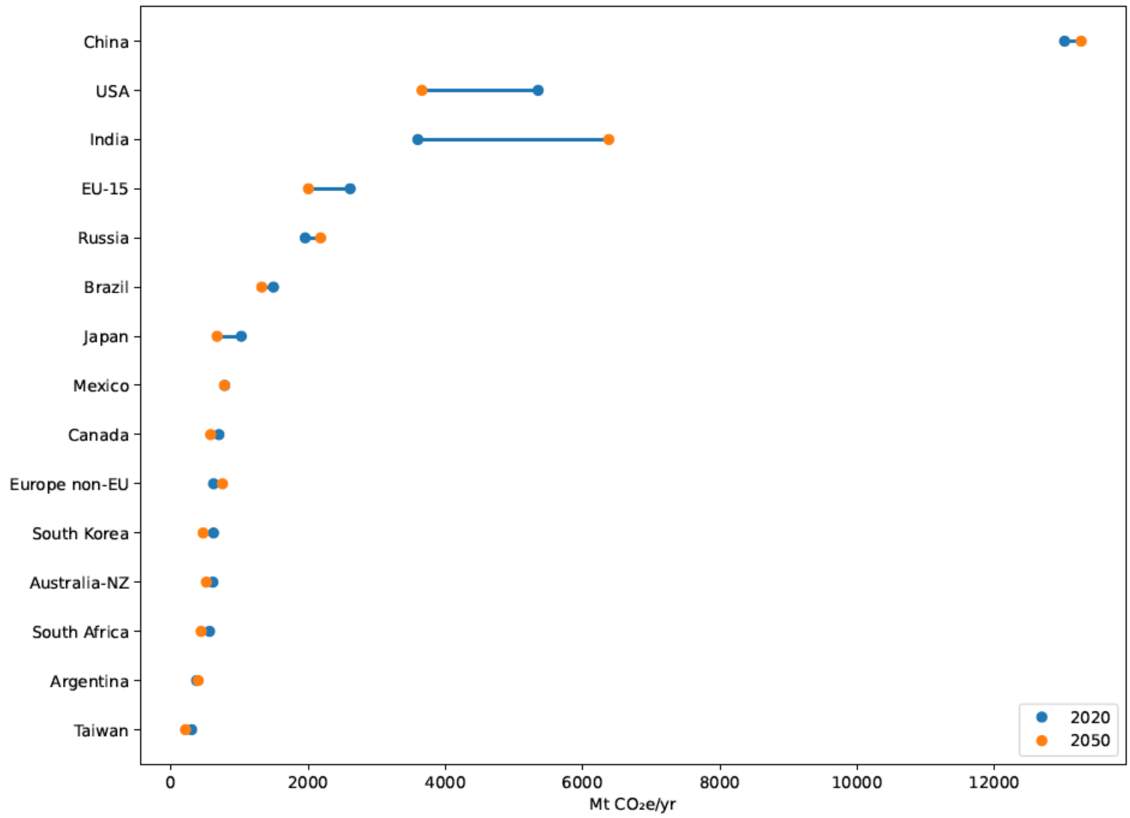
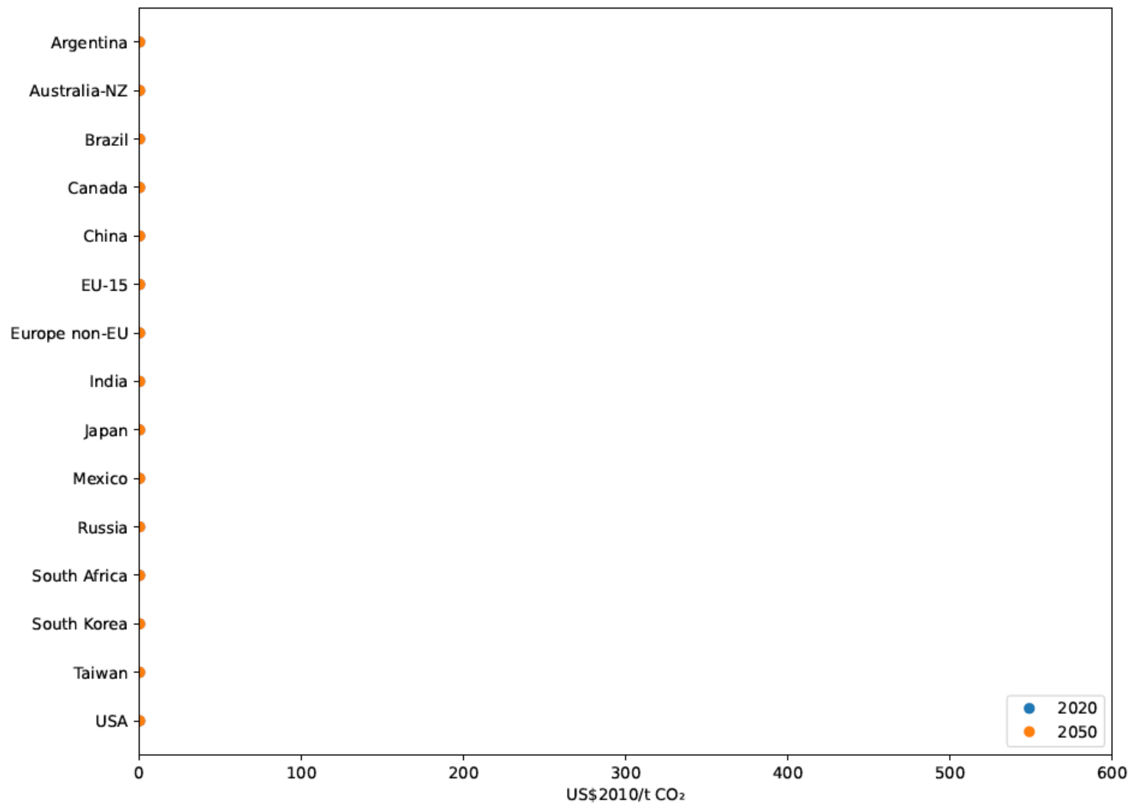


Figure 4: Price in the BAU scenario, 2020 vs. 2050



2.4.3 Region-sector heatmaps

Figures 5 to 7 present the path misalignment, budget overshoot, and abatement ratio indicators for the BAU scenario relative to the NZ scenario over 2020-2030. Figures 8 to 10 report the same indicators over 2020-2050. The definition of sectors is provided in Appendix A.3.

We observe substantial heterogeneity across indicators and horizons. Between 2020 and 2030, the path misalignment and budget overshoot indicators yield broadly similar results. Sectors related to energy supply and electricity are the most affected. Some regions, particularly Canada, Australia, and Brazil, also stand out. The budget overshot and the abatement share are relatively close to each other, reflecting that, over the period 2020-2030, differences across regions and sectors of the denominator (emissions in the BAU and NZ scenarios) are limited and do change the pattern.

Expanding the horizon to 2020-2050 reveals different patterns. Under path misalignment, high-emitting industries fall into the brown zone, notably steel and cement. The budget overshoot appears less severe, likely because a few region-sector pairs exhibit extremely high values, which complicates cross-sector comparisons. Finally, the abatement share, bounded between 0 and 1, shows that in most regions, energy-intensive sectors must abate the bulk of their emissions. Most sectors in most regions are more affected than with the budget overshot indicator.

Figures 11 to 14 display the normalized transition costs for 2020-2030 and 2020-2050, respectively. We investigate two approaches for the normalization: (i) In Figures 11 and 13, we use the current carbon price available for each country or region.[3] (ii) In Figures 12 and 14, we assume a conventional carbon price of $20 for all regions.

As expected, regions where the current price is above $20 (like the United States or the European Union) are less affected by the transition when the current price is used, because the additional carbon cost is lower. Other countries like India and Russia are in the opposite situation.

[3] We rely on the website https://carbonpricingdashboard.worldbank.org/compliance/price. When the same country has several carbon price (carbon tax and ETS market, for instance), we take the largest price. For regions involving countries with different prices, we use an average price. For countries with no carbon price, we assume a price of 2$, to avoid infinite transition costs. Because of the lack of homogeneity across countries, this approach may not be reliable.

Figure 5: Path Misalignment (from 2020 to 2030)

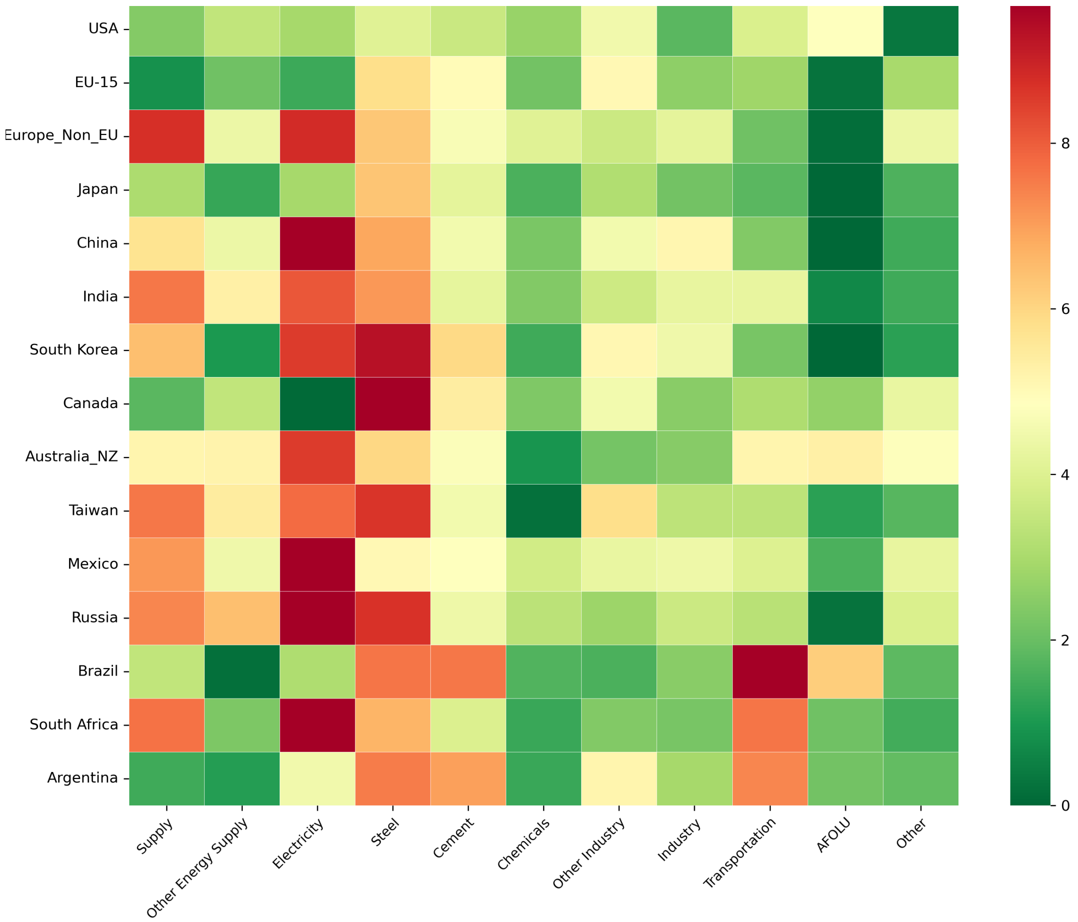


Figure 6: Budget Overshot (from 2020 to 2030)

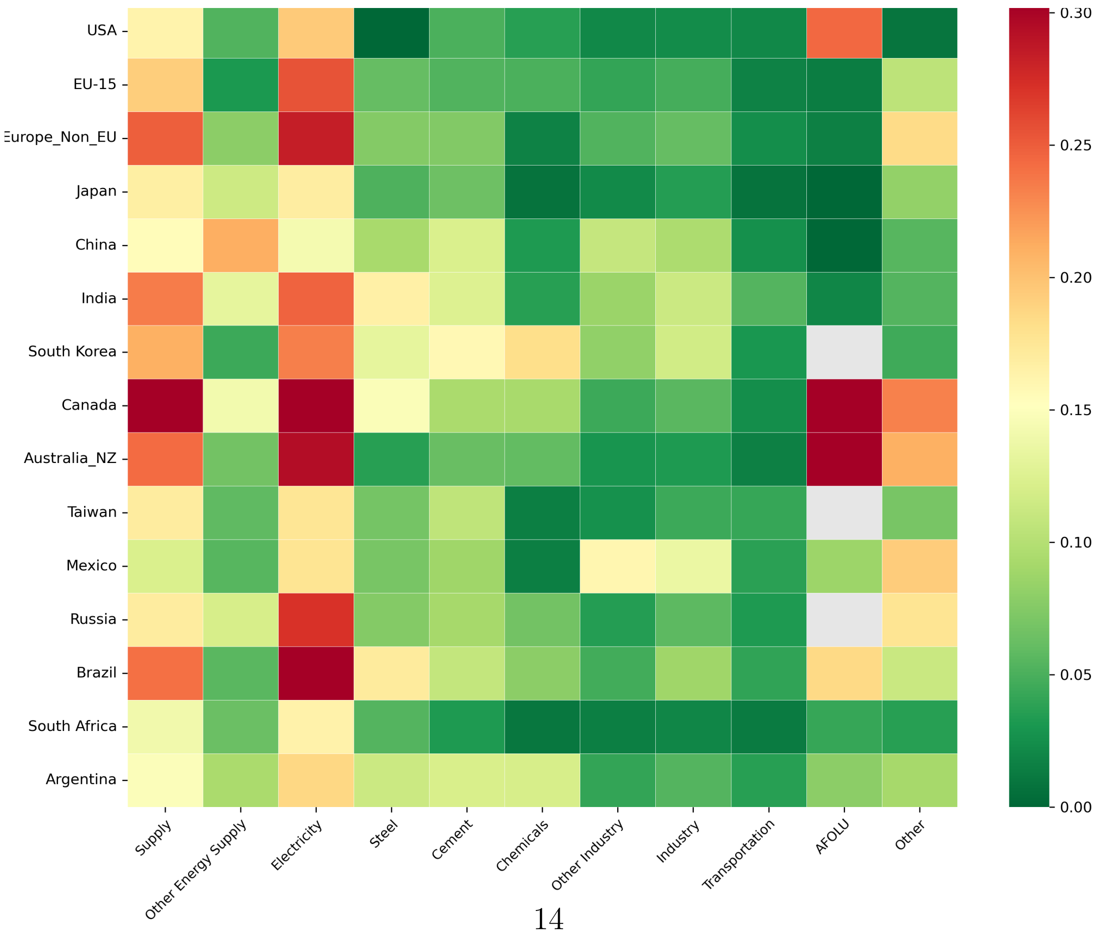


Figure 7: Abatement Share (from 2020 to 2030)

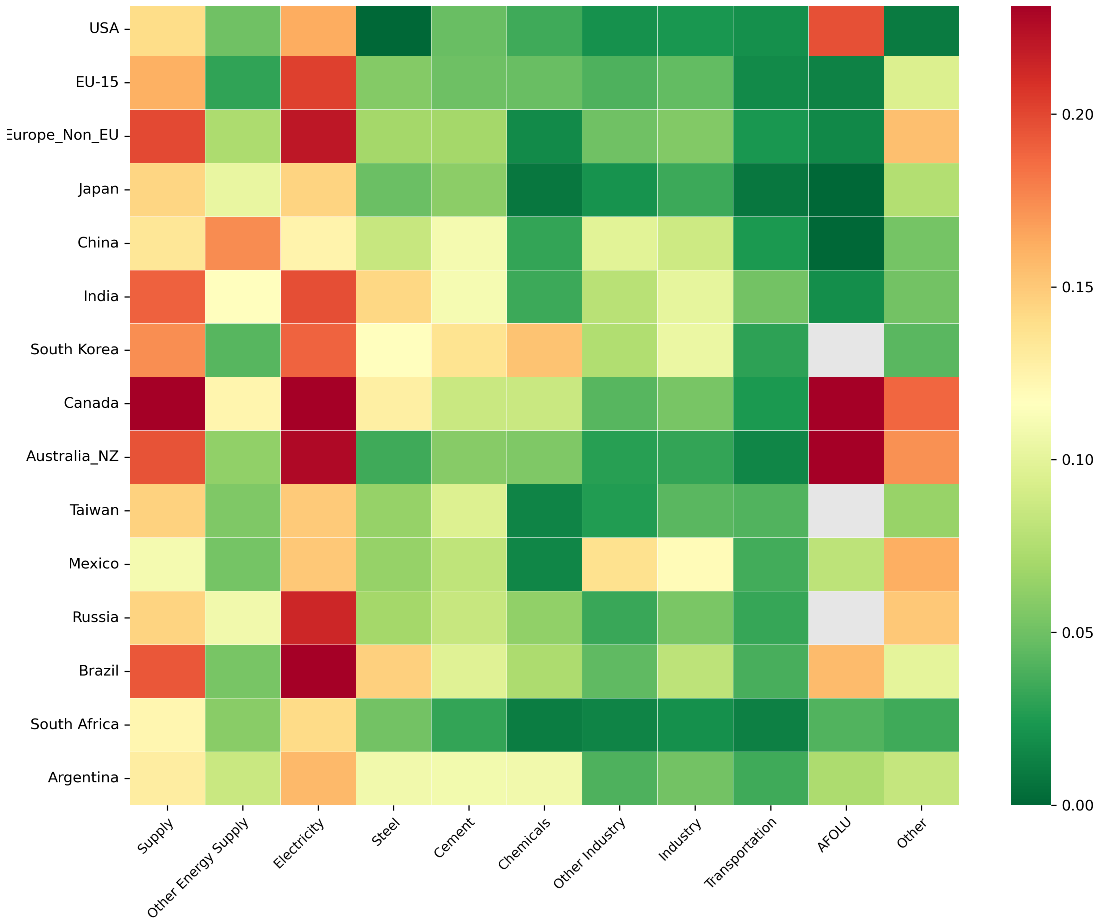


Figure 8: Path Misalignment (from 2020 to 2050)

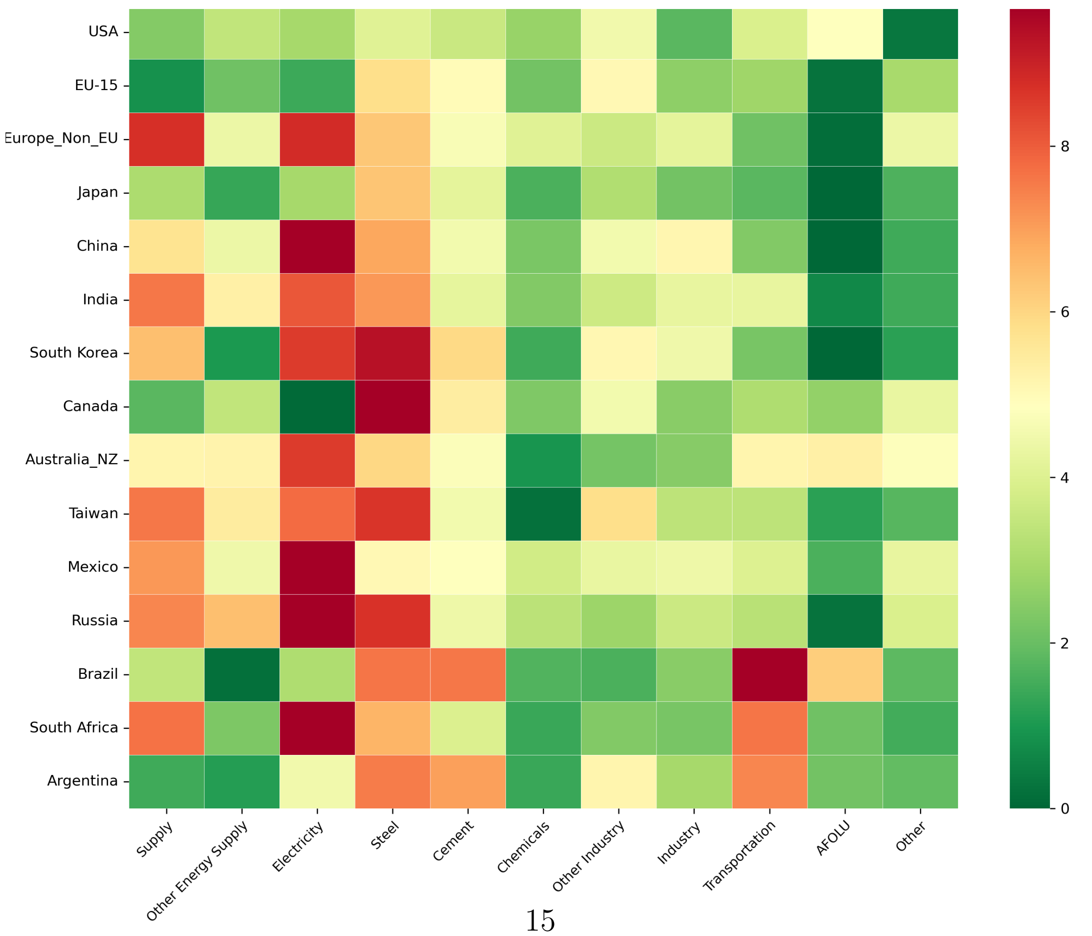


Figure 9: Budget Overshot (from 2020 to 2050)

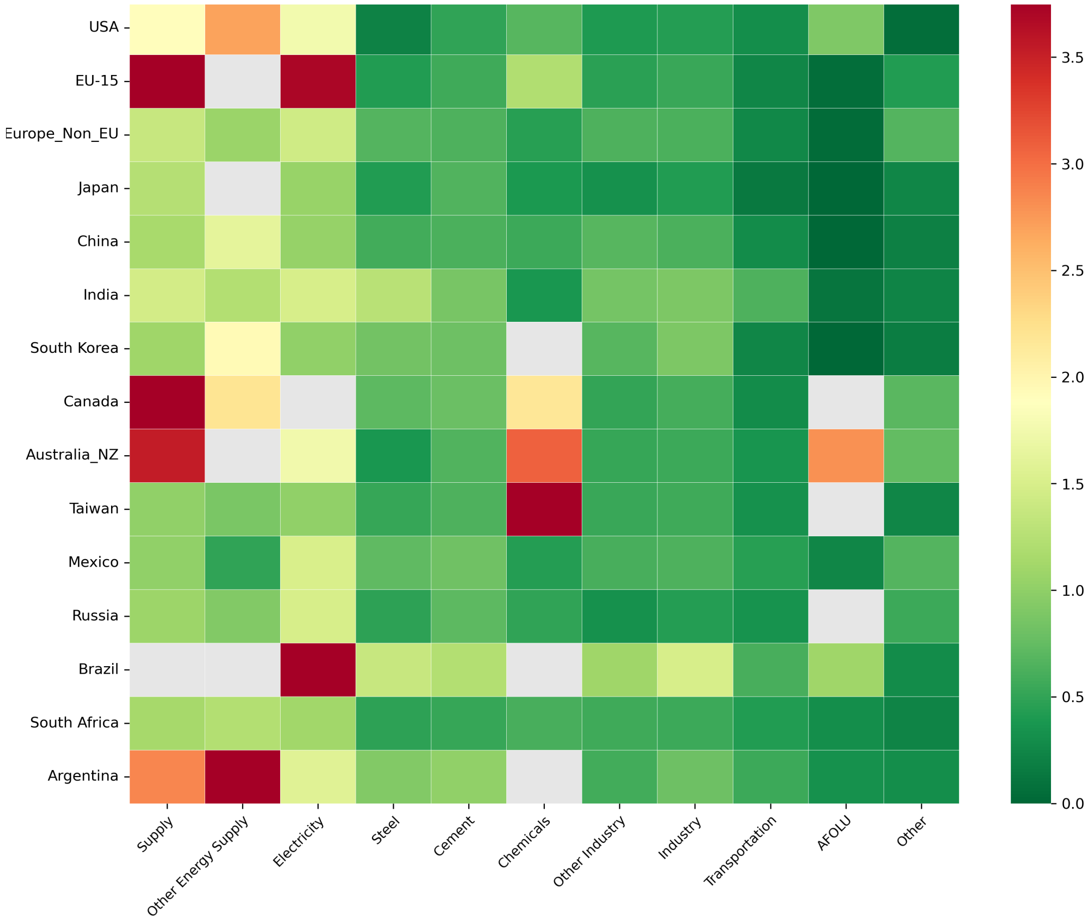


Figure 10: Abatement Share (from 2020 to 2050)

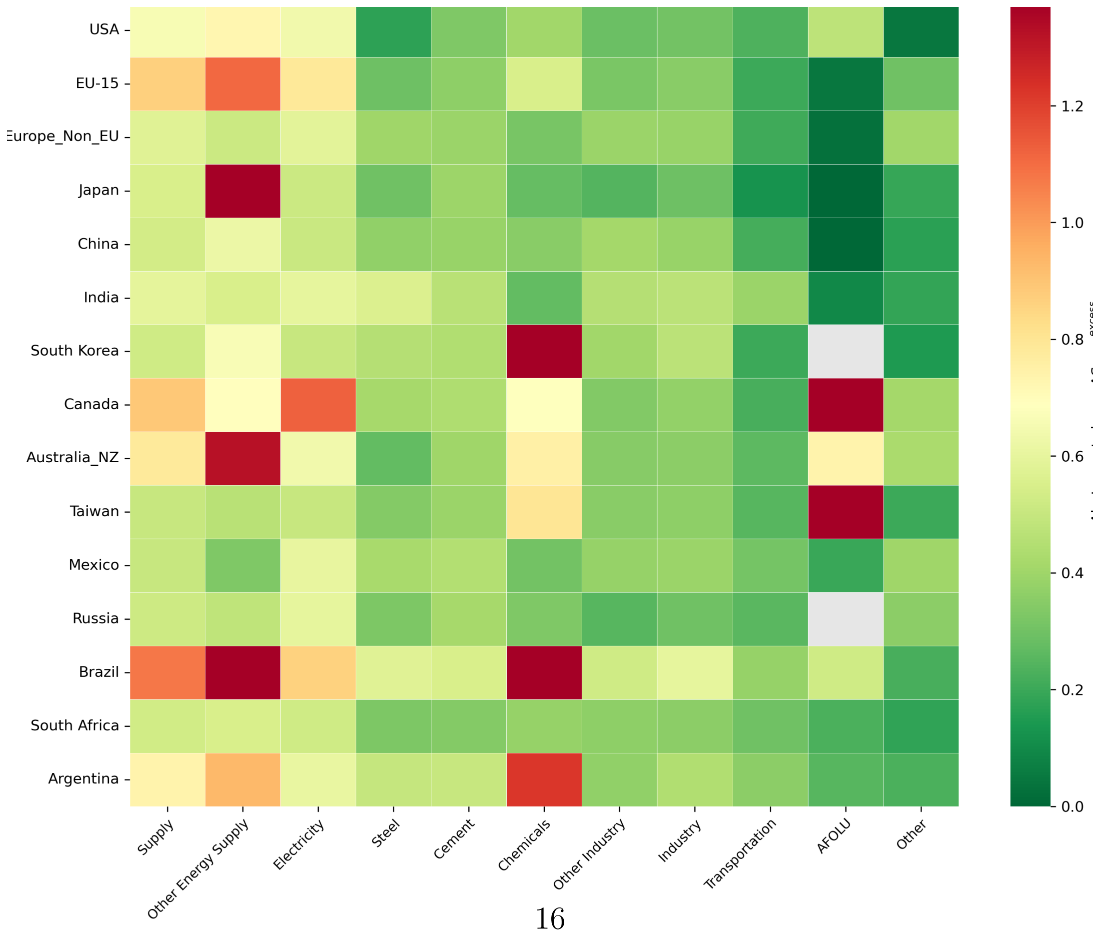


Figure 11: Normalized Transition Cost with Current Carbon Price (from 2020 to 2030)

Figure 12: Normalized Transition Cost with Carbon Price of $20 (from 2020 to 2030)

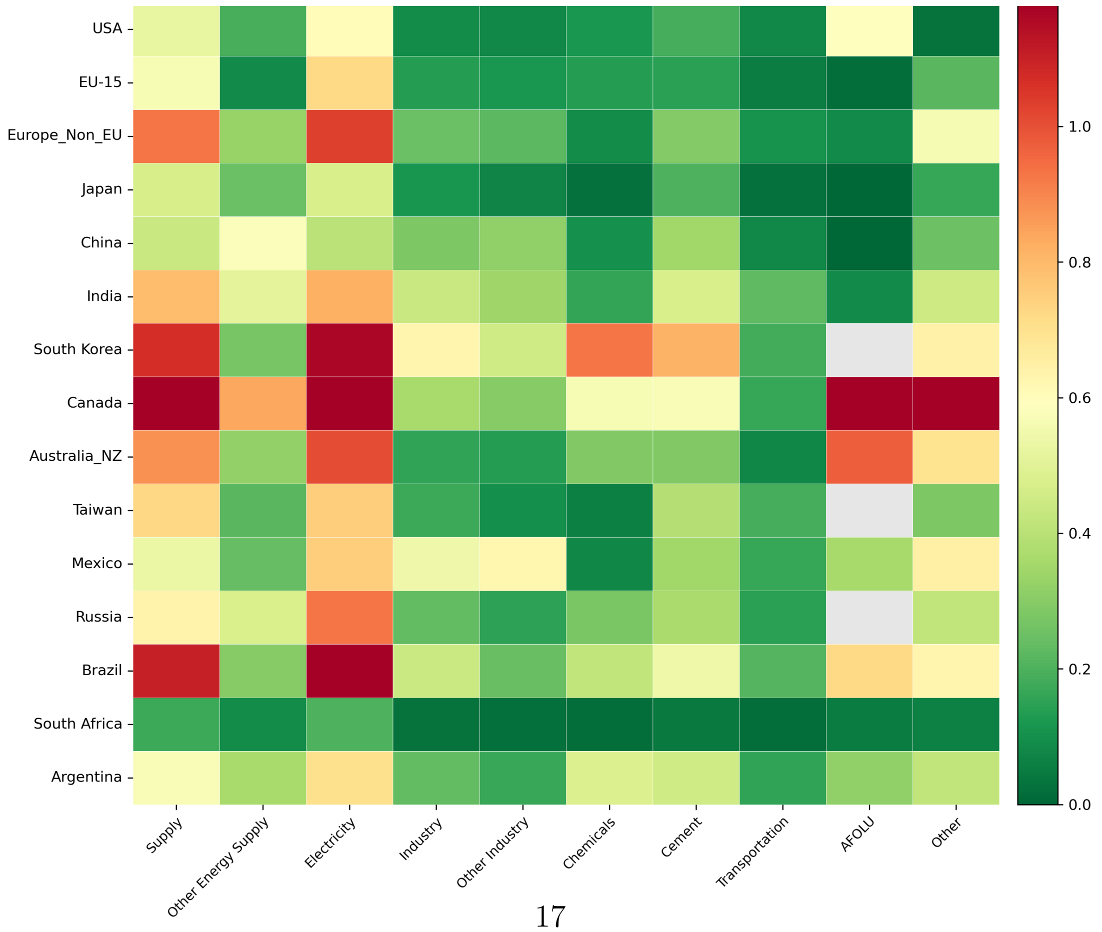


Figure 13: Normalized Transition Cost with Current Carbon Price (from 2020 to 2050)

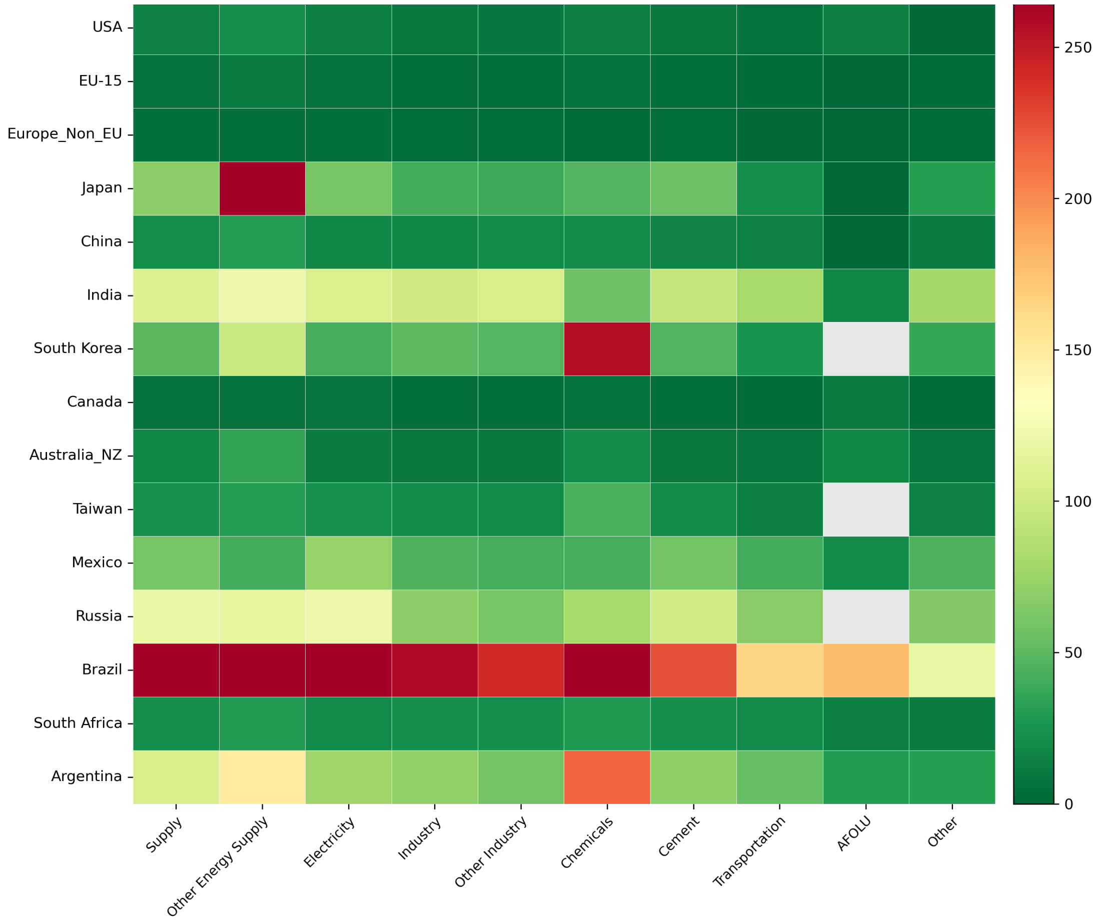
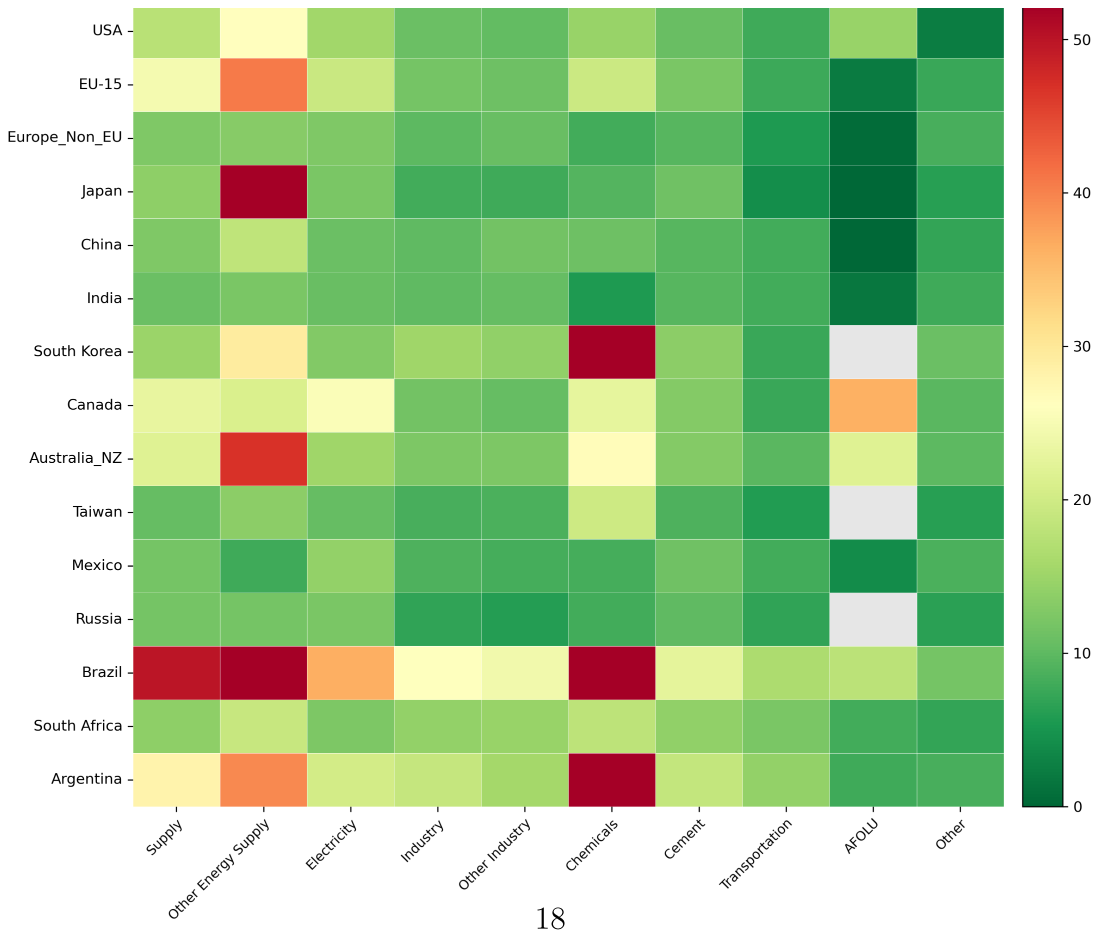


Figure 14: Normalized Transition Cost with Carbon Price of $20 (from 2020 to 2050)



3 Physical Risk

Very recently, the NGFS has developed a methodology to assess the economic and financial consequences of climate hazards, designed to complement its transition risk scenarios (NGFS, 2025). Physical risks arise from the direct impacts of climate hazards (e.g., heatwaves, droughts, floods, hurricanes) on the economy and the financial system. Low-probability, high-impact events are particularly relevant for systemic risk and financial stability. Such events may result from the compounding of multiple climate-related hazards, for example when severe flooding follows a prolonged drought. Details on the physical risk model are provided in Appendix B. The reference document for this model is NGFS (2025).

A key difficulty with compound events is that academic research lacks robust statistical models of the joint distribution of hazards that could be directly applied in catastrophe risk models. To address this gap, the NGFS developed physical risk scenarios based on the notion of *physical climate storylines*. These storylines are defined as physically self-consistent unfoldings of past events, or of plausible future events and pathways. Accordingly, NGFS physical risk scenarios are built from storylines describing compound events of two main types: (i) heatwave-drought-wildfire and (ii) storm-flood, both occurring at the continental scale.

These climate hazard projections are then linked to damage functions and vulnerability models to estimate their economic consequences. The magnitude of direct impacts in each storyline is expressed in terms of the share of capital stock damaged, output losses, and reductions in labor productivity. We note that the climate events described in this model are not probabilistic. A particular disaster (dry or wet) is assumed to occur at some point between 2025 and 2030 and the model measures the expected loss for corporates associated with this particular event.[4]

3.1 Storylines

The model considers four scenarios but only two of them are relevant for physical risks:[5]

[4]This approach is consistent with the logic of a NZ scenario, which assumes that the carbon tax is set to ensure the transition to net zero. This is different, however, from the standard approach in risk management, which relies on a probabilistic description of climate events.

[5]All scenarios are described in Appendix B.1.

- **Diverging Realities (DIRE)** (disorderly and insufficient emissions reductions) (transition and physical risks): Advanced economies (North America, Europe, Oceania, and parts of Asia) pursue a NZ transition consistent with the *Highway to Paris* pathway. The rest of the world is struck by a sequence of extreme weather events, whose effects propagate globally through trade and financial linkages. Supply chain disruptions in critical raw materials create spillover effects for advanced economies and raise the cost of their low-carbon transition.

- **Disasters and Policy Stagnation (DAPS)** (physical risk): A sequence of region-specific extreme weather events in 2026 and 2027 leads to capital destruction, reduced productivity, and lower output, triggering cascading economic impacts. Trade and financial linkages amplify these negative shocks across the globe, heightening financial and economic instability.

More precisely, for each continent (Africa, Asia, North America, South America, Europe, and Oceania), the climate physical storylines correspond to the following combinations of hazards: An event with a return period of 20 years in the Diverging Realities (DIRE) scenario and an event with a return period of 50 years in the Disasters and Policy Stagnation (DAPS) scenario. The choice of return period determines the severity of hazards and is scenario-specific.

- **Heatwave-drought-wildfire (HDW) storyline:** The continent-scale mega-event consists of the joint occurrence, in each country, of an x-year return period drought (measured by area affected), an x-year return period wildfire season (measured by burnt area), and an x-year return period heatwave (measured by population affected).

- **Storm-flood (SF) storyline:** The continent-scale mega-event consists of the joint occurrence, in each country, of an x-year return period storm, an x-year return period river flood, and an x-year return period coastal flood (all measured in terms of economic capital affected).

In the **DIRE** scenario, the combination of heatwaves, droughts, and wildfires is assumed to occur in Asia in 2025, South America in 2026, and Africa in 2027. Floods and storms occur in Asia in 2028, South America in 2029, and Africa in 2030. These events are less severe than in DAPS, corresponding to a return period of once every 20 years.

In the **DAPS** scenario, two types of compound events are modeled, one region at a time: (i) droughts, heatwaves, and wildfires ("dry events") in 2026; and (ii) floods and storms ("wet events") in 2027. These are plausible but extremely severe events, corresponding to a return period of once every 50 years.

In the NGFS short-term climate scenarios, the GEM-E3, EIRIN, and CLIMACRED models are integrated to assess the macroeconomic and financial impacts of climate risks. GEM-E3 provides detailed economic and technological projections, EIRIN models financial and monetary policy responses, and CLIMACRED assesses climate-related credit risk. Together, these models are used to analyze both transition risks (the impact of climate policies) and physical risks (the impact of climate events) on economies and financial systems. The structure of this modeling framework is described in Appendix B.2.

We next describe how these physical risk scenarios are linked to financial losses and probabilities of default

3.2 Financial Cost and Probability of Default

The NGFS short-term climate scenarios link climate disasters (e.g., floods, storms, droughts, heatwaves) to financial risks through a two-step procedure: (i) quantifying economic losses, and (ii) mapping these losses into probabilities of default (PDs) and expected credit losses.

3.2.1 Step 1: From Climate Hazard to Economic Loss

Climate projections take the form of storyline-driven compound shocks, downscaled to the regional level. Sectoral exposure data (capital stock, infrastructure, production, labor productivity) is combined with hazard intensity, and damage functions translate hazard intensity into direct impacts (via the GEM-E3 model):

- **Damaged capital:** the share of fixed capital destroyed per sector and country. Storms, floods, and wildfires entail capital destruction.
- **Output loss:** the share of annual production lost per sector and country. Output loss arises from storms, floods, and wildfires through business interruptions fol-

lowing the destruction of capital, and from droughts through reduced agricultural yields and lower output in water-dependent sectors.

- **Labor productivity loss:** the annual reduction in the supply of productive labor units. Labor productivity declines are induced by heatwaves.

The EIRIN model then aggregates these direct impacts across hazards and sectors.

3.2.2 Step 2: From Economic Loss to Probability of Default

Credit risk arises from the adjustment of market expectations regarding the materialization of a given scenario, whether physical or transition risk, and its impact on firms' cash flows and profitability. Climate credit risk can therefore emerge in the short term through changes in the valuation of firms as market expectations adjust.

To model the direct financial impacts of physical risk on corporates, NGFS relies on **CLIMACRED-PHYS**, a structural credit risk model. CLIMACRED-PHYS simulates climate shocks to firms' capital stock and production operations in order to estimate their effects on corporate assets and liabilities. A Merton-type approach is then applied to value corporate securities (Mandel et al., 2025). This produces an *event loss distribution*, i.e., the conditional size of losses given the occurrence of a disaster.

A simplified representation of the production process is used, whereby output $X_{i,t}$ is produced from capital in facility i according to a linear production technology:

$$X_{i,t} = f_i(K_{i,t}) = \lambda_i K_{i,t} \tag{17}$$

where $\lambda_i > 0$ is a sector-specific capital productivity parameter. The firm operates N facilities, indexed by $i = 1, \ldots, N$. Each facility has a target growth rate for its capital stock, denoted $\rho_i \in [0, 1]$, which is assumed to be determined exogenously by market and technological factors. Existing capital depreciates at rate $\delta \in [0, 1]$. Thus, in the absence of climate impacts, the target trajectory of capital is given by:

$$K_{i,t+1} = (1 + \rho_i)^t K_{i,0} \tag{18}$$

and gross investment in productive facility i at time t equals the target growth of capital plus replacement needs:

$$I_{i,t+1} = K_{i,t+1} - (1-\delta)K_{i,t} = (\rho_i + \delta)K_{i,t}. \tag{19}$$

Climate impacts are incorporated by inferring, from the direct impact simulations, the volume of capital damaged $\sigma^s_{i,t}K_{i,t}$ and the volume of production lost $\tau^s_{i,t}\lambda_i K_{i,t}$, in scenario s and period t for facility i. Here, $\sigma^s_{i,t}$ denotes the share of capital destroyed by the climate event, and $\tau^s_{i,t}$ the share of production lost.

Capital destruction, $\sigma^s_{i,t}K_{i,t}$, requires additional investment:

$$I_{i,t+1} = (\rho_i + \delta + \sigma^s_{i,t})K_{i,t}, \tag{20}$$

while production loss, $\tau^s_{i,t}\lambda_i K_{i,t}$, is reflected in the definition of firm profits in period t:

$$\Pi^s_t = \sum_{i=1}^{N} \pi_{i,t}(1 - \tau^s_{i,t})\lambda_i K_{i,t}, \tag{21}$$

where $\pi_{i,t}$ is a random and time-dependent profit rate capturing the economic uncertainty associated with facility i.

The financial structure of the firm is determined as follows. The initial capital stock ($K_0 = I_0$) is financed through debt D_0 and equity E_0:

$$K_0 = D_0 + E_0 \tag{22}$$

where D_0 is a zero-coupon bond with maturity date T. The firm does not raise new equity and therefore finances its investment needs, namely growth and the replacement of depreciated or climate-damaged capital, through debt and retained earnings. A share $\mu \in [0, 1]$ of profit is distributed as dividends each period, while the remainder is used for self-financing. Accordingly, debt at date t evolves as the repayment of debt from the previous period plus new investment (including the replacement of destroyed capital) net of retained earnings:

$$D_t = (1 + rR)D_{t-1} + (I_t - (1-\mu)\Pi^s_{t-1}) \tag{23}$$

Applying this formula recursively gives the debt at maturity T:

$$D_T = (1+R)^T D_0 + \sum_{t=0}^{T-1} (1+R)^{T-t-1} (I_{t+1} - (1-\mu)\Pi_t^s) \tag{24}$$

We define the *excess cash flow* as retained earnings net of investment expenses: $(1-\mu)\Pi_t^s - I_{t+1}$. At the facility level, this can be expressed per unit of capital $K_{i,t}$ as:

$$\gamma_{i,t} = (1-\mu)\pi_{i,t}(1-\tau_{i,t}^s)\lambda_i - (\rho_i + \delta + \sigma_{i,t}^s) \tag{25}$$

Excess cash flows are thus driven by two main risk factors: (i) baseline profitability, through realized profit margins $\pi_{i,t}$, and (ii) climate impacts, through business interruptions $\tau_{i,t}^s$ and capital destruction $\sigma_{i,t}^s$. Losses used to build physical risk heatmaps are based on the logic of Equation (25).

We now consider the conditions under which a firm may default. The firm's capital stock is defined as $K_t = \sum_{i=1}^N K_{i,t}$. A default at horizon T, accounting for climate risk, occurs if $K_T \leq D_T$, which can be written as:

$$K_T \leq (1+R)^T D_0 + \sum_{t=0}^{T-1} (1+R)^{T-t-1} (I_{t+1} - (1-\mu)\Pi_t^s) \tag{26}$$

or equivalently,

$$(1+R)^T D_0 \geq K_T + \sum_{t=0}^{T-1} (1+R)^{T-t-1} \sum_{i=1}^{N} \gamma_{i,t} K_{i,t} \tag{27}$$

Finally, the probability of default in scenario s is given by:

$$PD^s = \Pr\left[(1+R)^T D_0 \geq K_T + \sum_{t=0}^{T-1} (1+r)^{T-1-t} (1+\rho_i)^t \sum_{i=1}^{N} \gamma_{i,t} K_{i,0} \right] \tag{28}$$

The default probability provides a scenario-contingent valuation of the financial assets issued by the firm. Both bonds and equity can be priced accordingly. The value of a zero-coupon bond with maturity T is given by the expected payment at maturity:

$$D^s = \frac{1}{(1+R_0)^t} \left((1-PD^s) + PD^s \; \kappa \; E\left[\frac{K_T}{D_T^s} | K_T < D_T^s \right] \right) \tag{29}$$

where R_0 denotes the risk-free rate and $\kappa \in [0,1]$ is a bankruptcy cost parameter. The last term, $E\left[K_T/D_T^s \,\middle|\, K_T < D_T^s\right]$, represents the expected asset-to-debt ratio conditional on default. The value of bonds is affected by climate shocks through two channels: (i) the probability of default, which rises with cumulative destruction of productive capital and reduced cash flow due to business interruptions; and (ii) the net worth at maturity, which falls for the same reasons.

Equity is valued as the expected discounted stream of dividends plus the residual net worth at maturity in the absence of default:

$$E^s = E\left[\sum_{t=0}^{T-1} \frac{\mu\, \Pi_t^s}{(1+R_0)^t} + (K_T - D_T^s)_+\right] \tag{30}$$

The value of equity is influenced by climate shocks through three channels: (i) lower dividends, due to business interruptions; (ii) a higher probability of default, due to cumulative capital destruction and reduced cash flows; and (iii) a lower net worth at maturity, again reflecting cumulative destruction of productive capital and business interruptions.

3.3 Data Available in NGFS Database

For the analysis of physical risks, NGFS provides a dedicated short-term database (https://data.ece.iiasa.ac.at/ngfs-phase-5-short-term). This dataset is fully aligned with the NGFS short-term scenarios described above and offers ready-to-use quantitative inputs for financial stress-testing exercises.

Scope of data. The database provides:

- Climate hazards, including floods, storms, droughts, heatwaves, and wildfires,
- Broad coverage across countries and sectors,
- Scenario narratives consistent with NGFS short-term frameworks (e.g., DIRE, DAPS),
- Direct economic impacts, such as capital destruction, output losses, and labor productivity losses,
- Probabilities of default (PDs) and weighted average cost of capital (WACC), derived using the CLIMACRED model.

Relevance for financial applications. Unlike the Climate Impact Explorer, which focuses on long-term physical impacts and provides scientific projections of hazards and damages up to 2100 (see https://climate-impact-explorer.climateanalytics.org/), the NGFS short-term database is specifically designed for financial risk analysis. It directly links climate hazard scenarios to region- and sector-level economic losses, and to scenario-contingent probabilities of default. This feature makes it particularly well suited to quantify near-term physical risk costs within a macro-financial framework.

Time horizon. A key limitation is the short horizon: the scenarios and associated shocks are defined only up to 2030. While this restricts the ability to analyze chronic, long-term climate impacts, it ensures consistency with financial stability stress-testing exercises, where short-term losses and default probabilities are of primary concern.

3.4 Some Illustrations

3.4.1 Practical Implementation

The NGFS database for physical risks has several dimensions. To obtain a heatmap, some aggregations must be made to reduce the number of dimensions We proceed as follows:

- **Scenario dimensions:** Several different scenarios are disclosed in the database, but only one class of scenarios is of interest for the impact of climate hazard on firms. The main class of scenarios is called "direct_impacts", which corresponds specific climate events. For each narrative (DAPS and DIRE), the NGFS provides impacts on the different economic impacts (capital destruction, production and productivity losses, labor productivity loss). For DAPS, the most severe scenario, there is in fact a set of climate events, depending on the continent where the event takes place: "DAPS_NAM", 'DAPS_EUR", 'DAPS_ASIA", 'DAPS_LAM", 'DAPS_AFR", and 'DAPS_OCE" for an extreme climate event in North America, Europe, Asia, Latin America, Africa, and Oceania, respectively. By assumption, firms in a given country will be affected only by an event in its continent. For instance, for the United States, we only consider the "DAPS_NAM" scenario. For scenario DIRE, only one scenario is considered for all regions and this is a mild one.

- **Dimension of losses:** Four types of losses are considered in the database (capital destruction, production loss, productivity loss, labor productivity loss). In the model, there are assumed cumulative, as revealed by Equation (25). So, we sum the four losses for a given scenario-region-sector. We note that labor productivity loss only applies to heatwaves, with a substantial impact in some regions-sectors.

- **Dimension of hazards:** The scenarios are based on two composite storylines, one related to dry event (HDW, heatwaves, drought and wildfires) and the other related to wet events (SF, storms and floods). We consider both scenarios separately and add up the maximum of each impact (heatwaves, drought, and wildfires for HDW, and storms and floods for SF). In the end, we have two aggregate scenarios (HDW and SF). The aggregation is performed at the region $\times$ sector level over 2023-2030, and we take the peak impact across years to reflect the most adverse short-term outcome.

- **Dimension of countries:** The NGFS database for physical risks provides impacts for a very detailed set of countries. We reconstruct the regions used in the transition analysis. Countries are mapped to the canonical NGFS regions (USA, EU-15, EU-27, Europe non-EU, Japan, China, India, South Korea, Canada, Australia-NZ, Taiwan, Mexico, Russia, Brazil, South Africa, Argentina, Indonesia, and Other). For EU-15 and EU-27, which do not exist explicitly in the physical risk database, we compute averages across the corresponding set of member countries. Special aggregate categories appearing in the database (e.g., Oceania, Rest of Europe, Rest of World, Rest of Energy Producing Countries) are explicitly reassigned to the closest macro region, with any residual unmapped countries collected under "Other."[6] This ensures consistency of regional definitions between transition and physical heatmaps.

- **Dimension of sectors:** The physical risk database is much more granular than the transition risk database (56 sectors versus 11), due to the extremely detailed model used. For consistency with the transition risk heatmaps, we have aggregated these sectors to obtain 11 broad industries. These aggregate sectors are used in the main text. We have also identified the ten potentially most affected sectors: Power

[6] The "Other" group is dominated by two countries, Saudi Arabia and Turkey, which account for almost the entire signal.

Supply, Ferrous metals, Non-metallic minerals, Construction, Land transport, Water transport, Warehousing, Agriculture, Market Services, Non-Market Services. Heatmaps based on these sectors are reported in Appendix B.4.

Finally, to keep color segmentation informative, each heatmap is normalized by the 95th percentile of observed values, with larger exposures clipped at the maximum. Grid lines are drawn to emphasize the region $\times$ sector structure, and missing values are masked. The resulting matrices provide a harmonized view of physical risk exposure that is directly comparable, in structure if not in scale, to the transition risk heatmaps.

3.4.2 Region-sector heatmaps

Figures 15 and 16 display the normalized financial cost (in % of baseline, BAU, production) of an extreme compound climate event in the DIRE and DAPS scenarios, respectively. As explained above, regions and sectors are essentially the same as in the transition risk case. In these figures, we combine the two types of climate events (HDW and SF) by aggregating the two aggregate losses into a single financial cost.

As the figures reveal, even in the mild climate scenario (DIRE), two sectors are particularly affected by climate compound event: These are construction and agriculture in Asia (India and Indonesia) and Latin America (Brazil and Argentina), with cumulative impact close to 3% at its peak. Several other sectors are also impacted in the same continents, notably mining and warehousing. In the most extreme scenario (DAPS), construction and agriculture are affected in most regions, including Europe and East Asia. In several regions, these sectors may suffer from a production decline by more than 4% at the peak.

Figures 17 and 18 display the normalized financial cost of extreme Heatwave-Drought-Wildfire or Storm-Flood compound events in the DAPS scenario, respectively. Again, in the HDW storyline, agriculture and construction would be the most affected, with a production decline by more than 3.5%. The most affected regions would be South Asia and Latin America due to labor productivity losses. In the SF storyline, most industrial sectors in most countries would experience losses between 1% and 1.5%. Mining, electricity, transport, and warehousing would be the most affected sectors.

Figure 15: Cost of Extreme Climate Events in DIRE Scenario

Figure 16: Cost of Extreme Climate Events in DAPS Scenario

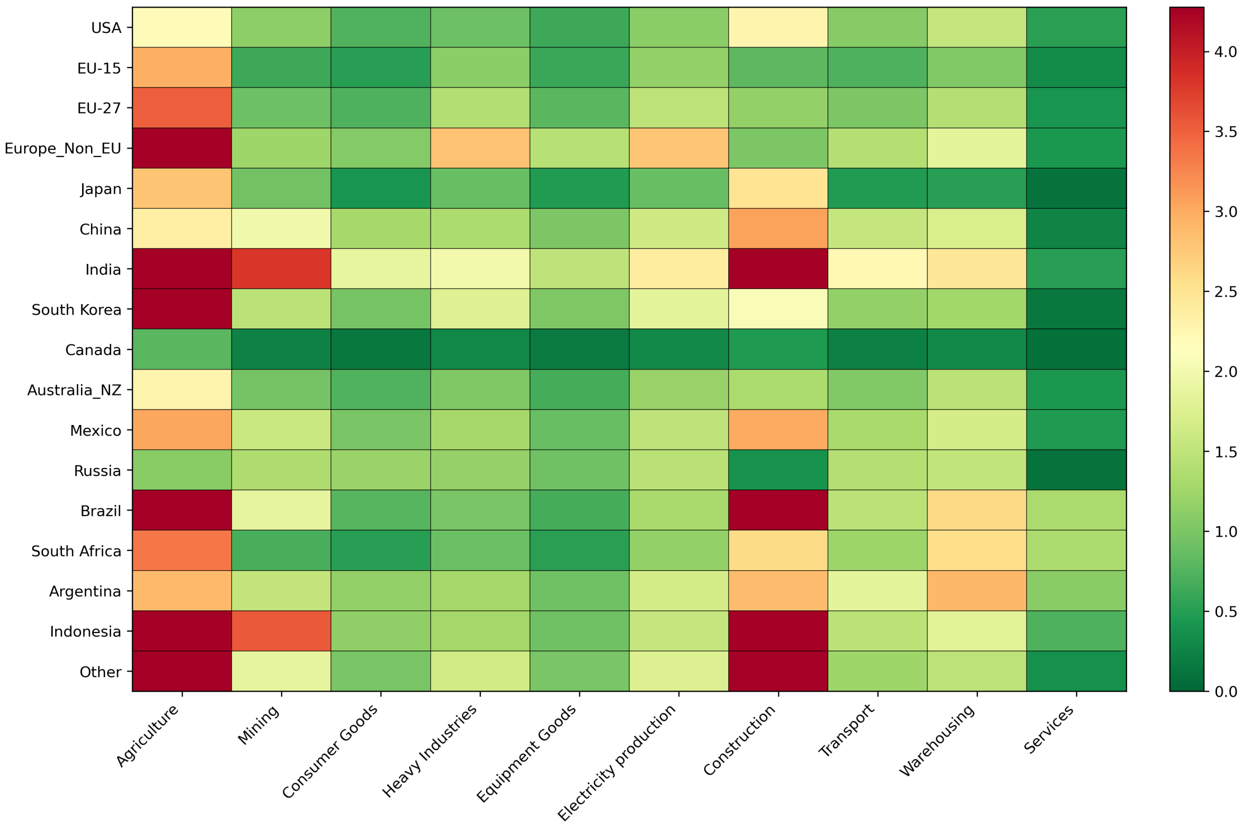


Figure 17: Cost of Extreme Heatwave-Drought-Wildfire Events in DAPS Scenario

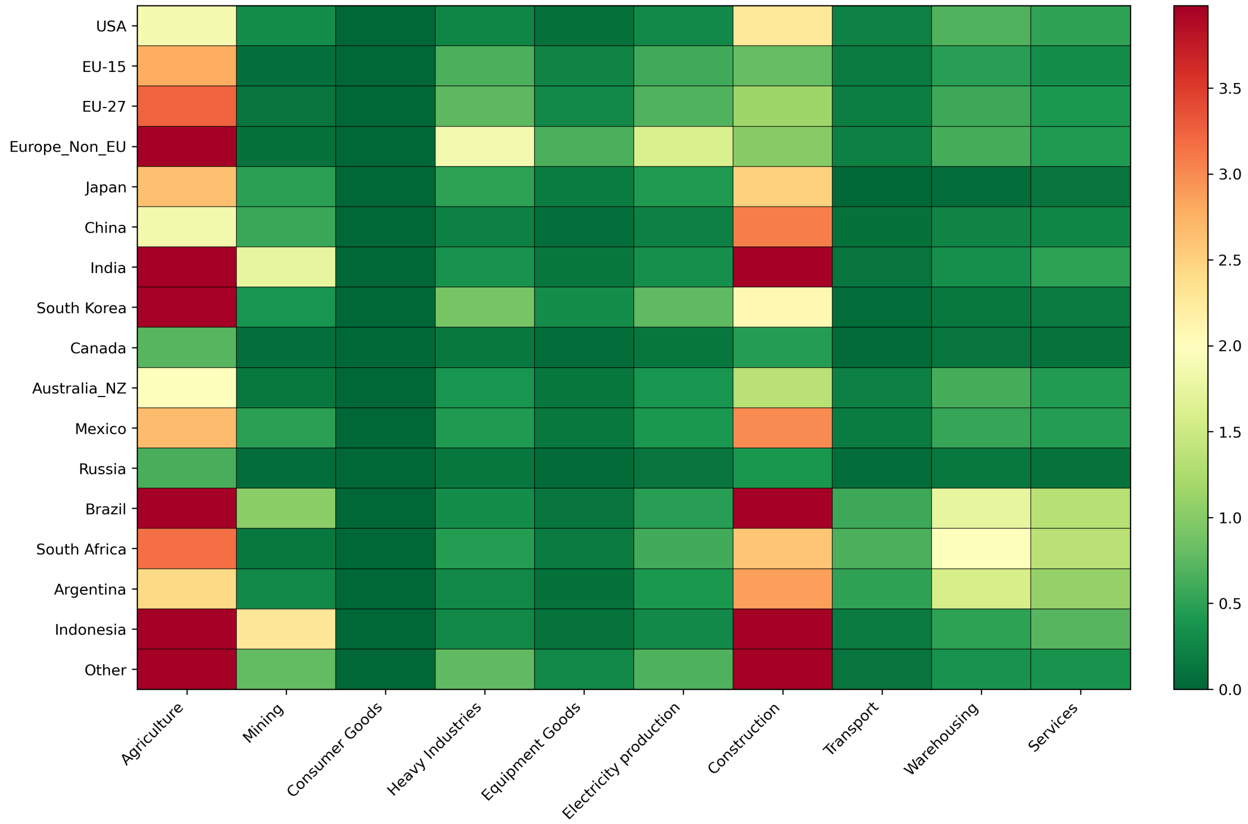
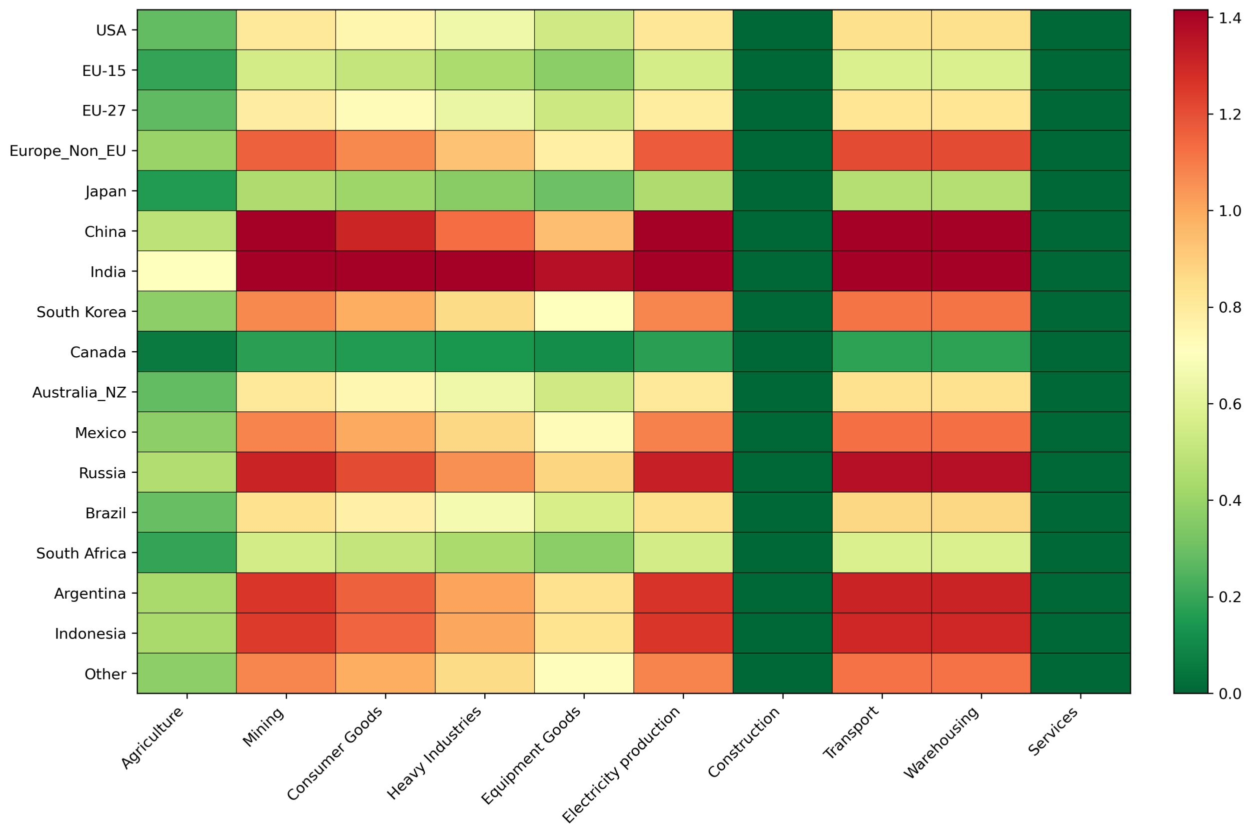


Figure 18: Cost of Extreme Storm-Flood Events in DAPS Scenario



4 Conclusion

This paper has developed a systematic framework to quantify both transition and physical climate risks at the region-sector level, drawing on the NGFS scenario datasets. For transition risks, we introduced indicators such as path misalignment, budget overshoot, abatement share, and normalized transition costs, which reveal how exposure varies across industries and regions. For physical risks, we relied on the NGFS short-term storyline framework, linking compound climate hazards to economic damages and credit risk metrics. Together, these approaches demonstrate how climate scenarios can be operationalized to provide region-sector heatmaps that highlight the heterogeneity of risks and the distinct channels through which they materialize.

Beyond identifying which regions or sectors are most exposed, the comparative analysis of transition and physical risks underscores their fundamentally different nature. Transition risks arise gradually, shaped by policy choices and carbon price trajectories, whereas physical risks are driven by sudden shocks with potentially systemic spillovers. This complementarity implies that focusing on only one dimension of risk provides a misleading picture: regions with manageable transition costs may still face severe physical damages, while others with high transition costs may be relatively less exposed to extreme climate events. The heatmap approach thus offers a way to visualize these contrasts and to support financial institutions and policymakers in designing strategies that address both decarbonization pathways and resilience to climate hazards.

Methodologically, the approach demonstrates the usefulness of NGFS scenarios as a standardized and transparent basis for climate-related financial risk analysis. The publicly available nature of the data ensures replicability and regular updates as new scenario vintages are released. Nevertheless, important limitations remain, including the short time horizon of the physical risk scenarios, the simplifying assumptions on carbon pricing in the BAU scenario, and the absence of firm-level heterogeneity beyond sectoral averages. These caveats call for caution in interpreting the absolute magnitude of losses, though the relative patterns across regions and sectors appear robust.

Future research could extend this framework in several directions: integrating firm-level financial exposures to connect heatmaps more directly with balance-sheet risks; refining damage functions to capture localized hazard impacts; and exploring dynamic interactions between transition and physical risks within a unified setting. Ultimately, the results underscore the need for forward-looking, granular, and scenario-consistent analysis to guide the financial system in managing the dual challenge of decarbonization and resilience to climate hazards.

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A NGFS Climate Scenarios for Transition Risk

The Network for Greening the Financial System (NGFS) has developed a set of climate change scenarios commonly used by financial institutions and central banks to analyze climate risks. These scenarios span Orderly, Disorderly, Hot-house world, and "Too little, too late" pathways, each reflecting different policy timelines and climate outcomes. The NGFS scenarios provide a framework of 8 distinct pathways (including Net Zero 2050, Below 2 °C, Low Demand, Delayed Transition, Divergent Net Zero (phased out in latest vintage), Nationally Determined Contributions (NDCs), and Current Policies) to explore how varying climate policy ambition (immediate vs delayed, coordinated vs fragmented) influences future transition and physical risks. Each scenario carries assumptions about the timing of climate policy, carbon pricing, technological change, and energy demand, leading to different projections for global warming (from 1.4 °C in the most ambitious pathways to over 3 °C in the worst case). These scenarios have been embraced as common reference points for climate risk analysis across the financial sector, helping avoid inconsistent in-house scenario assumptions and enabling comparability.

A.1 Overview of NGFS Climate Scenarios

The NGFS scenarios are grouped into several families that cover a spectrum of climate policy futures, from aggressive mitigation to inaction. In the latest NGFS scenario set (Phase IV, 2022-2023), there are seven long-term scenarios (Phase III had six, without the Low Demand and Fragmented World variants). These can be categorized by the level of transition risk (policy disruption to the economy) vs physical risk (damage from climate change), often aligned to four quadrants: Orderly, Disorderly, Hot-house world, and Too Little, Too Late. The scenario narratives and assumptions are as follows:

1. **Net Zero 2050 (Orderly)** – Limits warming to 1.5 °C by 2100 through stringent climate policies and innovation, achieving global net-zero CO_2 emissions around 2050. Policies are implemented immediately and ramp up smoothly; carbon prices reach high levels early, driving rapid decarbonization. This scenario assumes coordinated action (e.g., major economies reach net zero around mid-century) and significant technology deployment (including some carbon removal). Physical risks are minimized by meeting Paris goals, while transition risks are moderate (the

transition is costly but spread over decades).

2. **Below 2 °C (Orderly)** – A scenario with slightly lower ambition, giving a 67% chance of limiting warming to ¡2 °C. Climate policy is immediate but slightly less stringent than Net Zero; global CO_2 emissions fall to net-zero later in the century (after 2050). Carbon pricing and technology changes are moderate. Physical risk is low-moderate (warming 1.6-1.7 °C) and transition risk remains manageable. This can be seen as a "Paris Well-Below-2°C" pathway, where policy tightening is gradual.

3. **Low Demand (Orderly)** – An additional new scenario (Phase IV) that reaches 1.5 °C with less reliance on high carbon prices by emphasizing significant demand-side measures and behavioral change. Energy demand is actively reduced (through efficiency, lifestyle shifts, etc.), easing the pressure on the supply-side transition. Policies still start immediately; transition risk is arguably even lower than Net Zero 2050 because society curbs energy use, though it implies major changes in consumer behavior. Physical outcome is 1.5 °C warming, similar to Net Zero, with presumably lower carbon prices due to dampened demand.

4. **Delayed Transition (Disorderly)** – A scenario where climate policy action is delayed until 2030, after which extremely stringent measures are needed to still meet 1.6-1.8 °C by 2100. For about a decade, emissions continue to grow or plateau (no new action), then a sharp policy shock ensues in the 2030s (e.g., very high carbon prices post-2030). Because of the late start, transition risk is high 8(the sudden shift causes economic disruption, stranded assets, etc.) while physical risk is medium (warming kept below 2 °C but overshoots in mid-century). Negative emissions technologies (like BECCS) are limited in this scenario, so the transition relies on rapid absolute emissions cuts post-2030. This scenario highlights the costs of procrastination: higher near-term macro losses due to the scramble to decarbonize after delay.

5. **Divergent Net Zero (Disorderly)** – (Included in earlier NGFS iterations, now phased out in latest vintage.) This pathway also hits net-zero CO_2 around 2050 (1.4 °C warming) but with uncoordinated policies across sectors and regions, leading to inefficiencies. For example, certain sectors might decarbonize very fast (e.g., power)

while others lag, requiring steeper action later. This divergence drives up transition costs (e.g., premature scrapping of infrastructure in some sectors). NGFS dropped this scenario in Phase IV, noting that an uncoordinated yet successful net-zero transition appeared less plausible given cumulative delays. The concept now partly lives on in the Fragmented World scenario (described below).

6. **Nationally Determined Contributions (NDCs, Hot-house)** – This scenario assumes all countries implement their current climate pledges (NDCs under the Paris Agreement) fully, but no further strengthening of policies thereafter. Many NDCs target 2030, so emissions trajectory improves short-term but still follows a higher warming path (2.5-2.6 °C by 2100). Essentially, it is a world where policy ambition stalls at today's pledges (which are insufficient for 2 °C). Physical risks are high (significant warming), and transition risk is relatively low in the near term (policies are modest), but could increase later as damages mount or if policies suddenly tighten after 2030. This scenario often aligns with IEA's "Announced Pledges Scenario." Notably, NGFS updated the NDC scenario in 2022 to reflect new pledges (e.g., net-zero by 2050 pledges by many countries), slightly lowering the long-term warming relative to prior versions.

7. **Current Policies (Hot-house)** – A baseline where only existing climate policies are retained, with no new initiatives at all. It portrays a world on track for 3 °C or more warming by 2100, with severe physical risks (e.g., extreme weather, irreversible impacts like multi-meter sea-level rise in the long run). Transition risk in this scenario is minimal (there is little policy disruption, which is why it's called "Hot-house world" with too little transition), but the chronic physical costs to the economy grow ever larger over time. Many central bank stress tests use Current Policies as a "no-transition" adverse scenario for physical risk analysis. It essentially assumes the status quo of climate action (as of today) persists, which leads to steadily increasing emissions until mid-century and catastrophic climate outcomes beyond.

8. **Fragmented World (Too Little, Too Late)** – A new scenario (Phase IV) designed to explore a failure to coordinate globally: climate policy is both delayed and divergent across countries, so while some regions eventually enact strong policies,

others do very little. This results in the world missing the net-zero goal (warming likely exceeds 3 °C) and experiencing a disorderly transition in parts of the economy. In effect, it combines the worst of both worlds: high physical risk and high transition risk. Policies come "too late" (delayed action) and "too little" (insufficient overall effort), yet whatever transition does occur is abrupt and uneven. For example, one bloc might suddenly impose carbon tariffs or bans on coal in 2040, while others continue expanding fossil fuels, causing economic shocks. NGFS positioned this in the "Too Little, Too Late" quadrant to stress test simultaneously large transition and physical impacts. It's an adverse scenario that many consider increasingly plausible if multilateral efforts falter.

A.2 Structure of the Models

Sectoral and regional coverage in NGFS outputs is improving but still coarse. The IAMs underlying NGFS partition the world into on the order of 10-30 regions (e.g., GCAM uses 32 regions, REMIND 12, MESSAGE 11) and can project variables like emissions, energy mix, and GDP at those regional levels. Key economies (USA, EU, China, India, Brazil, etc.) are either individually represented or can be derived from downscaled data, for instance, NGFS Phase IV introduced country-level downscaling for many indicators. Sectorally, the models distinguish major sectors of emissions and energy demand (power, industry, transport, buildings, agriculture/land use). Recent NGFS data releases have added sectoral CO_2 emission breakdowns for transportation, industry, and buildings , and include various energy system details (e.g., electricity generation by source, final energy demand by sector). Still, these remain broad sectors; granular distinctions (e.g., steel vs cement within industry, or specific technologies) are often aggregated. Different IAMs offer different levels of detail, for example, GCAM has a rich representation of energy and land systems with price-elastic demand, while REMIND links a macro-economic growth model with a land-use module, and MESSAGE focuses on least-cost energy supply with detailed technology choices. Users should be aware that scenario outputs (e.g., emissions or GDP by region/sector) can vary across models due to these structural differences, even under the same scenario assumptions.

Behind the NGFS scenarios are three flagship IAM frameworks (GCAM, REMIND-MAgPIE, and MESSAGEix-GLOBIOM) each with distinct structures. GCAM (from the

University of Maryland) is a partial equilibrium model of the energy-economy-land system that simulates market equilibrium in each period (myopically) with price-responsive demand. REMIND (PIK) is a intertemporal general-equilibrium model that optimizes an economic objective (maximizing welfare) over the long term, coupled with MAgPIE for land-use; it assumes perfect foresight in the core economic module. MESSAGEix-GLOBIOM (IIASA) is an integrated model that combines an energy system optimization (cost-minimization) with a global land-use model; it has often been used in a general-equilibrium mode with an implicit macro feedback, and typically assumes perfect foresight for the energy system planning.

A.3 Sectoral and Regional Granularity

Sectoral decomposition. The NGFS scenario data include a broad breakdown by economic sectors, especially for energy-related variables. At a high level, results are often provided for sectors such as Power/ Electricity generation, Transportation, Industry, Buildings (Residential and Commercial), and Agriculture/Forestry/Land Use (AFOLU). For example, the NGFS Scenario Explorer (hosted by IIASA) contains variables like CO_2 emissions from energy vs. land-use, and even recently added sector-specific CO_2 emissions for Transportation, Industry, and Residential/Commercial buildings in its 2024 edition. This means users can see, for instance, how much CO_2 each scenario projects for the transport sector in 2030, 2040, 2050, etc. In addition, the energy demand and supply side are detailed: we have primary energy mix by fuel (coal, oil, gas, nuclear, renewables), electricity generation by source, and final energy consumption by sector. The NGFS web portal highlights indicators like “Electrifying buildings, industry, transport” or “Decarbonising electricity” which implies data for those sectors are available. Indeed, one can compare how, say, electric vehicle adoption (reflected in transport sector electrification) differs between scenarios, or how steel/cement production emissions (often part of industry sector) are mitigated.

However, the granularity is limited to major sectors. For instance, “Industry” as a whole is given, but within industry, the models might internally distinguish steel, cement, chemicals, etc., yet the public outputs aggregate them. Similarly, “Transport” may combine road, aviation, shipping, etc., though some IAMs provide further breakdown (e.g., passenger vs freight). The level of sectoral detail can also vary by model:

MESSAGE-GLOBIOM and REMIND-MAgPIE have detailed energy technology representations (with transport modes, building technologies, etc.), whereas GCAM has a rich agriculture/land module in addition to energy. But when aligning for NGFS, they harmonize to common sector categories. One noticeable gap historically was that NGFS scenarios did not explicitly give financial sector variables (like bank lending, insurance losses), those must be derived. Additionally, certain cross-sectoral metrics like "stranded assets" or "investment by sector" are available in some documentation (NGFS reports often cite power sector stranded assets or energy investment needs), but not always in the raw data.

The list of sectors available in the heatmaps is the following:

1. Energy supply Encompasses the full energy supply system. Includes: electricity generation, other energy conversion (refineries, synthetic fuels, solid fuel transformation), fugitive emissions, pipelines, and CO_2 transport and storage. Corresponds to IPCC categories 1A1-1C.

2. Other energy supply: Sub-category of energy supply that excludes electricity. Includes: refineries, synthetic fuels, solid fuel transformation, fugitive emissions.

3. Electricity: Covers electricity and combined heat and power generation, plus distribution and storage. Includes: coal, gas, oil, nuclear, hydro, and renewables. Corresponds to IPCC 1A1a/b.

4. Steel: Energy use and emissions from the steel industry. Corresponds to IPCC 1A2 (manufacturing industries and construction – iron and steel).

5. Cement: Energy use and emissions from cement production. Corresponds to IPCC 1A2 (manufacturing industries and construction – non-metallic minerals).

6. Chemicals: Energy use and emissions from the chemical industry. Includes subsectors: ammonia, high-value chemicals. Corresponds to IPCC 1A2.

7. Other industry: Residual industrial activities not included in steel, cement, chemicals, or non-ferrous metals. Covers diverse smaller manufacturing and industrial processes.

8. Industry (aggregate): Aggregate of the industrial sector. Includes: steel, cement, chemicals, non-ferrous metals, other industry, and feedstocks.

9. Transportation: Energy use and emissions from transport. Includes: road, aviation, shipping, rail, passenger and freight. Excludes: pipeline emissions. Corresponds to IPCC 1A3.

10. AFOLU (Agriculture, Forestry and Other Land Use): Covers GHG emissions (CO_2, CH_4, N_2O, F-gases) from agriculture, forestry, and land-use change. Includes: cropland, pasture, forest, fertilizers, livestock. Corresponds to IPCC category 3.

11. Other: Covers fuel combustion emissions from residential, commercial, and institutional sectors. Corresponds to IPCC 1A4a/b (Other sectors).

Regional breakdown. The NGFS scenarios cover the globe but split it into regions. Each IAM has its own native regional resolution: GCAM uses 32 geographical regions (which include individual large countries like the the United States, China, and India, and aggregates of smaller countries). REMIND-MAgPIE commonly runs with 12 regions (e.g., the United States, the European Union, China, India, "Other Asia", etc.). MESSAGEix-GLOBIOM uses about 11 regions (similar groupings). In the NGFS Phase III/IV data, results from each model are available at their respective region breakdown. This typically covers the major economies either singly or within a block. For example, you can extract scenario data for the United States, the European Union, China, India, Japan, Brazil and so on. NGFS has worked with IIASA to provide a downscaled dataset to country-level for many variables (especially for Phase III 2022 and Phase IV updates). This means even if a model region was "Other Latin America", NGFS may offer an estimated split for, say, Mexico, Argentina, etc., using downscaling algorithms that preserve regional totals.

For practical purposes, data for 10-15 key countries/regions is obtainable and reasonably robust. Typically, analyses focus on big emitters or economies: e.g., the United States, the European Union, China, India, Japan, Russia, Brazil, Rest of Asia, Rest of World. One user noted GCAM's 32 regions are sufficient to include the important countries, as GCAM's native output has discrete entries for most G20 members and more. REMIND's 12-region scheme has groupings like "EU" (which covers a dozen countries) and "REST ASEAN", but again, the downscaling can give country estimates within those. It is worth mentioning that different models' regions do not always map one-to-one, so NGFS ensures comparability by often focusing on global indicators or a common set of macro regions. If one needs consistent data for a specific country (say France or Australia), one might rely on whichever model in NGFS has that country explicit (or use the downscaled data). For instance, REMIND and MESSAGE both have an "EU" region rather than France separate; GCAM might have France within "OECD Europe". The NGFS data portal (hosted by Climate Analytics/IAMS) allows selecting country outcomes, which suggests a harmonization was done.

B NGFS Climate Scenarios for Physical Risk

The short-term model adopted by the NGFS for physical is very recent (NGFS, 2025). In this appendix, we briefly describe the scenarios for physical risk, different from those for transition risk. We begin with the description of the short-term climate scenarios, then provide a short description of the models used by NGFS to establish its scenarios. Finally, we comment on the sectoral and regional granularity.

B.1 Overview of NGFS Climate Scenarios

The model considers four scenarios:

1. **Highway to Paris (HWTP) (transition risk only - net zero target)**: A technology-driven (and orderly) transition unfolds gradually. Carbon tax revenues are reinvested into green subsidies and investments. While short-term energy prices rise, economic growth from higher investments offsets these impacts. Consumers and investors increasingly favor green sectors, while high-polluting sectors face rising credit risks and capital costs.

2. **Sudden Wake-Up Call (SWUC) (transition risk only - net zero target)**: A world of widespread climate unawareness is challenged by a sudden change in policy preferences. Consumer and investor preferences shift abruptly toward green sectors. A sharp surge in carbon prices triggers a supply shock. The transition occurs too suddenly for markets to adapt, leading to a "Climate Minsky Moment", a wave of financial instability as asset values adjust abruptly.

3. **Diverging Realities (DIRE, disorderly and insufficient reduction in emissions) (transition and physical risks)**: Advanced economies (North America, Europe, Oceania and part of Asia) pursue a net-zero transition in line with Highway to Paris. The rest of the world is hit by a sequence of extreme weather events, with effects that propagate globally via trade and financial linkages. Supply chain disruptions in critical raw materials create spillover effects for advanced economies and increase the cost of their transition to a low-carbon economy.

4. **Disasters and Policy Stagnation (DAPS) (physical risk)**: A sequence of region-specific extreme weather events occurring in 2026 and 2027 result in capital destruction, reduced productivity and production, and creates cascading economic impacts. Trade and financial linkages spread the negative impacts across the world, amplifying financial and economic instability.

B.2 Structure of the Models

In short-term climate scenarios by the NGFS, the GEM-E3 model, EIRIN model, and CLIMACRED model are integrated to assess the macroeconomic and financial impacts of climate risks. GEM-E3 provides detailed economic and technological projections, EIRIN models financial and monetary policy responses, and CLIMACRED assesses climate-related credit risk. These models are used to analyze both transition risks (impact of climate policies) and physical risks (impact of climate events) on economies and financial systems.

Scenarios are based on a combination of models:

- GEM-E3 model is a multi-regional, multi-sectoral, recursive dynamic computable general equilibrium (CGE) model which provides details on the macro-economy and its interaction with the environment and the energy system. It is an empirical, large scale model, written entirely in structural form. GEM-E3 imposes that, in all scenarios, the economic system remains in general equilibrium. In addition, it incorporates micro-economic mechanisms and institutional features within a consistent macro-economic framework and avoids the representation of behavior in reduced form. See E3-Modelling Ike (2017).

- The EIRIN model is a Stock-Flow Consistent (SFC) behavioral model used to analyze the economic and financial impacts of climate change and climate policies. It focuses on how different agents (like households, firms, and the government) interact within an economy and how their interactions are affected by climate-related risks and policies. EIRIN model provides the monetary policy channel (level of short-term interest rate levels and transmission mechanisms). See Monasterolo and Raberto (2018).

- CLIMACRED model is a climate credit risk model that allows for climate scenario-contingent financial valuation of firms' bonds and equity. CLIMACRED carries out an analysis of scenarios-contingent adjustments in firms' probability of default (PD), the firms' costs of capital, and in the valuation of firms' financial instruments. See Battiston et al. (2023).

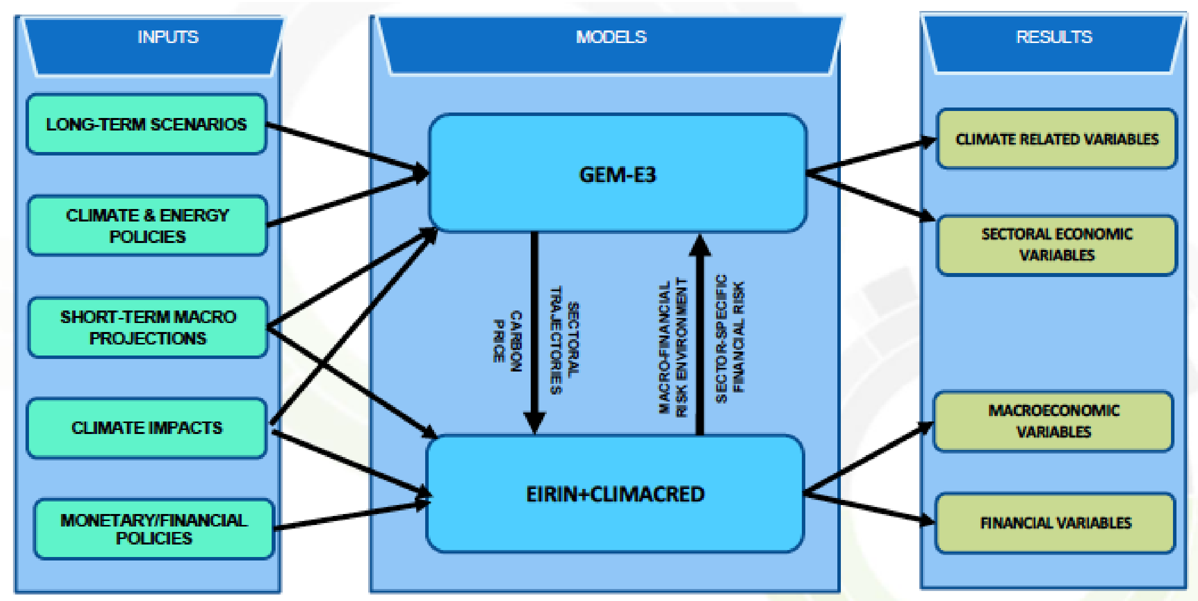
Interactions between the three models depend on the type of climate risk:

- Physical Risk Impacts: GEM-E3 is used to assess the direct economic impacts of physical risks (e.g., extreme weather events) on various sectors and regions. The results from GEM-E3 are then fed into CLIMACRED to analyze the financial consequences, such as changes in the probability of default and asset valuations.
- Transition Risk Impacts: GEM-E3 takes climate policies and objectives as inputs and projects the macroeconomic and sectoral impacts. These projections, in turn, influence the financial sector, which is analyzed by CLIMACRED. EIRIN also factors in the impact of climate policies on monetary policy.
- Feedback Loops: The models are not used in isolation. For example, the financial stability implications analyzed by CLIMACRED can influence investment decisions, which are then fed back into GEM-E3's economic projections.

The initiating run is performed by GEM-E3. The carbon price is determined by GEM-E3, as a function of climate policies, energy prices and technological characteristics/dynamics, which is then used as an input in EIRIN to represent the stringency of the energy system transition. EIRIN produces macro-financial dynamics contingent to the climate scenarios.[7] Variables include, among the others, the evolution of the in-

[7]The acute nature of the shocks is represented by considering that impacts on capital stock are short-lived (capital is reconstructed after a year) and impacts on productivity decay at a 50% rate. Additional persistence arises endogenously through general equilibrium effects.

Figure A1: General structure of the GEM-E3-CLIMACRED-EIRIN modeling framework.



Source: NGFS (2025).

flation and risk-free rate. CLIMACRED takes the risk-free rate from EIRIN and the sectoral trajectories from GEM-E3 to calculate adjustments in the sectoral probability of default, valuation of equity, corporate and sovereign bonds, and resulting changes in cost of capital. These updated costs of capital are then fed into GEM-E3. The second run of GEM-E3 then produces updated macro-economic dynamics that account for macro-financial feedbacks and financial risk assessment.

B.3 Sectoral and Regional Granularity

The world version of the GEM-E3 model simultaneously represents 50 sectors and 46 countries/regions linked through endogenous bilateral trade flows.

Sectoral decomposition. The sectoral structure of GEM-E3 is very detailed: the world version includes more than 31 sectors, ranging from agriculture and raw materials to specific manufacturing branches (steel, cement, chemicals), energy carriers (coal, oil, gas, biomass), electricity technologies (coal-fired, nuclear, renewables, CCS), transport modes, and even advanced equipment goods (e.g., PV panels, wind turbines, electric vehicles).

Several reasons explain such a large number of sectors and such diversity among sectors. First, policy relevance: The model was designed to support the European Commission and national authorities in detailed policy analysis (energy, climate, taxation, competition). Many climate and energy policies target specific technologies or industries (e.g., coal, cement, aviation), so they must be modeled separately. Second, energy-environment-economy linkages: Emissions and abatement costs differ strongly by sector. Cement has process emissions, power supply is heterogeneous by technology, agriculture has methane/nitrous oxide. Aggregating them would hide key mitigation pathways. Third, investment and innovation dynamics: Sectors like wind, PV, CCS, EVs are singled out to represent clean technology deployment and endogenous learning effects.

Sectors have different sensitivities depending on the type of climate hazard, notably Heatwave-Drought-Wildfire compound events and Storm-Flood compound events. A few examples are:

- Droughts induce a reduction of output proportional to the number of drought months in the agricultural sector and in GEM-E3 sectors that are identified as highly exposed to water risk: agriculture, biofuels, biomass solid, hydroelectric power generation, nuclear power generation, basic pharmaceutical products, batteries, chemical products, computer, electronic and optical products, ferrous metals, non-ferrous metals and advanced electric appliances.
- Heatwaves induce a reduction in labor supply and productivity for sectors with outdoor and physically intensive activities: agriculture, biomass solid, coal, construction, crude oil, market services/ non-market services.
- Wildfires induce destruction of capital stocks and business interruptions in the market and non-market service sectors proportional to the area affected.
- Storms and floods induce capital destruction proportional to hazard intensity and, in turn, business interruption proportional to the extent of capital destruction. Sector-specific exposure depends on the localization and concentration of sectoral activities, and of the sectoral composition of the capital stock (tangible vs intangible).

These direct impacts directly affect the capital stock and the output in GEM-E3 and then propagate across sectors and regions through global supply chains as modeled by general-equilibrium linkages.

Regional breakdown. Physical risks are highly region-specific. NGFS links hazards to impacts using regional downscaling of GCM outputs, enabling stress tests for countries or blocks (e.g., the United States, the European Union, China, India). Coastal regions face disproportionate sea-level risks, while tropical and arid regions are more exposed to heatwaves and droughts.

Granularity limits. While sectoral and regional mapping is improving, physical risk outputs remain relatively coarse in resolution. They provide broad coverage of main hazards and regions but cannot yet capture localized or industry-specific risks (e.g., a single city's flood damage, or a specific crop).

B.4 Additional Heatmaps

Figures A4 and A5 display the normalized financial cost (in % of baseline, BAU, production) of an extreme Heatwave-Drought-Wildfire compound event in the DIRE and DAPS scenarios, respectively. As explained above, regions are essentially the same as in the transition risk case, but sectors are defined differently. As the figures reveal, even in the mild climate scenario (DIRE), two sectors are particularly affected by heatwave, drought and wildfire: these are construction and agriculture in Asia (India and Indonesia) and Latin America (Brazil), with cumulative impact close to 14% at its peak. Several other sectors are also impacted in the same continents, notably power supply and services. In the most extreme scenario (DAPS), construction and agriculture are affected in all regions, including Europe and East Asia. In several regions, these sectors may suffer from a production decline by more than 20% at the peak.

Figures A6 and A7 display the normalized financial cost of an extreme Storm-Flood compound event in the DIRE and DAPS scenarios, respectively. Again, in the DIRE scenario, some sectors in Asia (India and Indonesia) and several Latin American countries would be affected in a substantial way, with a production decline by more than 5%. The most affected sectors would be power supply, transport, and warehousing. In the DAPS scenario, the same sectors in additional countries, including the United States, the European Union, and China would experience losses between 3% and 5%.

Figure A2: Cost of Extreme Climate Events in DIRE Scenario

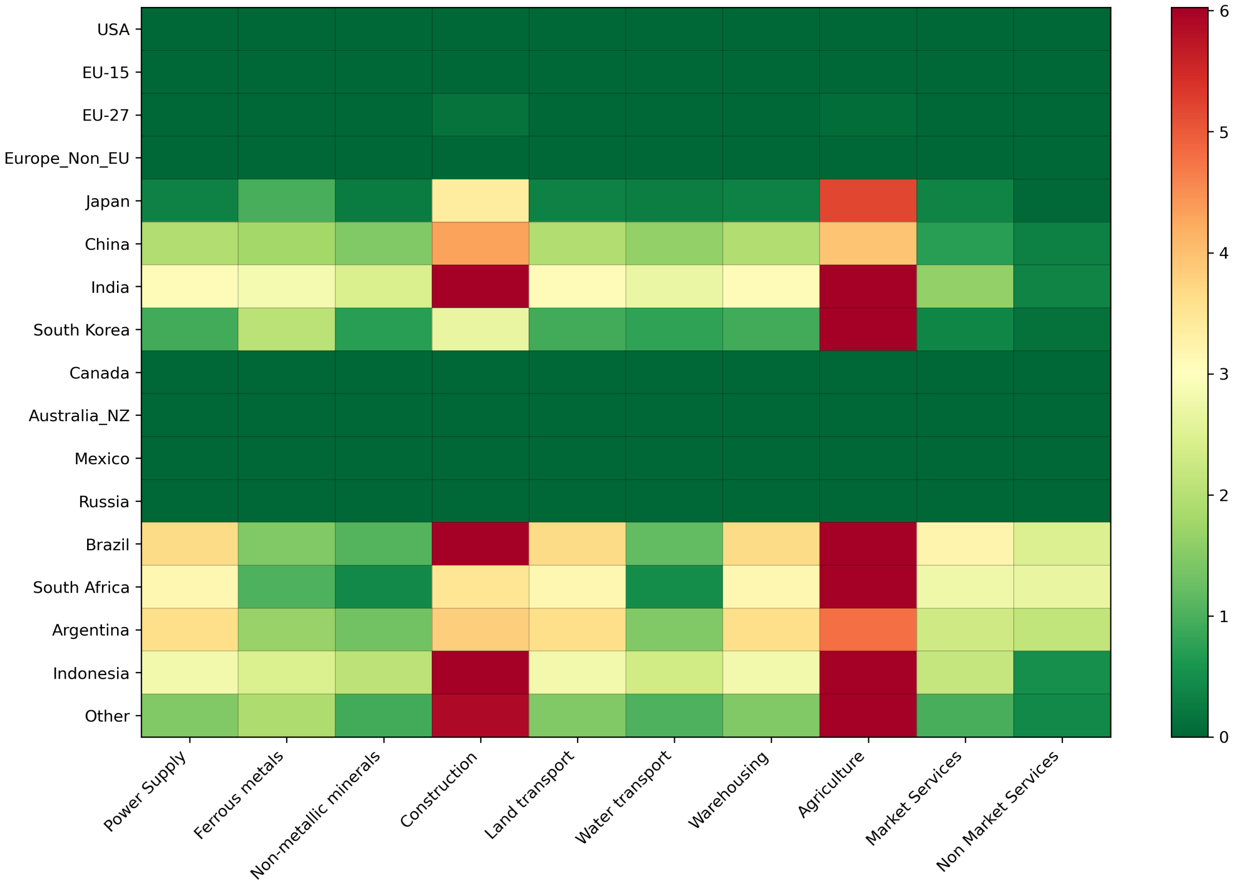


Figure A3: Cost of Extreme Climate Events in DAPS Scenario

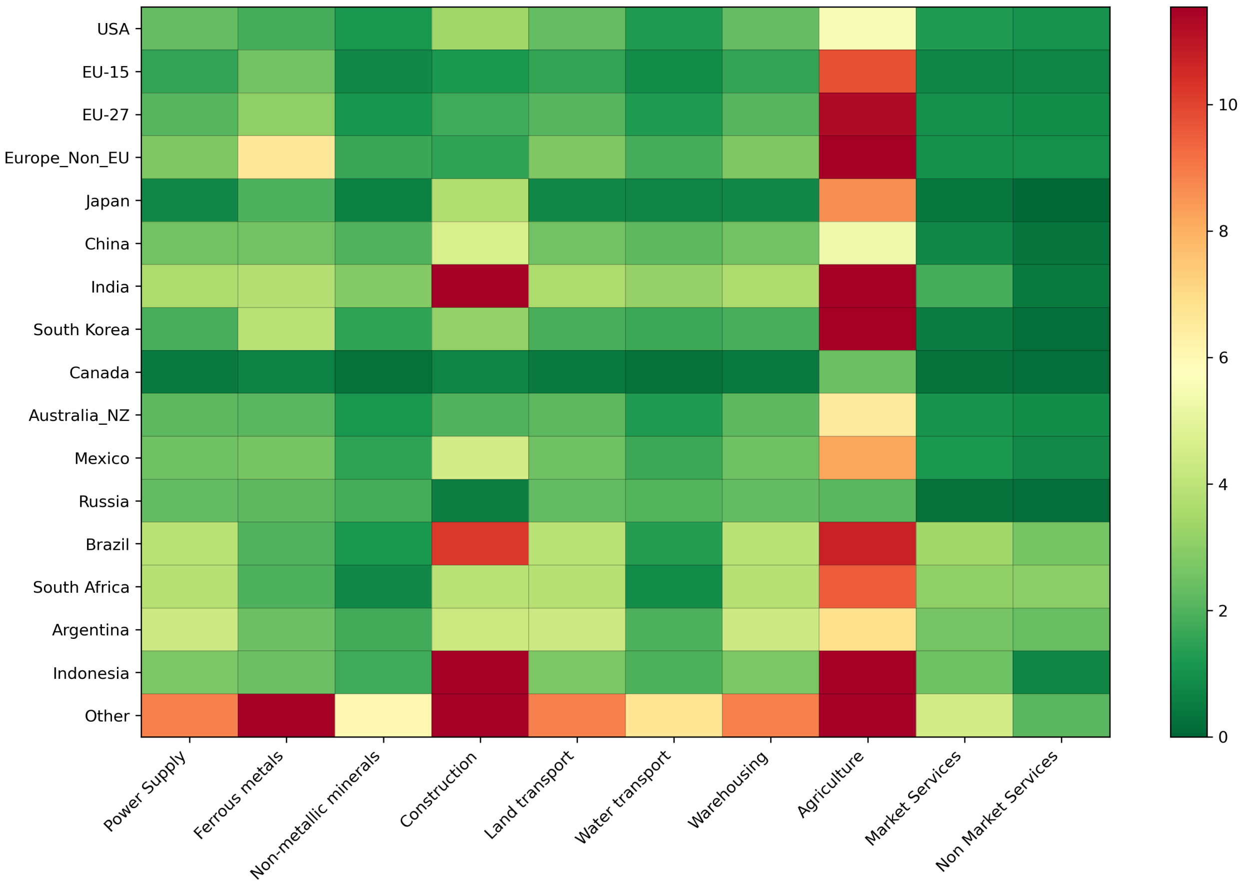


Figure A4: Cost of Extreme Heatwave-Drought-Wildfire Events in DIRE Scenario

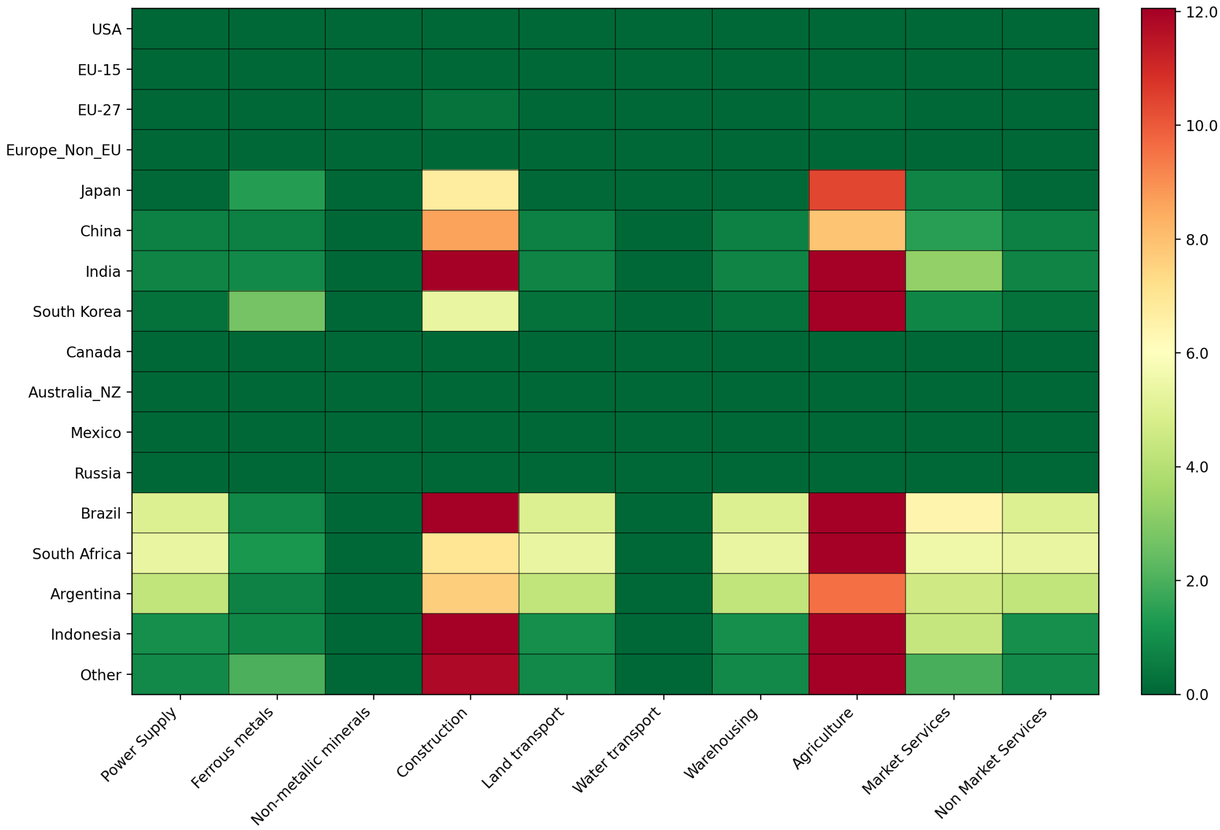


Figure A5: Cost of Extreme Heatwave-Drought-Wildfire Events in DAPS Scenario

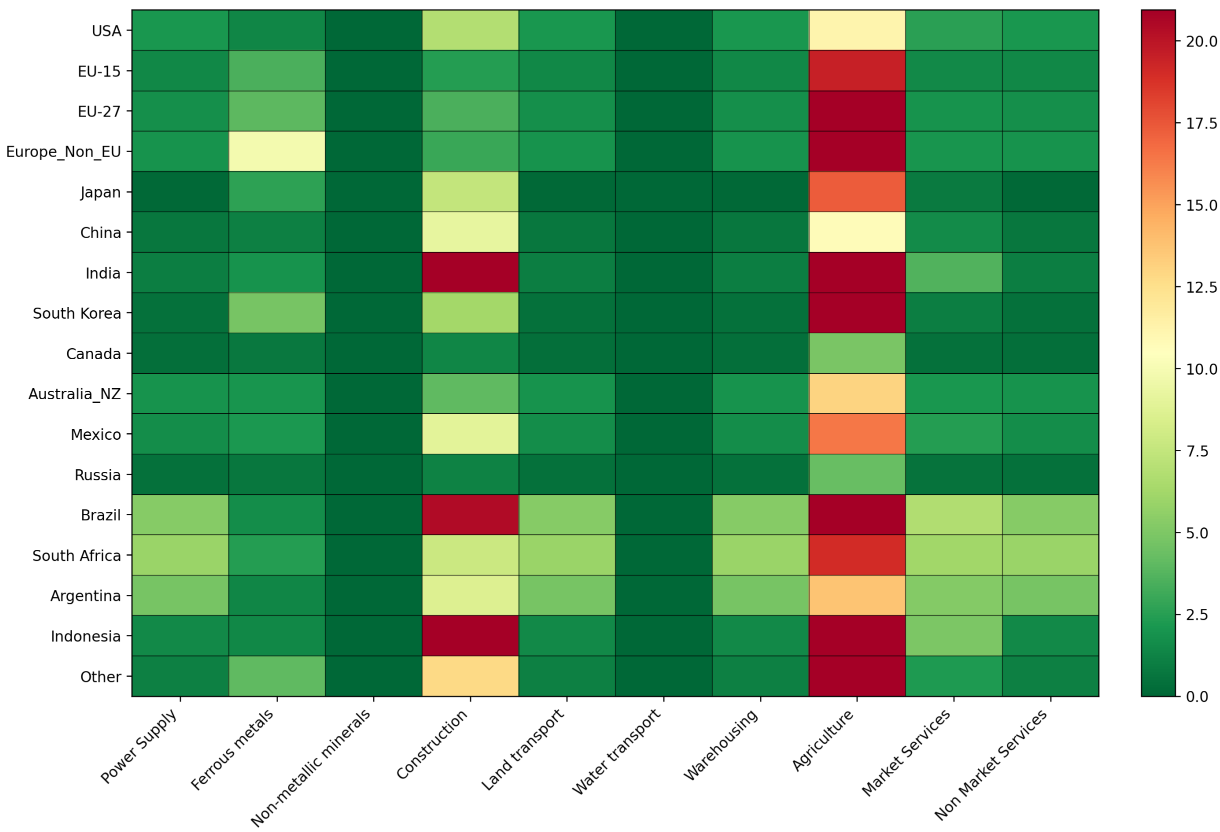


Figure A6: Cost of Extreme Storm-Flood Events in DIRE Scenario

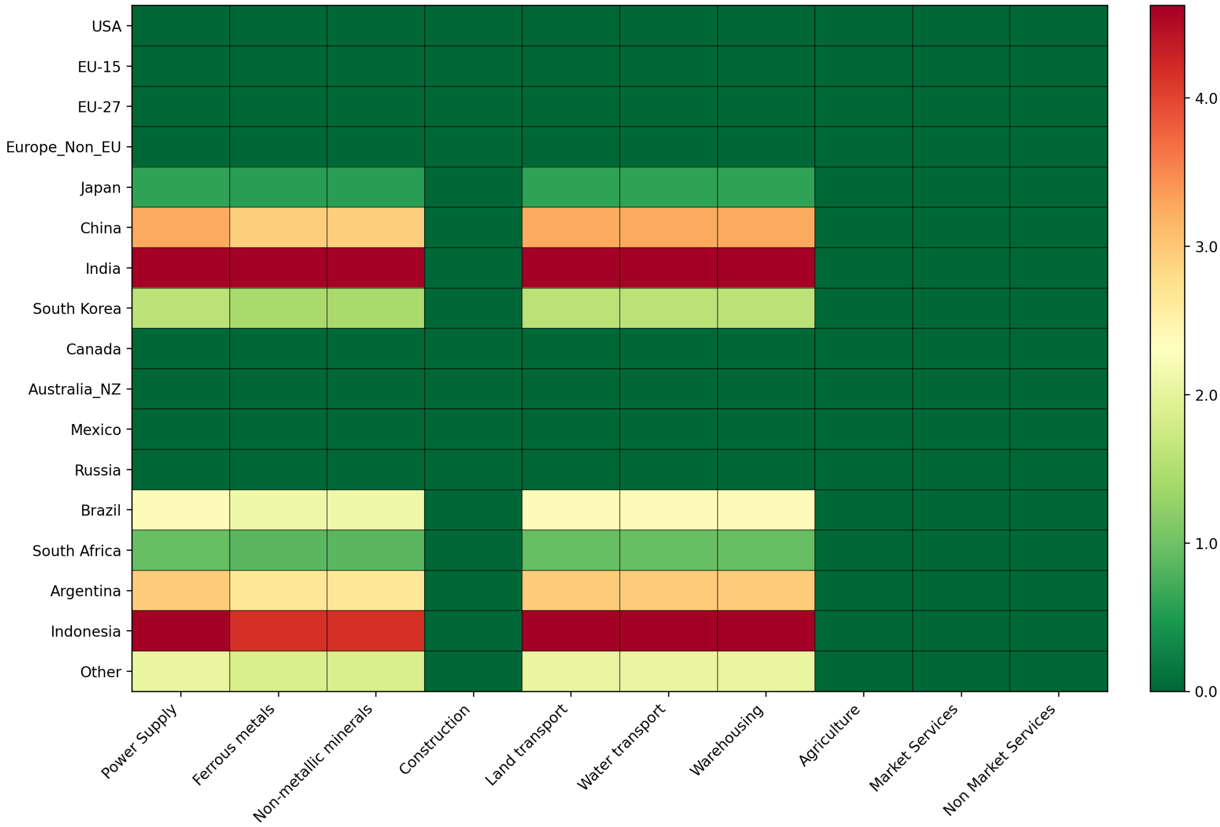


Figure A7: Cost of Extreme Storm-Flood Events in DAPS Scenario

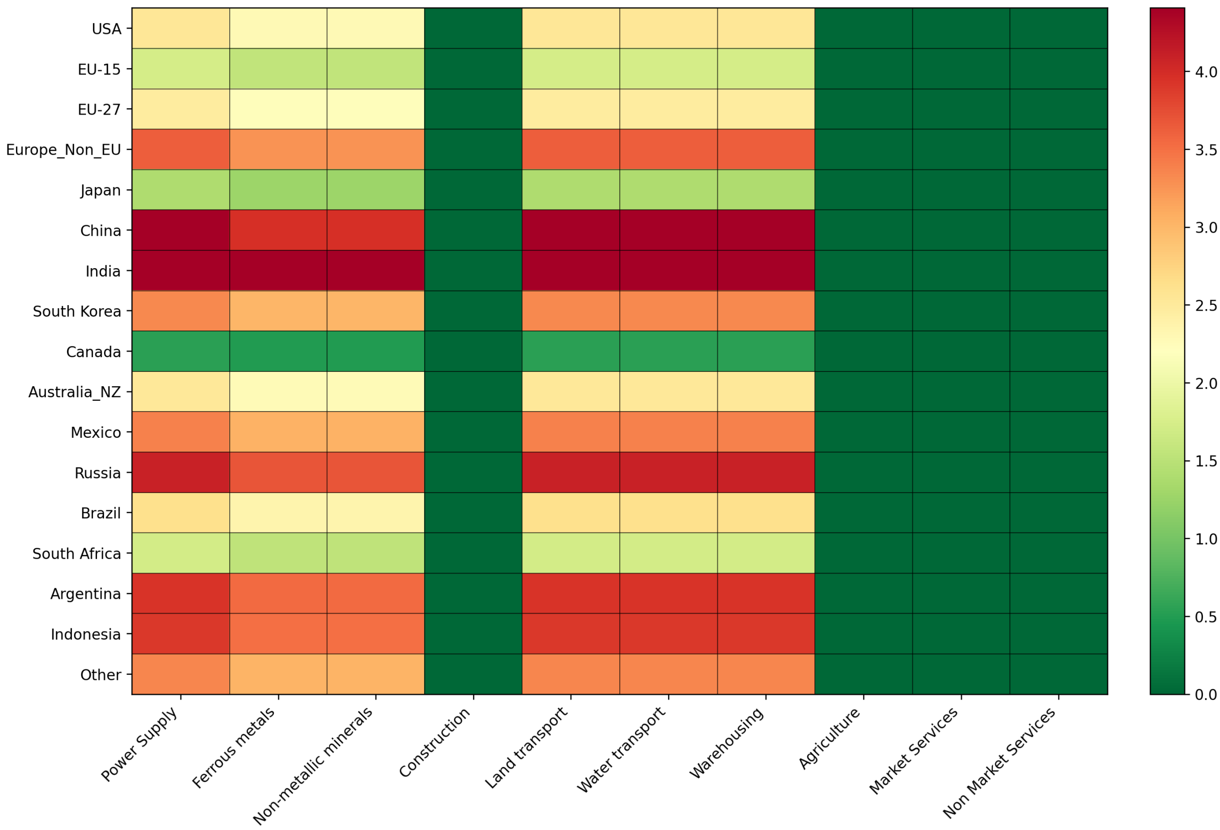


Table A1: Mapping of GEM-E3 sectors to NACE Rev. 2 sectors (Table E.2)

GEM-E3 Sector	**NACE Rev. 2 (2-digit) and description**
Agriculture	A01: Crop and animal production, hunting and related service activities; A03: Fishing and aquaculture
Biomass Solid	A02: Forestry and logging
Coal	B05: Mining of coal and lignite
Crude Oil	B06: Extraction of crude petroleum and natural gas; B07: Mining of metal ores; B08: Other mining and quarrying; B09: Mining support service activities
Consumer Goods Industries	C10: Manufacture of food products; C11: Manufacture of beverages; C12: Manufacture of tobacco products; C13: Manufacture of textiles; C14: Manufacture of wearing apparel; C15: Manufacture of leather and related products; C16: Manufacture of wood and of products of wood and cork, except furniture; manufacture of articles of straw and plaiting materials
Paper products, publishing	C17: Manufacture of paper and paper products; C18: Printing and reproduction of recorded media
Oil	C19: Manufacture of coke and refined petroleum products
Chemical Products; Biofuels	C20: Manufacture of chemicals and chemical products
Basic pharmaceutical products	C21: Manufacture of basic pharmaceutical products and pharmaceutical preparations

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GEM-E3 Sector	**NACE 2-digit**
Rubber and plastic products	C22: Manufacture of rubber and plastic products
Non-metallic minerals	C23: Manufacture of other non-metallic mineral products
Ferrous metals; Non-ferrous metals	C24: Manufacture of basic metals
Fabricated Metal products	C25: Manufacture of fabricated metal products, except machinery and equipment
Computer, electronic and optical products	C26: Manufacture of computer, electronic and optical products
Advanced Electric Appliances; Advanced Heating and Cooking Appliances; Batteries	C27: Manufacture of electrical equipment
Equipment for wind power technology; Equipment for PV panels; Equipment for CCS power technology; CO_2 Capture	C28: Manufacture of machinery and equipment n.e.c.
Transport equipment (excluding EV)	C29: Manufacture of motor vehicles, trailers and semi-trailers
EV Transport Equipment	C30: Manufacture of other transport equipment
Other Equipment Goods	C31: Manufacture of furniture; C32: Other manufacturing; C33: Repair and installation of machinery and equipment

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GEM-E3 Sector	NACE 2-digit
Gas; Power Supply; Hydrogen; Clean Gas; Coal fired; Oil fired; Gas fired; Nuclear; Biomass; Hydro electric; Wind; PV; Geothermal; CCS coal; CCS Gas; CCS Bio	D35: Electricity, gas, steam and air conditioning supply
Construction	F41: Construction of buildings; F42: Civil engineering; F43: Specialised construction activities
Land Transport	H49: Land transport and transport via pipelines
Water transport	H50: Water transport
Air transport	H51: Air transport
Warehousing and support activities	H52: Warehousing and support activities for transportation; H53: Postal and courier activities
Market Services	I55: Accommodation; I56: Food and beverage service activities; K64: Financial service activities, except insurance and pension funding; K66: Activities auxiliary to financial services and insurance activities; K65: Insurance, reinsurance and pension funding, except compulsory social security; R90: Creative, arts and entertainment activities; R91: Libraries, archives, museums and other cultural activities; R92: Gambling and betting activities; R93: Sports activities and amusement and recreation activities;

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GEM-E3 Sector	NACE 2-digit
	E36: Water collection, treatment and supply; E37: Sewerage;
	E38: Waste collection, treatment and disposal activities; materials recovery; E39: Remediation activities and other waste management services;
	J58: Publishing activities; J59: Motion picture, video and television programme production, sound recording and music publishing activities;
	J60: Programming and broadcasting activities; J61: Telecommunications;
	J62: Computer programming, consultancy and related activities; J63: Information service activities;
	L68: Real estate activities;
	M69: Legal and accounting activities; M70: Activities of head offices; management consultancy activities;
	M71: Architectural and engineering activities; technical testing and analysis; M73: Advertising and market research;
	M74: Other professional, scientific and technical activities; M75: Veterinary activities;
	N77: Rental and leasing activities; N78: Employment activities; N79: Travel agency, tour operator and other reservation service and related activities;
	N80: Security and investigation activities; N81: Services to buildings and landscape activities;
	N82: Office administrative, office support and other business support activities;
	S94: Activities of membership organisations; S95: Repair of computers and personal and household goods; S96: Other personal service activities;

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GEM-E3 Sector	**NACE 2-digit**
	T97: Activities of households as employers of domestic personnel; T98: Undifferentiated goods- and services-producing activities of private households for own use; U99: Activities of extraterritorial organisations and bodies; G45: Wholesale and retail trade and repair of motor vehicles and motorcycles; G46: Wholesale trade, except of motor vehicles and motorcycles; G47: Retail trade, except of motor vehicles and motorcycles
Non Market Services	P85: Education; O84: Public administration and defence; compulsory social security; Q86: Human health activities; Q87: Residential care activities; Q88: Social work activities without accommodation
R&D	M72: Scientific research and development

Table A2: Mapping of our 10 sectors to NACE Rev. 2 sectors

GEM-E3 Sector	**NACE Rev. 2 (2-digit) and description**
Agriculture; Biomass Solid **(1) Agriculture**	A01: Crop and animal production, hunting and related service activities; A02: Forestry and logging; A03: Fishing and aquaculture
Coal; Crude Oil **(2) Mining**	B05: Mining of coal and lignite; B06: Extraction of crude petroleum and natural gas; B07: Mining of metal ores; B08: Other mining and quarrying; B09: Mining support service activities
Consumer Goods Industries; Paper products, publishing **(3) Consumer Goods**	C10: Manufacture of food products; C11: Manufacture of beverages; C12: Manufacture of tobacco products; C13: Manufacture of textiles; C14: Manufacture of wearing apparel; C15: Manufacture of leather and related products; C16: Manufacture of wood and of products of wood and cork, except furniture; manufacture of articles of straw and plaiting materials; C17: Manufacture of paper and paper products; C18: Printing and reproduction of recorded media

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GEM-E3 Sector	NACE 2-digit
Oil; Chemical Products; Biofuels; Basic pharmaceutical products; Rubber and plastic products; Non-metallic minerals; Ferrous metals; Non-ferrous metals; Fabricated Metal products	C19: Manufacture of coke and refined petroleum products;
(4) Heavy Industries	C20: Manufacture of chemicals and chemical products; C21: Manufacture of basic pharmaceutical products and pharmaceutical preparations; C22: Manufacture of rubber and plastic products; C23: Manufacture of other non-metallic mineral products; C24: Manufacture of basic metals; C25: Manufacture of fabricated metal products, except machinery and equipment;
Computer, electronic and optical products; Advanced Electric Appliances; Advanced Heating and Cooking Appliances; Batteries; Equipment for wind power technology; Equipment for PV panels; Equipment for CCS power technology; CO_2 Capture; Transport equipment (excluding EV); EV Transport Equipment; Other Equipment Goods	C26: Manufacture of computer, electronic and optical products

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GEM-E3 Sector	NACE 2-digit
(5) Equipment Goods	C27: Manufacture of electrical equipment C28: Manufacture of machinery and equipment n.e.c. C29: Manufacture of motor vehicles, trailers and semi-trailers; C30: Manufacture of other transport equipment C31: Manufacture of furniture; C32: Other manufacturing; C33: Repair and installation of machinery and equipment
Gas; Power Supply; Hydrogen; Clean Gas; Coal fired; Oil fired; Gas fired; Nuclear; Biomass; Hydro electric; Wind; PV; Geothermal; CCS coal; CCS Gas; CCS Bio **(6) Electricity production**	D35: Electricity, gas, steam and air conditioning supply
(7) Construction	F41: Construction of buildings; F42: Civil engineering; F43: Specialised construction activities
Land Transport; Water transport; Air transport **(8) Transport**	H49: Land transport and transport via pipelines; H50: Water transport; H51: Air transport
Warehousing and support activities **(9) Warehousing**	H52: Warehousing and support activities for transportation; H53: Postal and courier activities
Market Services; Non Market Services	I55: Accommodation; I56: Food and beverage service activities;

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GEM-E3 Sector	NACE 2-digit
(10) Services	K64: Financial service activities, except insurance and pension funding; K66: Activities auxiliary to financial services and insurance activities; K65: Insurance, reinsurance and pension funding, except compulsory social security; R90: Creative, arts and entertainment activities; R91: Libraries, archives, museums and other cultural activities; R92: Gambling and betting activities; R93: Sports activities and amusement and recreation activities; E36: Water collection, treatment and supply; E37: Sewerage; E38: Waste collection, treatment and disposal activities; materials recovery; E39: Remediation activities and other waste management services; J58: Publishing activities; J59: Motion picture, video and television programme production, sound recording and music publishing activities; J60: Programming and broadcasting activities; J61: Telecommunications; J62: Computer programming, consultancy and related activities; J63: Information service activities; L68: Real estate activities; M69: Legal and accounting activities; M70: Activities of head offices; management consultancy activities; M71: Architectural and engineering activities; technical testing and analysis; M72: Scientific research and development; M73: Advertising and market research;

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GEM-E3 Sector	NACE 2-digit
	M74: Other professional, scientific and technical activities; M75: Veterinary activities; N77: Rental and leasing activities; N78: Employment activities; N79: Travel agency, tour operator and other reservation service and related activities; N80: Security and investigation activities; N81: Services to buildings and landscape activities; N82: Office administrative, office support and other business support activities; S94: Activities of membership organisations; S95: Repair of computers and personal and household goods; S96: Other personal service activities; T97: Activities of households as employers of domestic personnel; T98: Undifferentiated goods- and services-producing activities of private households for own use; U99: Activities of extraterritorial organisations and bodies; G45: Wholesale and retail trade and repair of motor vehicles and motorcycles; G46: Wholesale trade, except of motor vehicles and motorcycles; G47: Retail trade, except of motor vehicles and motorcycles P85: Education; O84: Public administration and defence; compulsory social security; Q86: Human health activities; Q87: Residential care activities; Q88: Social work activities without accommodation