Transition risks, asset stranding and financial instability

Louis Daumas

Abstract

This paper analyses how financial instability can emerge due to technological displacement and asset stranding along mitigation pathways limiting global warming to 1.5°C or 2°C. To do so, it develops a model for the study of transition risks with an embedded financial system with bank and non-bank financial agents and an explicit representation of asset stranding as the decommissioning of excess high-carbon capital. The framework is used to simulate decarbonisation pathways and carbon price paths embedded in scenarios provided by the Network for Greening the Financial System (NGFS). The model follows the literature in showing that more climate-ambitious and more technically constrained scenarios yield higher transition risks. It further shows that distinct types of financial institutions are not equally affected by different transition scenarios. For instance, banks are much less affected in delayed-action scenarios than non-bank institutions. The model also illustrates the importance of accounting for the reaction of the financial sector along decarbonisation scenarios. Finally, by studying decarbonisation pathways from various integrated assessment frameworks, I show the necessity to consider a wide array of scenarios generated by different models.

Keywords: Transition risks, stock-flow consistent modelling, asset stranding

JEL Code: E12, E44, Q54

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Introduction

Former Governor of the Bank of England Mark Carney coined the "transition risk concept" in an epoch-making speech at Lloyd's in 2015. On this occasion, he suggested that a rapid transition to a low-carbon economy would leave substantial amounts of impaired, "stranded," assets in its wake and thus imperil the viability of the global financial system.

Following this speech, a consortium of central banks and financial regulators, the Network for Greening the Financial System (NGFS), developed a conceptual and operational apparatus to study transition risks (Bertram et al., 2020). This framework takes the form of a portfolio of reference scenarios, simulated by a suite of well-established Integrated Assessment Models (IAMs). Three kinds of scenarios were retained. "Orderly" scenarios feature a smooth transition, in which technological availability and/or sufficiently progressive climate action preclude financial disturbances. "Disorderly" scenarios are more constrained technologically, are more climate ambitious or feature late climate action. These aspects may result in a brisk adjustment triggering financial instability. "Hot House World" scenarios include little or no climate action. These scenarios have been mobilised in "climate stress tests" to assess the extent of transition risk along these scenarios (Allen et al., 2020; Battiston et al., 2021; ECB, 2021a; Fazekas et al., 2021).

Yet, most models used in these studies do not include an embedded financial sector. They remain focused on non-financial companies (Allen et al., 2020; Fazekas et al., 2021) and offer little insight into the financial sector proper[1]. Also, they do not account for the financial instability consequences of stranded assets, although it is a key aspect of the low-carbon transition (Jacquetin, 2021).

Further, most macroeconomic modules used in these studies rely on neoclassical or Neo-Keynesian assumptions, which treat the low-carbon transition as a negative macroeconomic shock. Yet, more Keynesian underpinnings would emphasise multiplier effects and a positive macroeconomic effect from the transition effort,

[1] Exceptions include ESRB (2016) or ECB (2021a).

which may temper the extent of transition risks, including in “disorderly” transitions (Fazekas et al., 2021). In addition, focusing on negative macroeconomic shocks may occult instability potentials emerging from long-run structural change, which may be more relevant for a long-run phenomenon like the low-carbon transition.

To tackle these issues, this paper develops a model at the world level, embedding a financial sector, with a simple representation of transition dynamics that can be used to compare scenarios and their variants from different IAMs. I measure the impact of transition risks on both financial and non-financial companies and account for asset stranding, represented as the premature decommissioning of high-carbon assets. Conversely, because I include an embedded financial sector, I can represent how the financial sector will reorganise around a transition pathway. The model builds on the ecological Stock-Flow Consistent (SFC) models literature (see Dafermos et al., 2017a; Jackson, 2019; Monasterolo and Raberto, 2018). It prolongs existing proposals by focusing on financial transition risks along reference mitigation pathways and carbon price schedules. I further implement a method to account for asset stranding on non-financial companies’ balance sheets. I finally adopt a clear distinction between an emerging “challenger” low-carbon sector and an adapting “incumbent” high-carbon sector to focus on large-scale technical displacement.

I simulate a sample of scenarios proposed by the NGFS (Bertram et al., 2020). Unlike other exercises based on SFC models (Gourdel et al., 2022), I force my model to match the decarbonisation trajectory of each scenario. In parallel, I apply an exogenous carbon tax to mimic the implementation of climate policy. I first focus on results measuring the realisation of transition risks (defaults, asset price decreases) and then examine their actual impact on financial institutions’ viability.

The model shows first that distinguishing between transition risk realisations and financial agents’ vulnerability is crucial. For instance, higher default rates may not bear large consequences if portfolios are well-diversified. Second, financial agents are differentially affected depending on the transition scenario. Banks seem more affected by early-action, disruptive scenarios, while non-bank agents are more vulnerable to delayed action. Finally, I show that results can significantly differ across IAMs for the same scenario.

Section 1 describes the NGFS's framework and motivates the paper. Section 2 presents the model used to run the simulation. Section 3 describes my calibration strategy and Section 4 my translation of NGFS scenarios into the model's term. Section 5, before discussions and concluding remarks, will present the main results of the study.

1 The NGFS approach and scenarios

1.1 The NGFS climate risk narrative

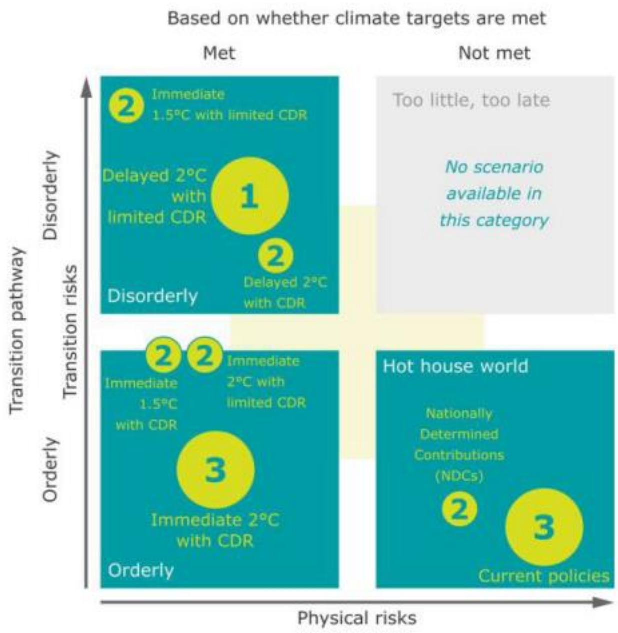
For the study of climate-related risks, the NGFS designed a reference conceptual framework based on the trade-off between transition and climate damage (physical risks) highlighted by Mark Carney (2015). Waiting for too long before transitioning would imply climate change, entailing systemic risks for the financial system (ECB, 2021a). On the other hand, the low-carbon transition will entail a massive reallocation of resources throughout the economy. If carried out disruptively, it could trigger downward asset revaluations in some sectors, with adverse financial instability consequences (van der Ploeg, 2020). By contrast, a smooth low-carbon transition would limit financial instability, with gradually phased-in climate policies, anchored expectations and progressive technical change.

1.2 The NGFS scenarios

This narrative led the NGFS to propose three types of scenarios (Bertram et al., 2020)[2], summarised in Fig. 1-1.

[2] These scenarios correspond to the NGFS's 2020 scenario vintage. A new series was published in 2021 (NGFS, 2021), exploring fragmented policy action and refining previous scenarios. Yet, because this series has not yet been used in prospective exercises, I chose to focus on results from the 2020 vintage in the body of the article. For results for the 2021 vintage, see Annex A2.

Figure 1-1



Taken from Bertram et al. (2020). Figures indicate the number of IAMs by which the scenario is generated

Physical risks depend on whether climate targets (1.5°C or 2°C) are achieved. Scenarios going 2°C were dubbed "Hot House World" and include two variants: a prolonging of current trends and a scenario in which countries follow their Paris pledges (NDCs).

Other scenarios suppose the achievement of a climate goal. The extent of transition risks depends on three elements. Starting the transition late, usually in 2030 instead of 2020, would require disruptive climate action in the short run. This disruptive course of events could have adverse financial stability outreaches. Another factor of transition risks is climate ambition. Targeting a 1.5°C requires changes in the economy than targeting 2°C. Finally, a greater availability of carbon dioxide removal (CDR)[3] technologies decreases transition risks.

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[3] These technologies include Carbon Capture and Storage (CCS), Direct Air Capture (DAC) or afforestation (Giannousakis et al., 2020). Because they allow for negative emissions in the long run, they reduce the need for sharp decarbonisation in the short run.

The NGFS has produced two broad categories of transition scenarios: “Orderly” transition scenarios entail an immediate climate action and fulfil at least one of these two conditions: (i) 2°C target or (ii) high CDR availability. By contrast, “Disorderly” scenarios feature delayed climate actions or climate-ambitious but technology-constrained scenarios.

These scenarios were simulated by well-established Integrated Assessment Models (IAMs): MESSAGEix-GLOBIOM (Krey et al., 2016), GCAM (JGCRI, 2019) and REMIND-MagPIE (Luderer et al., 2015). I summarise Model/scenario correspondences in Table 1-1.

Table 1-1 Summary of model-scenario correspondences

Model	Current Policies	NDCs	2°C – High CDR	2°C – Low CDR	1.5°C – High CDR	1.5°C – Low CDR	Delayed – High CDR	Delayed – Low CDR
GCAM	x		x					
MESSAGE	x	x	x	x	x	x	x	
REMIND	x	x	x	x	x	x	x	x

1.3 Applications of the 2020 vintage: innovations and limits

This scenario matrix has been used in “climate stress tests” (Allen et al., 2020; ECB, 2021a; Fazekas et al., 2021). These exercises measure the extent of physical and transition risks along scenarios. Early studies focussed on the real-economy side of transition risks (Fazekas et al., 2021). More recent works have intended to systematically link real-economy developments to financial variables, like default probabilities for companies and changes in asset prices (Daumas, 2021).

Yet, in these studies, the financial sector is rarely explicitly modelled, with two consequences. The probability of default and/or asset price losses are not related to loss metrics for financial institutions[4]. Hence, the impact of financial losses on the viability of financial institutions is not measured. Besides, the macroeconomic consequences of the financial sector's reorganisation around the transition are yet to be explored (Daumas, 2021). This could take the form of higher interest rates or less reliable sources of funding for high-carbon companies (Ivanov et al., 2020). It could harm further their financial viability.

Then, the financial consequences of asset stranding are under-assessed. Most theoretical models have remained focused on real stranding (Coulomb et al., 2019; van der Ploeg and Rezai, 2020). Applied studies linking financial and real-economy models do not explore the consequences of balance sheet losses on financial instability (Jacquetin, 2021)[5]. Hence the need to go beyond only a shock approach and provide a dynamic view of transition risks encompassing stranded assets.

Finally, stress tests are based on the idea of applying a "strong but plausible shock". However, the structure of traditional economic models may require that these shocks be "unreasonably large" to detect any meaningful effect (Borio, 2014). This reliance on large macroeconomic shocks poses identification issues within traditional modelling frameworks applied to the low-carbon transition (Allen et al., 2020). This is further problematic because potential disturbances are expected to arise more from the displacement of carbon-intensive productions than from large, symmetrical, macroeconomic shocks. Indeed, risks can emerge from structural changes, with some activities being displaced to the benefit of others, even though macroeconomic effects are not large. Decarbonisation pathways rarely exhibit high costs for the transition in terms of GDP Finally, that the that low-carbon transition should have negative

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[4] An exception is ECB (ECB, 2021a), which computes loss-given default. However, because they include physical damage even in transition scenarios, disentangling the pure transition-risk content of these losses is not possible. The authors nonetheless attribute most shocks to physical damage arising in delayed-action scenarios.

[5] An exception is Botte et al. (2021), who measure stranding as an asset's inability to generate enough income to cover its financing costs. Asset losses (scrapping, or permanent stranding) are a consequence of stranding proper and occur, within their agent-based model once firms go bankrupt. However, they do not explore the possibility for write-offs on balance sheets that may fragilize an agent's financial position.

macroeconomic consequences is not given, since investment expenses for the transition may trigger multiplier effects (Cambridge Econometrics, 2020; Fazekas et al., 2021).

1.4 A complementary approach

Given these limits, this article proposes a complementary approach to transition risks. It will develop a structural change Stock-Flow Consistent (SFC) model able to accommodate NGFS scenarios.

Stock-Flow Consistent models start from a balance-sheet representation of the economy and are structured around an inventory of financial flows (Godley, 2012; Nikiforos and Zezza, 2017). They embed the financial system within the economy (Godley and Lavoie, 2007), allow for financial frictions (Dafermos et al., 2017a) and adopt a realistic description of credit relationships (Lavoie, 2014). Hence, this approach has been increasingly considered a viable complementary for the study of transition risks (NGFS, 2020). For our purpose, it allows for the measure of the effect of financial sector preparedness and reorganisation on the transition risk content of decarbonisation pathways.

The model further builds on (post-)Keynesian macroeconomic foundations, which allow for strong multiplier effects. This allows the transition to have positive macroeconomic effects. I thus adopt an optimistic view of the transition, which allows me to focus on the structural change content of transition risks. The model also includes supply-side constraints in the form of inflationary pressures. I do not incorporate climate damage, similarly to Allen et al. (2021)[6], to analytically isolate transition risks.

The model builds on previous proposals put forward by the literature (Dafermos et al., 2017a; Jackson, 2019; Monasterolo and Raberto, 2018). Because I focus on large-

[6] The inclusion of physical damage (ECB, 2021a; Gourdel et al., 2021), albeit relevant, would make it difficult to disentangle the net effect of transition risks. In addition, large uncertainties surround damage functions (Burke et al., 2015), calling for caution in adopting them.

scale structural change, I adopt a sectoral disaggregation inspired by Caiani et al. (2012) and represent the low-carbon transition as a process through which an incumbent high-carbon sector must face the emergence of a low-carbon challenger.

Finally, the paper introduces a representation of asset stranding. It will take the form of asset decommissioning that will harm firms' financials[7]. Relatedly, I also explicitly model loan vintages to allow for a more rigorous representation of credit relationships.

[7] This approach differs from the seminal work of Jackson (2019), who considered asset stranding as structural underutilisation. I chose to model sheer asset decommissioning to explore more directly balance-sheet shows and brisk asset devaluation effects.

2 The model

This section depicts the general modelling strategy deployed in the model and provides an overview of key relationships and equations. An exhaustive description of the model is postponed to Annexes.

2.1 Modelling architecture

The model is at a world scale. It features a non-financial and a financial sector, a representative household, a government and a central bank. The economy is structurally operating below full-capacity (Palley, 2021). As usual in SFC frameworks, output is demand-determined, with the utilisation rate of capital moving with aggregate demand. Non-financial companies comprise two consumption good branches and an investment good sector. Financial companies include banks and non-bank financial institutions. Expectations are adaptive or trend-following depending on the variable.

It aims to depict a transition to a low-carbon economy in which an incumbent, high-carbon (H) capital stock is progressively replaced by a low-carbon (L), non-emitting alternative. These two firms produce the same consumption good with a Leontief technology. They service a monopolistic-competition market. Prices are a mark-up on top of labour costs. Markups move with utilisation to figure inflationary pressures (Godley and Lavoie, 2007; Rowthorn, 1977). Nominal wages are determined based on expected inflation and output growth, while productivity grows with output.

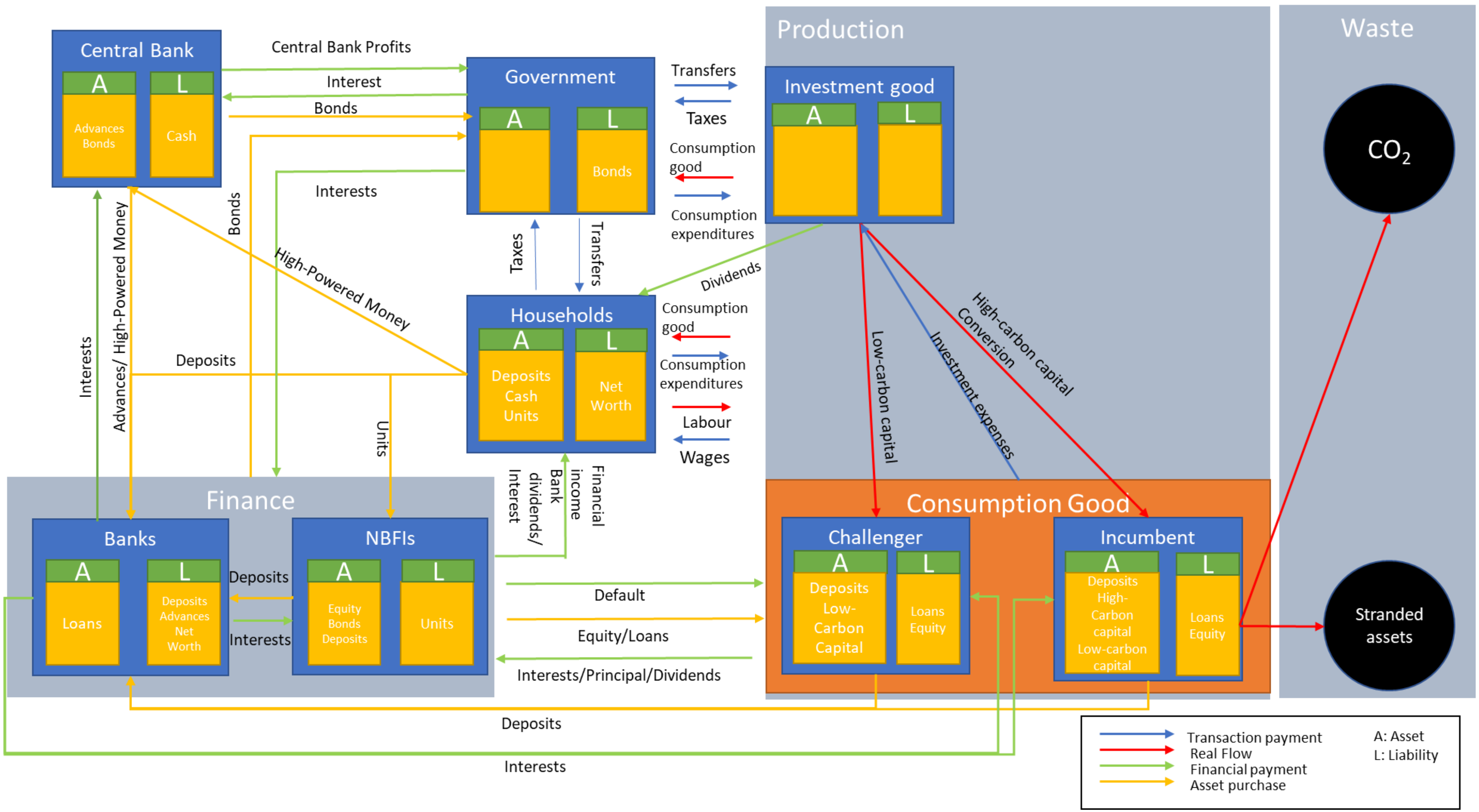
Investments are funded in three ways: accumulated funds, bank loans, on which firms pay interest and principal and equity emissions, on which NFCs pay dividends. A representative Bank (B) extends loans and perform both price and quantity rationing. Interest rates rise with observed firms' leverage, while quantity rationing increases with firms' portion of profits dedicated to paying interests and principals. I also allow for loan vintages to better represent the dynamics of principal repayments and interest changes. A representative Non-Bank Financial Institution ($NBFI$) purchases equities, collects household savings and pays households a financial income based on collected dividends. Banks and NBFIs also purchase government bonds and NBFIs hold deposits at banks to make for possible shortfalls.

The government (G) in this model collects taxes (including a carbon tax), provides transfers and targets a constant deficit. The central bank (CB) applies a constant base rate, provides advances to close banks' balance sheets if needed and buys the residual of government bonds, if necessary (Lavoie, 2014).

Finally, households (H) collect wages from their labour work and are paid financial income by NBFIs they possess Units of. Households possess Banks through their own funds and Investment Good firms and collect the profits of these two sectors. Households consume and hold three kinds of financial assets: deposits, high-powered money and NBFI units.

A general picture of the model is given in Figure 2-1. Stock-flow tables show in Annex.

Figure 2-1 A Diagrammatic Representation of the Model



2.2 Decarbonisation process

Consumption good producers (Incumbents and Challengers) conduct decarbonisation through two channels. First, in the spirit of Caiani et al. (Caiani et al., 2012), a newcomer, challenger (CH) sector will emerge and compete with the incumbent (IN) sector, which possesses the high-carbon capital stock at the start of the transition. The challenger only invests in low-carbon capital and will snatch market shares from incumbents. In parallel, the incumbent sector will try to adapt its production process by retrofitting part of its high-carbon capital stock into a low-carbon alternative[8]. Both types of firms shape the consumption-good sector which is assumed to bear the whole decarbonisation effort. Capital goods are bought from an investment good (IG) sector which, because it does not employ capital, is non-polluting. The pace and intensity of the transition depend on an exogenous decarbonisation target.

Formally, the model will target a share of low-carbon capital $S^T_{L,t}$ to be achieved at the next model stage to be consistent with the simulated decarbonisation:

$$S^T_{L_t} = \left(1 - \frac{E_{t+1}}{x_{IN_t}\varepsilon}\left(1 - S_{IN_t}\right)\right)^{\zeta} \quad (1)$$

With E_{t+1} the emissions to be achieved in $t+1$, x_{IN_t} real consumption serviced by the incumbent sector, ε the carbon intensity of production, S_{IN_t} the market share of incumbents, $\zeta < 1$ an adjustment parameter to ensure that emissions follow the targeted path. By contrapose, incumbents determine $S^T_{H_t} = 1 - S^T_{L_t}$ the desired share of high-carbon capital. If there is excess capital, they anticipate an amount of real stranding corresponding to this excess capital. In a bid to hedge against conversion, companies will convert a fraction of their capital stock by equating the investment cost of converting with the expected balance-sheet loss due to stranding. Once

[8] I assume for simplicity that the high-carbon sector only retrofits its current stock and does not invest in a low-carbon alternative. Sensitivity checks with a simple allocation rule for investment showed similar results.

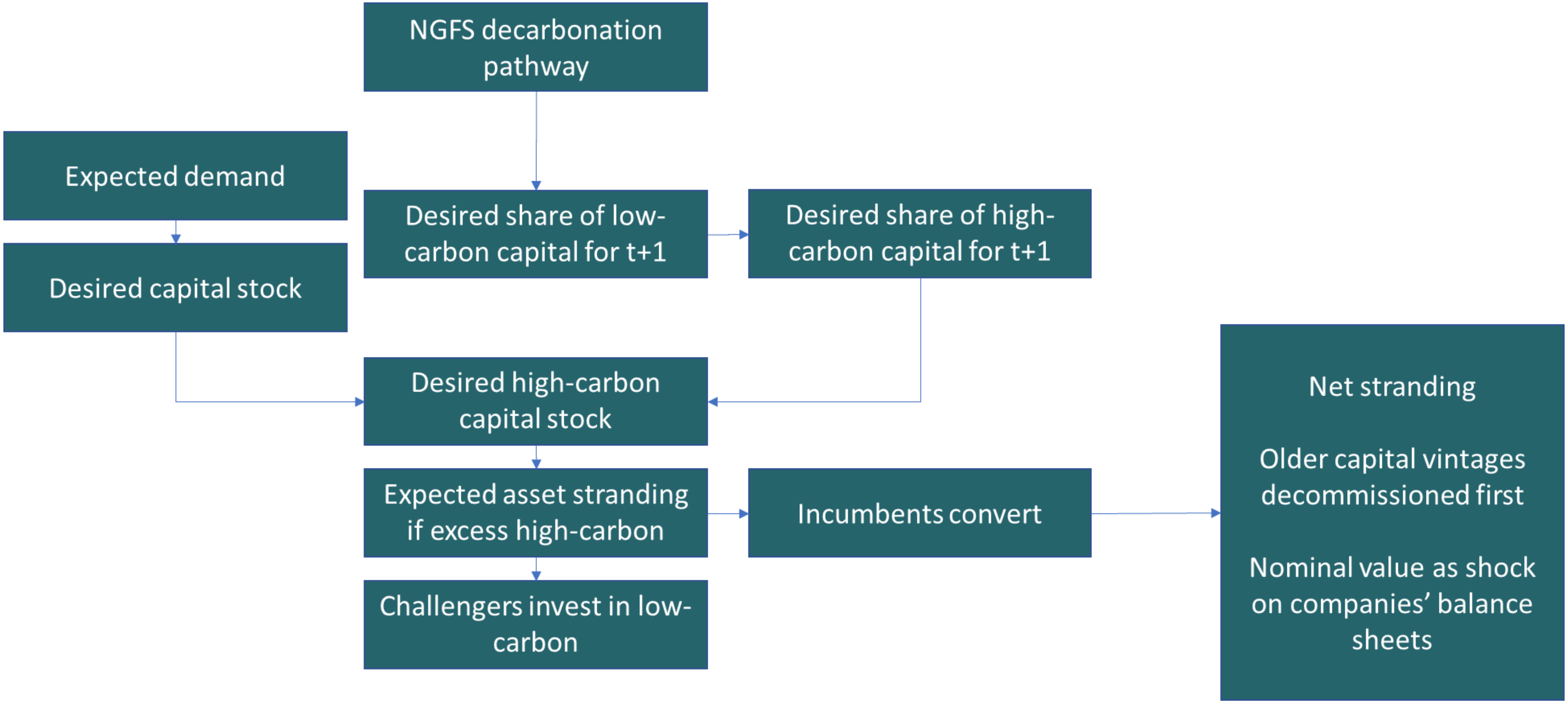
conversion demand is determined, the Challenger sector invests in the residual desired low-carbon capital stock to match the target. Figure 2-2 summarises the decarbonisation process.

The choice of a challenger-incumbent structure to depict decarbonisation is motivated by the desire to clearly represent that the low-carbon transition will entail a large-scale transformation of our economies, with important amounts of stranded assets (Daumas, 2021). This is further justified by the important cross-sectoral interactions that may exist between high and low emitters (Cahen-Fourot et al., 2021; Godin and Hadji-Lazaro, 2020), which invite to consider a whole high-carbon production system instead of sole sectors. It finally allows me to picture a losing sector, which can only adapt to the low-carbon transition at a cost and explicitly represent winners.

2.3 Asset stranding

The model also features a representation of asset stranding through the decommissioning of capital vintages. Over the course of the transition, Incumbents will face excess capital with respect to decarbonisation goals. To avoid large losses on their balance sheet, they will convert a fraction of this expected excess capital into low-carbon capital. The residual is sheer stranding, whose nominal value will represent a shock to incumbents' balance sheets.

Figure 2-2 – The model's decarbonisation process



NB: We call "low-carbon" a non-emitting or "zero-carbon" alternative. Although the wording is not exact, it is consistent with the literature. We also keep it for simplicity in comparing high- and low-carbon capital

2.4 Financial instability

The low-carbon transition will negatively affect the incumbent sector in four ways:

- Loss in market shares and proceeds
- Carbon tax
- Higher credit rationing
- Asset stranding will increase leverage and make banks ask for higher interest rates.

Because it will have to carry out very large investments, the challenger sector may also face higher credit rationing and interest rates if its leverage and debt service ratio increase, in a "green bubble" fashion (Nauman, 2021; Semeniuk et al., 2021).

These factors will increase the financial fragility of incumbents and affect in turn financial institutions in several ways.

First, non-financial companies (NFCs) can default on their loans depending on their illiquidity, measured through their total cash inflow to total cash outflow ratio based on an independent probability function taken from Dafermos et al. (2017a):

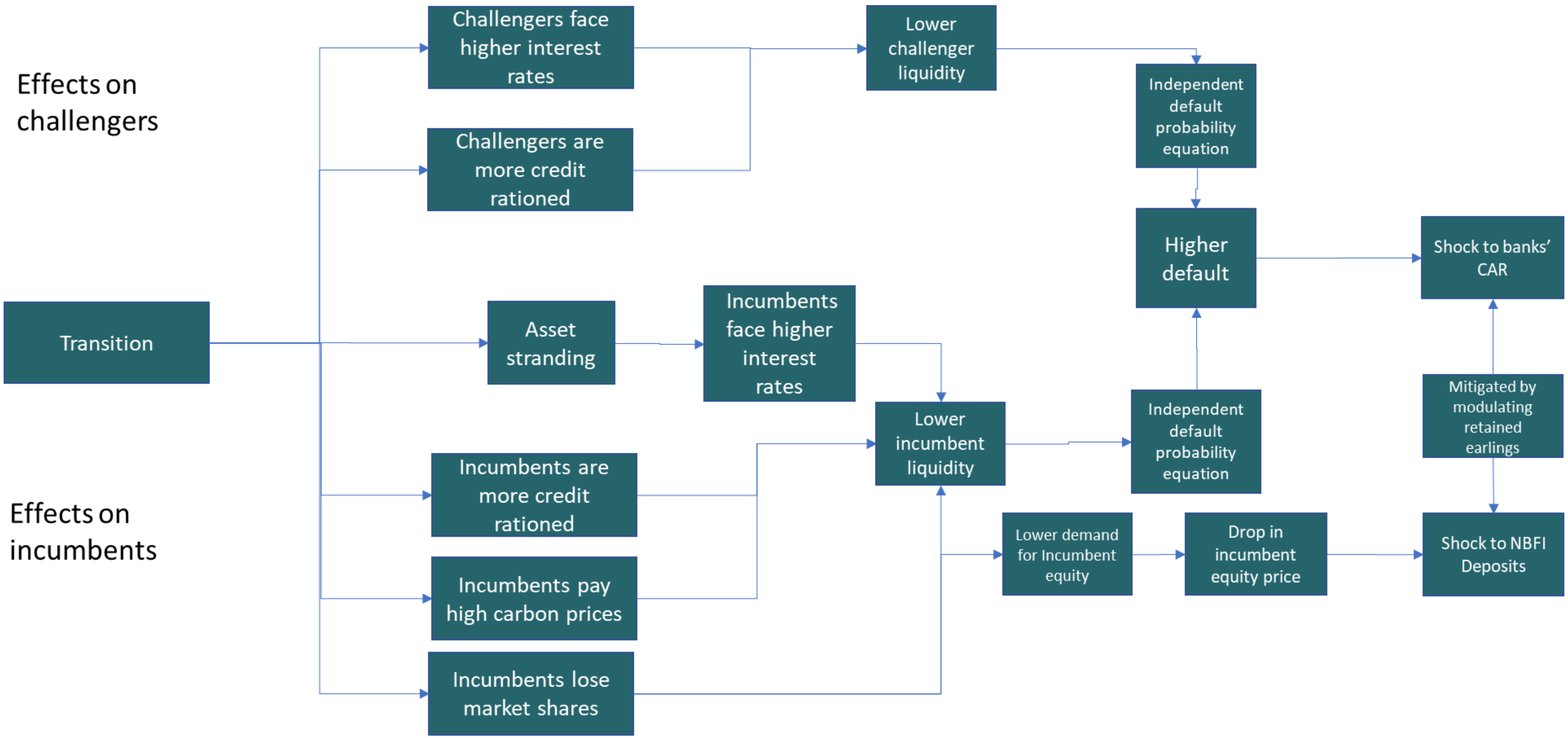
$$\varphi_{NPL_{\ell_t}} = \frac{1}{1 + \varphi_0 \exp\left(\varphi_1 - \varphi_2 \iota_{\ell_t}\right)} \tag{2}$$

Where NPL stands for "non-performing loans" and with φ_0, φ_1 and φ_2 calibrated parameters. ι_{ℓ_t} is a measure of consumption firms' illiquidity ($\ell \in \{IN, CH\}$), computed as the ratio of all financial outflows (wages, dividends, interests, taxes...) to financial inflows (proceeds, loans, equity funding). Based on this equation, an increase in financial outflows (like a carbon tax) or a decrease in inflows (lower proceeds, credit rationing) will result in higher default probabilities.

An increase in $\varphi_{NPL_{\ell_t}}$ will increase the amount of non-performing loans in the economy, which will be a hit to banks' own funds. This in turn affects the financial viability of banks, measured by their capital adequacy ratio, *i.e.,* the ratio of their own funds to their loan exposure. Banks can alleviate the shock by modulating their purchases of government bonds.

Finally, NBFIs are affected through diminished dividends from incumbents, which may force them to dissave from their deposits to pay the financial income due to households. Because the demand for incumbent equity will diminish with the sector's market share, capital losses can arise. NBFIs absorb such losses with deposits. Figure 2-3 summarises these channels.

Figure 2-3 – Paths to financial instability within the model



3 Calibration and scenarios

3.1 General calibration method

The model was first calibrated by ensuring equality between supply and demand under various constraints at a "year zero", assuming a 2% expected growth for output. Solving was performed with Excel's non-linear generalised reduced gradient algorithm, with corporate markups as solving variables. To allow the model to reach a steady state, this "year zero" is calibrated to target 2019 values for key variables after around twenty simulation periods (including year zero). Targeted variables include nominal world GDP, the nominal value of the capital stock, the wage share, labour intensities and inflation rates. Because the model has its own monetary unit and price indices, no real variable was targeted. Also, given my simplified representation of the financial sector and the lack of consistent data at a world level, the values of financial stocks (loans, deposits) were calibrated based on key ratios (*e.g.,* leverage) and applied to ensure stock-flow consistency. The model is labelled in tens of billion US$. Calibration was realised by disregarding the Covid crisis to stick closest to decarbonisation pathways.

3.2 Targeted endogenous variables

The value of the target nominal world GDP and target inflation are drawn from the World Bank database (2022). The nominal value of the capital stock, the wage share and labour intensities are drawn from the World Input-Output Database (Timmer et al., 2015). Because it is assumed that the capital stock at the start of the transition is polluting, it is attributed in full to the incumbent sector. Labour intensity is supposed to be higher for conversion to represent the fact that retrofitting is costly. Table A3-1 summarises key targeted endogenous variables and the starting value yielded after twenty simulation periods. All are satisfactorily in line with actual values. An exception is default propensities, which are underestimated. I keep this calibration to avoid too high default propensities in baseline scenarios (see Section 4).

3.3 Parameters

Data on capital intensities, the capital stock, productivities, wage rates and income shares at the world level were drawn from the World Input-Output Database, (Timmer et al., 2015). The target utilization rate was drawn from Botte's (2017) estimate of the normal utilization rate in the U.S. The Kaldor-Verdoorn effect was calibrated based on Dafermos et al. (2017). Payout ratios were derived from an average at the world level (McCrum, 2018), while leverage ratios were taken from Graham et al. (2014) and Ferrari et al. (2018). Data on the maturity of industrial and commercial loans were drawn from the World Bank (2022). The starting-point CAR (18%) corresponds to the unweighted CAR of EU banks (ECB, 2020). Coefficients on default probability equations were set to allow for a 2-3% default probability throughout the baseline run, which corresponds to a weighted average over national default over gross debt drawn from the World Bank (2022). Absent data on credit rationing practices, I set coefficients to allow for 2% credit rationing over the baseline run. Interest rates were calibrated to match a weighted average of rates for commercial loans given by the World Bank (2022). Coefficients ruling demand for high-powered money and government bonds on deposits were calibrated instrumentally. Banks' payout ratio was set conservatively at 40%, which is roughly the lower bound for payout ratios within the European Union between 2000 and 2020 (Muñoz, 2020). For NBFIs, Tobin coefficients were calibrated instrumentally by respecting verticality and horizontality conditions (Godley and Lavoie, 2007). The proportion of reinvested deposits and the dividend payout ratio were chosen to ensure sufficient nominal demand for securities.

The consumption function was calibrated to yield a growth rate of around 2% after twenty iterations, within the lines of central IPCC hypotheses (Riahi et al., 2017).

The normal government deficit was taken from World Bank (2022). Tax rates were calibrated by applying the world-average corporate (Bray, 2021) and personal income (Global Economy, 2020) tax rates. Subsidies and transfers amount, at a world scale, to 43% of total government expenses, which themselves amount to 23% of GDP (World Bank, 2022). As a result, transfers amount to a rough 10% of world GDP. Since no data were available on the dispatch between firms and households, I allocated half to firms and half to households. I assume that investment good firms do not receive subsidies, while incumbents and challengers receive subsidies based on their market share.

Finally, parameters on the nominal wage-setting equation and in the law of motions ruling mark-ups were calibrated to reach an inflation rate close to 2% in 2020. Table A3-2 summarises parameter values.

3.4 Scenario implementation

3.4.1 The NGFS scenarios

I detail here the various narratives and scenarios used by the NGFS, that were expounded in Section 1.

- "Hot House World" scenarios, which feature insufficient transition efforts, are of two kinds:
  - "Nationally Determined Contributions" (NDCs) scenarios suppose that Nation-States abide by their NDCs.
  - "Current Policy" scenarios, which are long-run projections of current policy and technological trends. They lead to higher emissions than NDCs.
- "Orderly" scenarios depict a world in which climate policy is introduced early and smoothly and/or with high technological availability. These scenarios include 2°C-consistent scenarios with greater or lesser carbon dioxide removal (CDR) availability and a 1.5°C scenario with high CDR availability.
- "Disorderly" scenarios are of two kinds:
  - Delayed-action scenarios feature late and sudden policies. The adjustment occurs in 2030. Two delayed-action scenarios were designed, with either low or high CDR availability. Delayed-action scenarios also suppose that Nation-States follow their NDCs between 2020 and 2030.
  - Disorderly scenarios also include a climate-ambitious, 1.5°C scenario with low CDR availability.

I expand this scenario portfolio by running "Disruptive Action" scenarios in which sharp climate policies are introduced from the "Current Policy" scenario. This is meant to simulate a "worst-case" transition risk scenario. Further, assuming that countries will abide by their NDCs between 2020 and 2030 seems misplaced given the slow progress in decarbonisation at the world level. It is also a way to operationalise my choice of the “Current Policy” scenario as a baseline (see below) for delayed-action scenarios.

To build it, I assume that the carbon price and emission trajectories follow those of the “Current Policy” scenario up to 2030. Then, I make the model target the decarbonisation pathway of the NGFS’s Delayed-Action scenario diminished uniformly by 20% to approximate a more intense decarbonisation effort while applying a 20% higher carbon price schedule. Table 3-1 summarises all scenarios and Figure 3-1 offers a visualisation of carbon price paths and decarbonisation schedules.

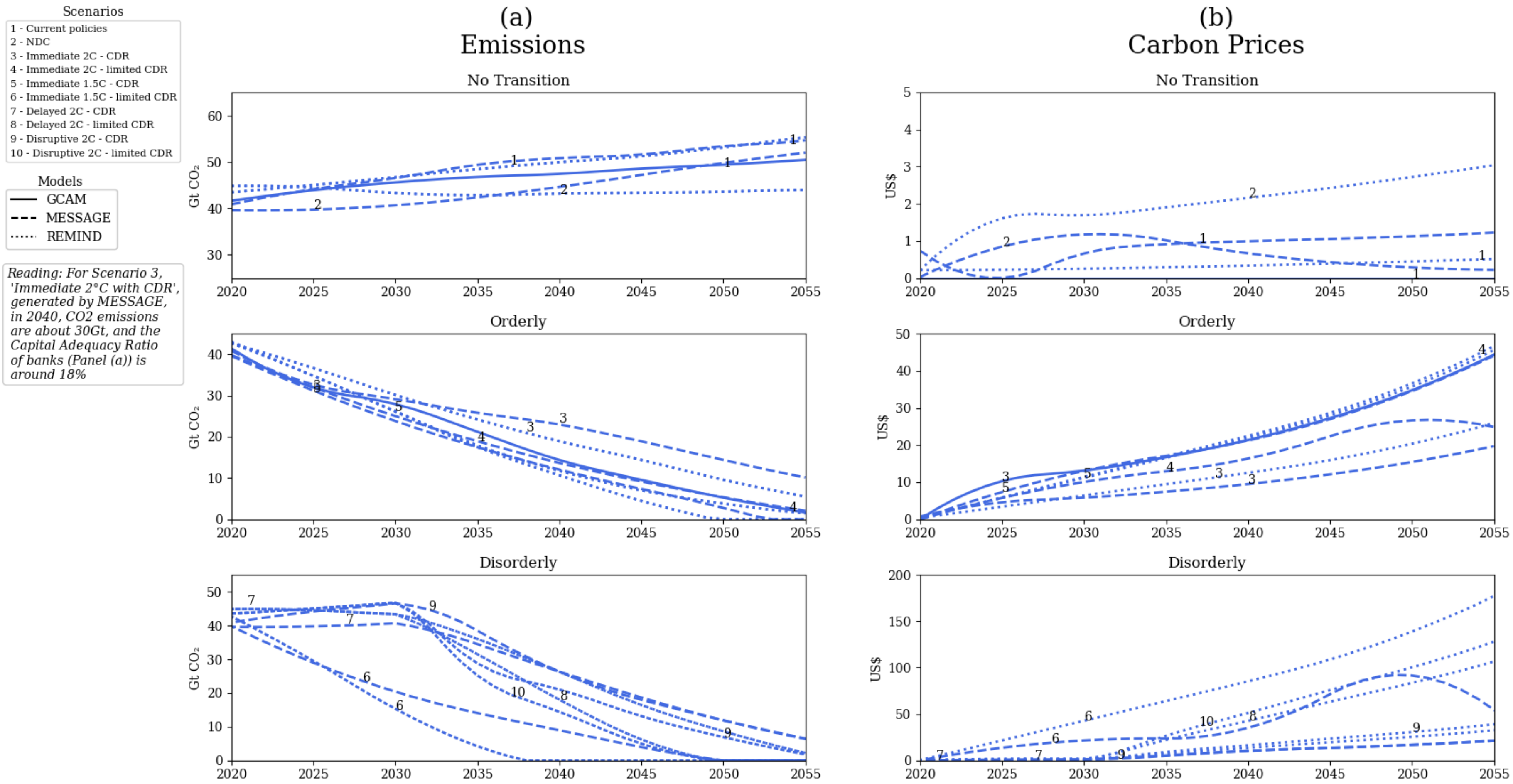
Table 3-1 Scenario Summary and Reference IAMs

Scenario	Simulated by	Description
Current policy	GCAM, MESSAGE, REMIND	Scenario prolonging current trends in policy and technological development
Nationally Determined Contributions	MESSAGE, REMIND	Scenario assuming that NDCs are respected
2°C–Early Action–High CDR	GCAM, MESSAGE, REMIND	
2°C–Early Action– Low CDR	MESSAGE, REMIND	
1.5°C–Early Action– High CDR	MESSAGE, REMIND	
1.5°C–Early Action–Low CDR	MESSAGE, REMIND	
2°C–Delayed Action–High CDR	MESSAGE, REMIND	Brisk shift in climate policy in 2030, from NDC
2°C–Delayed Action–Low CDR	REMIND	
2°C Target–Disruptive Action–High CDR	MESSAGE, REMIND (Homemade variant)	Brisk shift in climate policy in 2030, from Current Policies
2°C Target–Disruptive Action–Low CDR	REMIND (Homemade variant)	

3.4.2 Baseline Scenario

Most NGFS-based exercises consider either NDCs or “orderly” scenarios (Allen et al., 2020) references. Yet, Nation-States are lagging in implementing their NDCs (UNEP, 2021). Also, if choosing an “orderly” scenario for a baseline is useful in contrasting orderly and disorderly transitions, it does not allow to assess the potentially disruptive effects of “orderly” transitions.

Figure 3-1 Emission schedules and carbon price paths across NGFS scenarios



As a result, I chose the "Current Policy" scenario as my baseline.

3.4.3 Model-specific variants and model uncertainty

I simulate all model-scenario pairs. IAMs differ in terms of functional forms and modelling strategies. This can drive differences in decarbonisation pace, technological penetration and carbon price schedules for the same scenario and beg to explore "model uncertainty" (Kriegler et al., 2015) in studying transition risks.

3.4.4 Scenario translation

IAMs are large-scale tools with a very granular depiction of decarbonisation outcomes and a rich array of outcomes. This model adopts a simpler representation of climate mitigation. Hence, to reproduce NGFS scenarios, I reduce them to an emission schedule and a carbon price path. For each scenario, the model is forced to target an exogenous emission schedule through slower or faster low-carbon technology penetration (see Section 2). To mimic climate policy, a carbon tax schedule is imposed upon firms in parallel. Because the IAMs mobilised by the NGFS typically display their results with a timestep of five to ten years, while my model's timestep is yearly, I generate yearly emission and carbon price path through order-2 polynomial interpolation[9]. Finally, the emission intensity ε is calibrated by dividing the 2020 emissions given by the scenario under consideration by total real output.

This model does not incorporate carbon dioxide removal (CDR) technologies, while all scenarios imply net negative emissions. However, in most scenarios, net negative emissions appear only after 2050, outside the period concentrating most transition risks. Therefore, I assume that low-carbon technology penetration includes implicitly negative emission technologies and set post-2050 net negative emissions to zero in the schedule targeted by the model. The lack of CDR technologies is encapsulated in steeper carbon price and decarbonisation schedules.

[9] Robustness checks were run with simple linear interpolation and results did not change.

3.4.5 Macroeconomic assumptions

The model is further calibrated to match some macroeconomic assumptions. On GDP growth, I follow the NGFS scenarios (Bertram et al., 2020), which are calibrated on the assumptions of the second, "Middle-of-the-Road", Shared Socioeconomic pathway (Riahi et al., 2017). This entails targeting a 2% growth rate baseline. For indicators usually not displayed by IAMs but present in my model, like inflation, I keep the macroeconomic assumptions used to calibrate the model at year zero (see Table A4-1).

4 Results

Scenarios are run over a 2020-2100 period. To stick to the literature, I focus on the 2020-2050 period, which will likely concentrate transition risks (ECB, 2021b).

4.1 Outcomes of interests

I consider four outcomes of interest related to financial instability (Table 1). I focus on "sunset" industries, represented by the incumbent sector.

Table 4-1 Description of outcomes of interests

Outcome	Description	Variable (Symbol)
Default probability of Incumbent firms – Index, Base 100 in 2020	Default probability increasing with sector's illiquidity	$100\left(\frac{\varphi_{IN_t}}{\varphi_{IN_{2020}}}\right)$
Equity prices – Incumbent – Index, Base 100 in 2020	Ratio of nominal demand for equity to the real number of securities	$100\left(\frac{p_{A_{IN_t}}}{p_{A_{IN_{2020}}}}\right)$
Capital Adequacy Ratio	Ratio of own funds to loan exposure (Unweighted)	CAR_t
Year-to-year change in NBFI deposits	Measure of the shock to the buffer stock for NBFI	$100\left(\frac{D_{NBFI_t} - D_{NBFI_{t-1}}}{D_{NBFI_{t-1}}}\right)$

Default probability and equity prices are usual metrics in NGFS-based exercises (Allen et al., 2020; ECB, 2021a). Default probabilities show how much banks could be fragilized along a transition path, while equity price measure the extent of asset losses on stock exchanges. These variables measure realisations of transition risks, respectively of credit and market risks.

Once these realisations measured, remains to gauge their actual effect on financial institutions' financial health. The capital adequacy ratio measures the actual vulnerability of banks to transition shocks, while changes to NBFI deposits measure that of NBFIs. Indeed, NBFI a decrease in NBFI deposits will denote capital losses (see Annex 5 for a demonstration).

Results are presented as follows. I first present metrics showing the realisation of transition risks. I then move on to examine variables measuring how banks and institutions bear the losses associated with the first two variables. To draw a systematic link between the decarbonisation effort implied by each model and financial instability, Figures will be composed of decarbonisation schedules with colour shades corresponding to the value of the variable of interest.

4.2 Realisations of transition risks

Starting with incumbents' default probability, results are displayed on Figure 4-1, Panel (a).

Default probability in baseline and NDC scenarios stay around starting values of 2.5%. The slight increase over NDC scenarios in the short run compared to baseline arises from the greater decarbonisation effort in the NDC scenario. Default probabilities increase in all early-action scenarios. In the case of REMIND, they increase with scenario stringency. However, MESSAGE exhibit roughly equivalent default propensities across scenarios. This is because MESSAGE's decarbonisation schedules are highly similar in the short run[10] across scenarios.
REMIND shows slightly lower default propensities relative to MESSAGE and GCAM. This feature is due to the steeper decarbonisation schedule of these two models in the short run. The bulk of the effect seems to be driven by technical change. REMIND tends to yield the highest carbon prices of the model sample. Thus, if carbon prices were mainly responsible for default probabilities, one would expect higher default propensities for REMIND-generated trajectories, while it is not what it is observed.

In 2°C scenarios, the wave of defaults dies down in the longer run, while default surges emerge in the medium to long run in 1.5°C scenarios. These spikes can be attributed to credit rationing and interest hikes episodes, which are concomitant with asset stranding. The fact that for REMIND, stranding schedules are steeper and decarbonisation efforts more stringent in the medium run, leads to brisk increases in default propensities earlier than for MESSAGE. These spikes can also be imputed to higher carbon price schedules in the longer run, which may push incumbents' illiquidity ratios higher than in other trajectories.

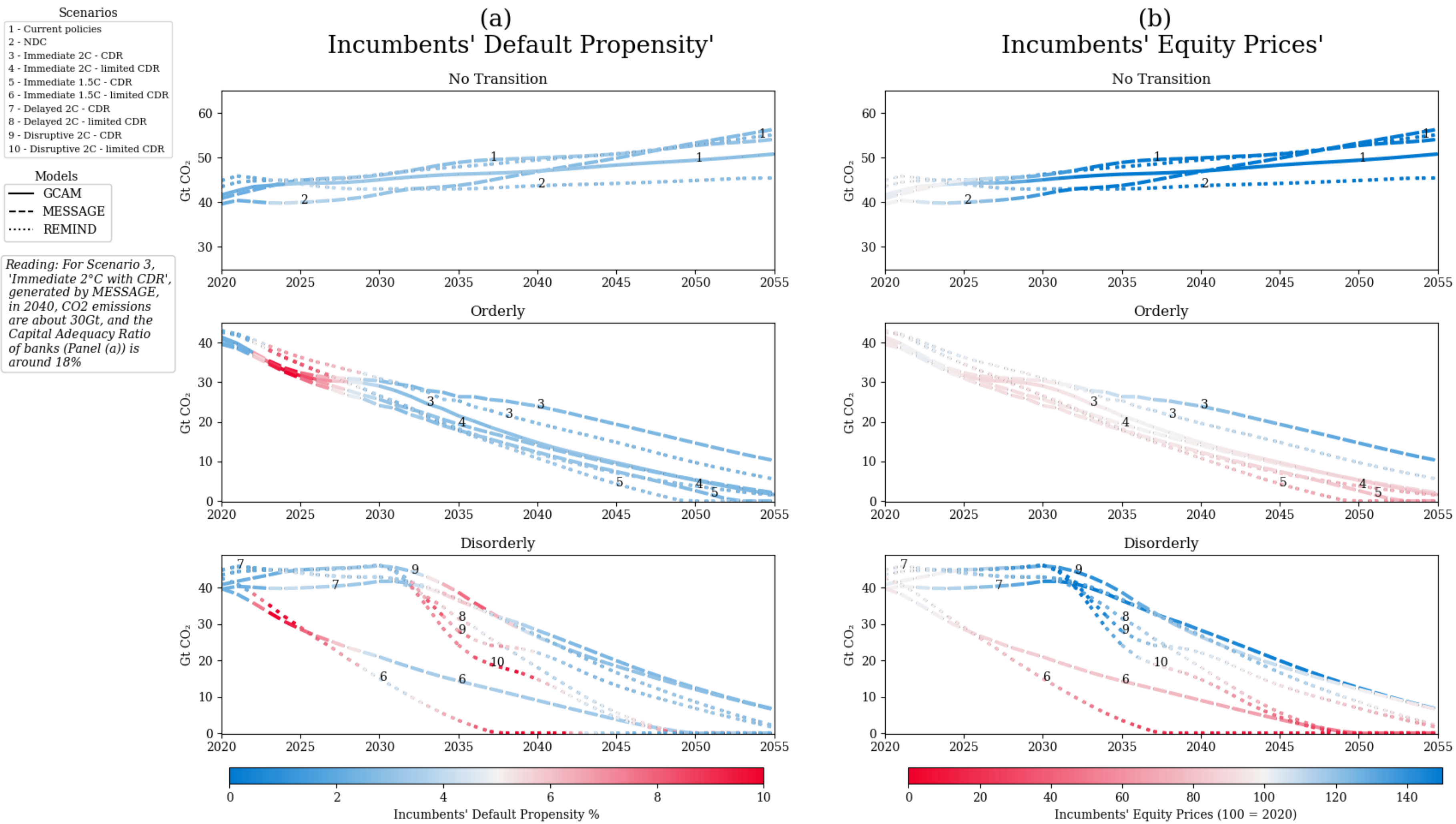
[10] This feature may be due to our interpolation procedure. Results should therefore be considered cautiously. Significant differences in terms of decarbonisation schedule shapes across IAMs for the same scenario is nonetheless a well-established result of the model intercomparison literature.

Delayed-action scenarios also show high default propensities in the short to medium run after the implementation of climate policy. For MESSAGE, default propensities are lower than in all early-action scenarios and span over a slightly longer period. For REMIND, "Disruptive" scenarios show steep increases in default propensities, which reach higher levels than in the 2°C-Early Action-High CDR scenario and lower than in the 1.5°C-Early Action-Low CDR. Higher default propensities also last longer. Plain "Delayed" scenarios, by contrast, exhibit default propensities in line with and sometimes lower than, some orderly scenarios. These results are consistent with ECB (2021a) for Europe. Here, they are attributable to multiplier effects and to low-carbon capital penetration and capital conversion in NDC scenarios. Because incumbents convert their capital stock before belated climate policy, they can absorb policy shocks. Plus, higher growth due to the necessarily rapid penetration of low-carbon capital results in higher proceeds. This allows firms to grow away from financial difficulties. By contrast, "Disruptive" scenarios feature no or lesser conversion and do not allow incumbents to bear at least part of the shock, resulting in higher default. Inflationary pressures are also higher in "Disruptive" scenarios. This weighs on aggregate demand and counterbalances the multiplier effects of low-carbon investment.

Results on incumbent equity price are displayed on Figure 4-1, Panel (b). Compared to baseline, NDC scenarios feature slowdowns in incumbent equity price growth, but no decrease.

In early-action scenarios, the extent and speed of asset price decreases depend on the stringency of the scenario. The Early Action-1.5°C-Low CDR scenario shows the sharpest drop and the Early Action-2°C-High CDR the least steep diminutions. Price trajectories follow closely that of decarbonisation schedules.

Figure 4-1 Transition Risk Realisations



No orderly, early-action scenario features very sharp drops in asset prices, with prices remaining almost throughout at around 80% of their 2020 value. It suggests that early-action scenarios exhibit "erosion risks" in the marketplace (Giese et al., 2021), as the incumbent sector loses market shares, which may be sufficiently progressive to avoid significant disruptions. Finally, REMIND shows sharper losses for very stringent scenarios than MESSAGE.

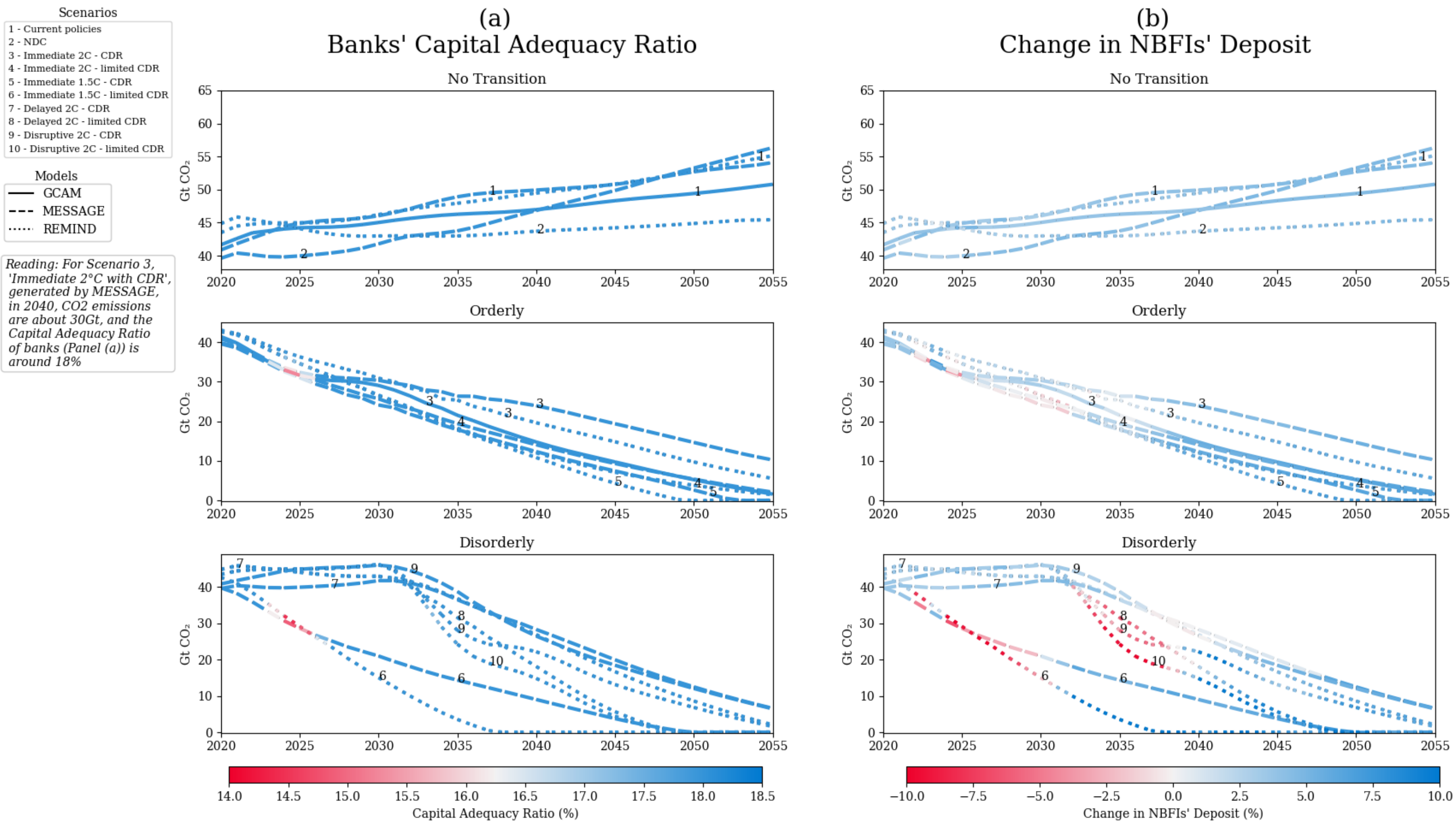
Delayed-action scenarios, by contrast, show sharper asset price drops, with shocks amounting to 30-40 basis points over two to three years. It is due first to the sudden decrease in dividends from incumbents and to the rapid development of the challenger sector, which diverts savings from the purchase of incumbent equity. This is mostly the case for REMIND-generated scenarios, equity prices for MESSAGE scenarios following more concave paths.

4.3 Financial institutions' vulnerability to transition risk realisation

How does this translate into vulnerability for financial institutions? Starting with banks, I display results for the evolution of their Capital Adequacy Ratio (CAR) in Figure 4-2, Panel (a).

Decreases in CAR appear because retained earnings are not enough to cover both additional non-performing loans and additional loan exposures. Decreases in CAR are confined to the short run (maximum five years after the introduction of climate policy). They are also limited, with a maximum three-point decrease in the Early Action-1.5°C-Low CDR scenario for REMIND.

Figure 4-2 Impact on Financial Companies



Climate-ambitious and technically constrained scenarios exhibit larger shocks because banks' total exposures increase (due to the development of the Challenger sector) and because of higher absolute NPLs (due to the shrinking of the Incumbent Sector).[11]

Also, banks seem able to navigate "Plain delayed-action" scenarios, with no or small decreases in CAR. This feature is due to the low increase in default propensities in Plain Delayed-action scenarios (see above), but also to the relative diversification of banks' portfolio loans before the introduction of climate policy. Current Policy and NDC scenarios feature a progressive development of the challenger sector, which is another source of profits for banks. In NDCs, the incumbent also converts part of its capital stock and limits its exposure to policy shocks. The rapid development of the challenger necessary to meet climate targets allows also banks to mitigate their exposures and reap more profits. By contrast, "Disruptive Delayed-action" scenarios exhibit sizeable shocks to CAR only for REMIND-generated pathways.

CARs show important cross-model variation. In GCAM, even a smooth transition yields high CAR shocks, while MESSAGE exhibits higher losses for "orderly" transitions and lesser risks for the early-action disorderly scenario. MESSAGE also exhibit lower CAR shocks in its low CDR scenario. These divergences follow the differences in decarbonisation schedules.

Regarding NBFIs, results are displayed in Figure 4-2, Panel (b).

NBFIs seem more vulnerable than banks in facing transition risks, with deposits being reduced by down to 10% over the course of the transition. Disorderly scenarios show much steeper decreases in NBFI liquidity, especially for high climate targets, or technologically constrained scenarios. They are also much more long-lived. Finally, some orderly scenarios feature very sluggish NBFI deposit growth by the mid-2030, suggesting that residual transition risks may emerge in the medium run.

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[11] These results are not driven by the fact that the challenger emerges from a zero market share in early-action scenarios. Robustness checks were run allowing for a 2%-market share for the challenger sector – to avoid a high growth in loan-taking from the challenger – and results did not change.

This decrease in NBFIs' deposit-to-asset ratio is due to the fall in the incumbents' equity price. It is also because challengers aim to keep their equity price constant, which precludes capital gains. However, NBFI deposits recover in the long run except for the Early Action-2°C-High CDR projection. This is due to the recovery of high-carbon equity prices and the increase in challenger equity prices at the end of the transition.

5 Discussion and conclusions

The model's findings can be summarised along three lines.

Quantitatively, the model yields limited credit transition risks, except for stringent scenarios. Market risks, on the other hand, seem more sizeable.

Qualitatively, credit transition risks seemed to matter more in early-action scenarios but appeared quite marginal in delayed-action scenarios. This highlights the importance of modelling banks' adaptation to the transition. Market risks are more important in delayed-action scenarios. Finally, the main determinant of transition risks seems to be primarily technological availability.

Methodologically, the transition risk content of a scenario depends on the model used to generate the scenario. Different IAMs show distinct decarbonisation paces in the short and long run for the same scenario. Hence, it seems crucial to compare different model results to fully map the uncertainty associated with transition risks. For instance, I only managed to broadly reproduce the distinction for REMIND-generated scenarios. In that case, delayed-action scenarios did not mandatorily result in higher credit transition risks than early-action scenarios. This can be attributed to my macroeconomic assumptions allowing for slack and multiplier effects and to my modelling of an aggregated banking sector. Further, GCAM and MESSAGE show distinct decarbonisation schedules and carbon price hypotheses. Hence, the dynamics of transition risks drifted from the orderly/disorderly distinction. This calls for caution in generalising a dichotomy that may hold only for a certain population of IAMs.

This study also examined how transition shocks propagate to the financial sector and showed that sizeable transition risk realisations need not come with important shocks to financial institutions.
Finally, accounting for the balance sheet effects of stranded assets and asset decommissioning seems important in fully grasping financial disturbances arising from sunset industries.

This model is built around a series of simplifying assumptions that could drive these results to a certain extent.

This general transition risk picture is conservative due to the positive macroeconomic effects exhibited by the model. Compared to similar models, assumptions of slack, no capacity constraint in the investment sector, constant returns to scale and a positive relationship between growth and productivity significantly lower the private costs of the low-carbon transition. Capital conversion is particularly easy due to the absence of increasing costs, which allows incumbent firms to diversify their production process more easily than could be expected.

Also, leverage from within the financial sector is not modelled, while credit between financial institutions represents today the greater share of banks' exposures (Finance Watch, 2019). Introducing these dimensions would likely exacerbate instability potentials (Battiston et al., 2017; Stolbova et al., 2018).

The model seems also particularly optimistic regarding the development of the challenger sector, which does not entail financial disturbances or "green bubble" dynamics. This could be due to my assumption of symmetric risk default propensity, while newcomers may carry greater intrinsic risk. Conversely, a shrinking sector could be growingly sensitive to illiquidity and carry more risk as its market share decreases.

Further, as is usual with post-Keynesian SFC models, expectations are backward-looking. Such structures mechanically restrict the hedging behaviour of agents, which may not diversify their activities sufficiently to avoid the carbon tax. For instance, that firms incur high losses in non-stringent scenarios could be because they do not smooth their carbon tax bill over time. Relatedly, like in most SFC frameworks, the model lacks a meaningful asset pricing theory. Asset prices are defined passively as the ratio between nominal demand for equity and the real amount of outstanding equity, with only a very loose relationship to firms' financials and especially no forward-looking pricing process.

Also, the model's financial sector is short-sighted and only reacts to developments in the real economy, while capital reallocation could occur autonomously based on decarbonisation expectations (Battiston et al., 2020).

Further, because the model only features aggregated banking and NBFI sectors, it implicitly assumes that all agents populating these aggregates are equally exposed to transition risks and that they move their exposures harmoniously. This could explain the relative innocuity of delayed-action scenarios, with banks all reshuffling their portfolios harmoniously at the same time. Yet, the literature documents a very skewed distribution of exposures, with some large players concentrating the largest vulnerabilities,(Baer, 2020; Battiston et al., 2017). This calls for a more disaggregated picture, which could be done by applying an agent-based framework to our financial system.

Also, the way the model figures decarbonisation is crude, with a readily available non-polluting capital, which amounts to a silver bullet. Diversifying portfolios or come up as a fully decarbonised sector is easier. This also drives the growth effects of the model: because a readily viable alternative is available, decarbonising through production curtailments is useless. This may overestimate multipliers.

Finally, the model in its current shape is not meant to explore particular policies (Monasterolo and Raberto, 2019) or the effect of various assumptions on investor expectations (Dunz et al., 2021). My work comes closest to a recent SFC proposal by Gourdel et al. (2021). I nonetheless adopt a simpler modelling proposal and focus exclusively on transition risks, while Gourdel et al. (2021) include damage from climate change (physical risks). Further, the authors leave actual emissions free, leading to small decarbonisation efforts (around 20% decrease by 2050 for Europe). This model, by contrast, intends to quantify what it would take to abide by a decarbonisation schedule. To the extent that such decarbonisation pathways are "optimal" in the sense of flowing from the optimisation programme of various IAMs, the model is meant to adopt a normative rather than positive view of transition risks.

Yet, although further model refinements are needed, this framework is easy enough to modulate and accommodate different carbon price paths while linking them to emission targets. Hence, it could be a simple tool to explore a broad array of scenarios generated by a large set of models and compare outcomes linked to financial instability. Applications of robust decision-making or scenario discovery methods (Lempert, 2019) could represent sound applications of this framework. This may help complement traditional scenarios with a financial-instability view.

My results also have policy implications. They first suggest that mitigating market risks is a priority compared to credit risks, which have received more attention within the literature (Basel Committee, 2021). They also call for caution in labelling *ex-ante* "orderly" or "disorderly" a possible transition path. As the model showed, carbon price assumptions and the timing of decarbonisation can change significantly financial instability prospects. At the very least, a much better metric to assess the "orderliness" of a transition scenario would be to consider its short-run decarbonisation targets, which can be very demanding even in early-action scenarios targeting "only" a carbon budget consistent with a 2°C warming. Another methodological takeaway is that focusing on default propensities and asset prices may not be helpful, in that it may not reflect the actual shock suffered by financial institutions. Finally, given the significant difference between scenarios assuming high and low CDR availability and in view of the uncertainties surrounding these technologies, regulators should take seriously the issue of technological risks for the transition.

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Annexes

A1. Model Description

A1.1 Non-financial sectors

A1.1.1. Production and employment

Consumption-good firms supplies a homogenous consumption good x^s with a Leontief technology:

$$x^s_{\ell_t} = \min\left(\lambda_{\ell_t} N_{\ell_t}, \kappa_\ell \omega_{\ell_t}\right) \qquad (A1)$$

With $\ell \in \{CH, IN\}$, t the time index and where L_{ℓ_t} and ω_{ℓ_t} are respectively employed labour and total capital stock in sector ℓ. λ_{ℓ_t} and κ_ℓ are respectively the labour and capital intensity in sector i. Because the incumbent sector possesses both high- and low-carbon capital, we have:

$$\kappa_{IN} = \kappa^H S^H_{IN_t} + \kappa^L\left(1 - S^H_{IN_t}\right) \qquad (A2)$$

Where κ^j, $j \in \{H, L\}$ denotes the capital intensity for high- and low-carbon capital, respectively and S^H_{IN} the share of high-carbon capital in the total of the incumbent sector. Because the challenger sector only invests in low-carbon capital, $\kappa_{CH} = \kappa^L$. I assume that capital intensities are the same for both types of capital, such that $\kappa^H = \kappa^L = \kappa_{IN} = \kappa_{CH}$. Capital intensities are held constant.

To best represent the dynamics of asset stranding, I allow for capital vintages. The high or low-carbon capital stock of both sectors can be represented as a vector $b^j_{i_t}$ of capital vintages:

$$b^j_{\ell_t} = \begin{pmatrix} (1-\delta^j)^t k^j_{\ell_0} \\ (1-\delta^j)^{(t-1)} k^j_{\ell_1} \\ \dots \\ k^j_{\ell_t} \end{pmatrix} \qquad (A3)$$

Where δ^j, $j \in \{H, L\}$ is the natural depreciation rate of capital, which is supposed to be the same for both high- and low-carbon capital.

It is assumed that capital stocks only differ by their time of installation and therefore have the same productivity κ_j. As a result, we can sum to obtain the total real j-type capital stock for sector ℓ:

$$\omega_\ell^j = \sum_{n=0}^{t} ((1-\delta^j)\,)^{t-n} k_{\ell_n}^j \qquad (A4)$$

For the incumbent sector, total real capital stock ω_{IN_t} is given by $\omega_{IN_t}^H + \omega_{IN_t}^L$ and $\omega_{CH_t} = \omega_{CH_t}^L$.

The valuation of capital good is made at historical costs, *i.e.,* at their purchase price:

$$B_{\ell_t}^j = \begin{pmatrix} (1-\delta^j)^t k_{\ell_0}^j p_0^j \\ (1-\delta^j)^{(t-1)} k_{\ell_1}^j p_1^j \\ \dots \\ p_t^j k_{\ell_t}^j \end{pmatrix} \qquad (A5)$$

With p_t^j the purchase price of the j-type of capital good. By summing, we obtain the total value of the j-type capital stock for sector ℓ:

$$\Omega_\ell^j = \sum_{n=0}^{t} (1-\delta^j)^{t-n} k_{\ell_n} p_n^j \qquad (A6)$$

Like in Monasterolo et al. (2018), the investment good sector only employs labour. It also uses a Leontief technology and produces two kinds of investment goods i_t^j, $j \in \{H, L\}$:

$$i_t^{j^S} = \lambda_{IG_t}^j N_{IG_i}^j \qquad (A7)$$

With λ_{IG}^j and L_{IG}^j respectively the labour intensity in producing the j-type of capital and the number of people employed. The investment good sector also provides a capital conversion service (from high- to low-carbon) o_t for the incumbent sector, which also employs labour:

$$o_t^s = \lambda_{IG_t}^o N_{IG_\ell}^o \qquad (A8)$$

With notations like the above.

In all sectors, output is demand-determined, and inventories are assumed away such that market always clear. capital is plentiful and structurally underutilised, with the utilisation rate of capital $u_i \leq 1$[12] defined as:

$$u_{\ell_t} = \frac{x_{\ell_t}^d}{\kappa_\ell \omega_{\ell_t}} \qquad (A9)$$

Where d denotes demand and $x_{\ell_t}^s = x_\ell^d \; \forall i, t.$

Output is dispatched across sectors based on their share of capital in total:

$$x_{CH_t}^d = x_t^d \frac{\omega_{CH_t}}{\omega_{IN_t} + \omega_{CH_t}} = x_t^d S_{CH_t} \qquad (A10)$$

$$x_{IN_t}^d = x_t^d \left(1 - S_{CH_t}\right) \qquad (A11)$$

Where x_t^d is total demand for the consumption good, determined as the sum of real household and government consumption:

$$x_t^d = c_t + g_t$$

Nominal values are determined by multiplying real value by their price. I assume that the consumption good is sold at the same price p_{x_t} regardless of the producer:

$$X_{IN_t} = x_{IN_t} p_{x_t} \qquad (A12)$$
$$X_{CH_t} = x_{CH_t} p_{x_t} \qquad (A13)$$

[12] If utilization in one sector reaches one, its assumed that all existing residual demand is addressed to the other sector. The model is further calibrated to avoid that any of the utilization rates goes above 1.

I finally define u_{x_t} the aggregate sectoral utilisation rate, with x denoting the whole consumption good sector:

$$u_{x_t} = \frac{x_t^d}{\kappa_{IN}\omega_{IN_t} + \kappa_{CH}\omega_{CH_t}} \qquad (A14)$$

For the incumbent sector, I assume that output demand is allocated between high- and low-carbon capital such that the utilization rate is equal across the two kinds of capital.

Since there is no intermediate consumption, nominal value-added is defined as:

$$VA_{IN_t} = X_{IN_t} \qquad (A15)$$

$$VA_{CH_t} = X_{LC_t} \qquad (A16)$$

And real value added is defined by deflating nominal value added by the corresponding price, namely:

$$va_{IN_t} = x_{IN_t} \qquad (A17)$$

$$va_{CH_t} = x_{CH_t} \qquad (A18)$$

I assume that government and households are served equally by both sectors.

Labour in the consumption good sector is determined as follows:

$$N_{\ell_t} = \frac{x_{\ell_t}^d}{\lambda_{\ell_t}} \qquad (A19)$$

It is determined in the same way in the investment good sector

$$N_{IG_t}^j = \frac{{i_\ell^j}^d}{\lambda_{IG_t}^j} \qquad (A20)$$

$$N_{IG_t}^o = \frac{o_t^d}{\lambda_{IG_t}^o} \qquad (A21)$$

Labour productivities for different activities are calibrated at the starting point. It is assumed that they are the same for consumption good sectors, such that $\lambda_{CH_t} = \lambda_{IN_t} = \lambda_{x_t} \forall t$. They are all assumed to grow with total real value-added growth:

$$\lambda_{x_t} = \lambda_{x_{t-1}}\left(1 + \nu_\lambda g_{va_{t-1}}\right), \forall t \quad (A22)$$

$$\lambda^j_{IG_t} = \lambda^j_{IG_{t-1}}\left(1 + \nu_\lambda g_{va_{t-1}}\right), j \in \{H, L\}, \forall t \quad (A23)$$

$$\lambda^o_{IG_t} = \lambda^o_{IG_{t-1}}\left(1 + \nu_\lambda g_{va_{t-1}}\right), \forall t \quad (A24)$$

With

$$g_{va_t} = \frac{va_t - va_{t-1}}{va_{t-1}} \quad A25$$

And va_t total real value added, defined below.

With ν_λ a calibrated parameter. This simplification is meant to translate an average Kaldor-Verdoorn relationship to each sector, typically detected at the macroeconomic level (Carnevali et al., 2020).

Finally, I assume a competitive labour market with homogenous skills, such that the nominal wage rate is the same for all activities. Its growth depends on past inflation and output growth, to mimic an expectation-augmented Phillips curve:

$$w_t = w_{t-1}\left(1 + \nu_{w_1} g_{p_{x_{t-1}}} + \nu_{w_2} g_{va_{t-1}}\right) \quad A26$$

With:

$$g_{p_t} = \frac{p_{x_t} - p_{x_{t-1}}}{p_{x_{t-1}}} \quad A27$$

A1.1.2. Pollution

Emissions are supposed to be embodied in production through an emission intensity ε, that is held constant. As a result, the high-carbon incumbent emits E_t gigatons of CO_2 proportionately to its share of output produced with high carbon capital:

$$E_t = \varepsilon x_{IN_t} \frac{\omega_{IN_t}^H}{\omega_{IN_t}^H + \omega_{IN_t}^L} = \varepsilon x_{IN_t} \frac{\omega_{IN_t}^H}{\omega_{IN_t}} \qquad A28$$

A carbon tax is levied in these emissions given by:

$$T_C = \theta_{c_t} E_t \qquad (A29)$$

Where θ_{c_t} is the time-varying price of a gigaton of CO_2.

A1.1.3. Prices and profits

Prices are determined as a markup on top of unit costs (Lavoie, 2014). Since there is no intermediate consumption, unit costs reduce to labour costs.

$$UC_{\ell_t} = \frac{w_t}{\lambda_{\ell_t}} \qquad (A30)$$

$$UC_{IG_t}^j = \frac{w_t}{\lambda_{IG_t^j}} \qquad (A31)$$

$$UC_{IG_t}^o = \frac{w_t}{\lambda_{IG_t^j}} \qquad (A32)$$

Consumption good sector

I suppose that $\lambda_{IN_t} = \lambda_{CH_t} \forall t$. It follows that $UC_{CH_t} = UC_{IN_t} = UC_{x_t}$. As mentioned above, I also consider that there is no price competition between challengers and incumbents, such that the homogenous consumption good x is sold at the same price whatever the seller:

$$p_{x_t} = (1 + \mu_{x_t}) UC_{x_t} \qquad (A33)$$

With μ_{x_t} an aggregate markup for the whole sector, which evolves as follows:

$$\mu_{x_t} = \mu_{x_{t-1}} + \eta_1 (u_{X_t} - u_X^T) - \eta_2 (\pi_{x_t}^* - \overline{\pi^N}) \qquad (A34)$$

Following Rowthorn (1977), firms first modulate their markup according to the distance between the utilization rate and their desired utilization rate u_X^T. The idea is that in situations close to full employment, firms' monopoly power increases as they do not have to compete for market shares.

On the one hand modulate their markup to reach an exogenous profitability target $\overline{\pi^N}$ writing as follows, with:

$$\pi_{x_t}^* = \frac{\left(\Pi_{IN_t}^N + \Gamma_{IN_t} + \Pi_{CH_t}^N + \Gamma_{CH_t}\right)}{x_t} \qquad A35$$

Π_ℓ^N $\ell \in \{CH, IN\}$ is defined as the net profitability of sector i and Γ_{ℓ_t} is the principal repayment charge of sector ℓ at time t. I apply this correction to allow firms to account for all their capital costs in renewing their markups. Indeed, our accounting definition of net profitability only considers interest charges[13]:

$$\Pi_{\ell_t}^N = \Pi_{\ell_t} - R_{\ell_t} - T_{\ell_t} + r_{D_{t-1}} D_{\ell_{t-1}} + \tau_{\ell_t} \qquad (A36)$$

Where Π_{ℓ_t} is gross operating profits, R_{i_t} is the interest charge, T_{ℓ_t} are total taxes, r_{D_t} the interest rate on deposits of the previous period, $D_{\ell_{t-1}}$ is the amount of deposits held by the firm in the previous period –on which it earns interest and τ_{ℓ_t} are government subsidies. Gross operating profits are defined as follows:

$$\Pi_{i_t} = X_{\ell_t} - W_{\ell_t} \qquad (A37)$$

With $W_{\ell_t} = w_t L_{\ell_t}$, $\ell \in \{CH, IN\}$ the wage bill.

Dividends are paid out of net profits based on a constant payout ratio and are zero if net profits are negative:

$$d_{\ell_t} = \max\left(0, \xi_\ell \Pi_{\ell_t}^N\right) \qquad (A38)$$

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[13] This definition is consistent with usual accounting, which does not report principal repayment in the computation of profits.

The residual forms retained earnings RE_{ℓ_t}, which are used to meet principal repayment and fund current investment expenses.

Investment good sector

Prices are also composed of a markup on top of unit costs, supposed constant across investment and conversion services.

$$p_t^j = \left(1 + \mu_{IG_t}\right) UC_{IG_t}^j, j \in \{H, L\} \tag{A39}$$

$$p_t^o = \left(1 + \mu_{IG_t}\right) UC_{IG_t}^o \tag{A40}$$

The markup in the investment good sector also evolves to target a constant profitability, averaged out across investment goods and services:

$$\mu_{IG_t} = \mu_{IG_{t-1}} + \eta\left(\pi_{IG_{t-1}}^N - \overline{\pi_{IG}^N}\right) \tag{A41}$$

With:

$$\pi_{IG_t}^N = \frac{\Pi_{IG_t}^N}{i_t^{HC} + i_t^{LC} + o_t} \tag{A42}$$

Because the investment good sector does not invest and does not face capital costs, there is no need to correct for principal repayment. Further, because the investment sector does not hold deposits, net profitability reduces to operating surplus corrected for taxes and transfers

$$\Pi_{IG_t}^N = \Pi_{IG_t} - T_{IG_t} + \tau_{IG_t} \tag{A43}$$

And gross operating surplus is given by:

$$\Pi_{IG_t} = p_t^H i_t^H + p_t^L i_t^L + p_t^o o_t - w_t(N_{IG}^H + N_{IG}^L + N_{IG}^o) \tag{A44}$$

All profits are paid in full to households, which are assumed to own the sector.

A1.1.4. Technological penetration and target investment

I assume that investment is purely demand-determined. This choice is motivated by our modelling purpose: introducing a profit motive could prevent sectors from investing enough to meet decarbonisation targets. Firms, given capital intensities, will compute a target capital stock that they will try to reach to meet the demand they expect for the next period.

First, total expected demand is determined as follows:

$$x_t^e = x_t\left(1 + g_{x_t}\right) \qquad (A45)$$

$$g_{x_t} = \frac{(x_t - x_{t-1})}{x_{t-1}} \qquad (A46)$$

I further assume that firms target the same utilisation rate u_x^T. Because capital stocks have the same capital-output ratio, firms can derive an aggregate target for the real capital stock for the next period:

$$\omega_{x_t}^T = \frac{x_t^e}{u_x^T \kappa_x} \qquad (A47)$$

Once this target set, we can determine the target share of low and high-carbon capital $S_{LC_t}^T$. Since the model is meant to simulate existing decarbonisation trajectories, this share is determined based on an exogenous decarbonisation schedule E_t^T. After some manipulation, this yields the following law motion for the target share of low-carbon capital:

$$S_{LC_t}^T = \left(1 - \left(\frac{E_{t+1}^T}{x_{HC_t}}\right)\left(\frac{1 - S_{CH\,t}}{e}\right)\right)^{\zeta} \qquad (A48)$$

Where, E_{t+1}^T is the emission target for the next period, e is the emission intensity of polluting output and $\zeta < 1$ is a parameter calibrated to match more closely emission schedules in each scenario. If $S_{LC_t}^T = 0$, the challenger sector does not emerge.

Once $S_{LC_t}^T$ determined, we can derive the targeted real high-carbon capital stock as follows:

$$\omega_t^{H^T} = \left(1 - S_{LC_t}^T\right)\omega_{x_t}^T \qquad (A49)$$

Incumbent firms will then compare this target to their total high-carbon stock ω_{H_t}:

- If $\omega_t^{H^T} - \omega_t^H > 0$, the incumbent firm formulates a target investment $i_t^{H^T}$ that also makes for the natural depreciation of capital Δ_{H_t}, which is the sum across all vintages of natural depreciation. In that case, target high-carbon investment is given by:

$$i_{IN_t}^{H^T} = \omega_t^{H^T} - \omega_t^H + \Delta_{H_t} \qquad (A50)$$

- If $\omega_t^{H^T} - \omega_{H_t} < 0$, then there is excess high-carbon capital, that the firm may have to scrap. I denote q_t^e the expected stranding based on the targeted high-carbon capital stock. In that case, I assumed that firms make only for total natural depreciation Δ_{H_t}, which is the sum across all vintages of natural depreciation. Target high-carbon investment writes:

$$i_{IN_t}^{H^T} = \Delta_t^H \qquad (A51)$$

In this latter case, firms anticipate a stranding q_t^e they will try to hedge against. To do so, they will try to convert a fraction χ_t^0 of their capital stock. To do so, they first compute the nominal value of the expected stranding Q_t^e (see Annex). Then, they solve this equation for χ_t^0:

$$\chi_t^0 p_t^o \omega_t^H = Q_t^e \qquad (A52)$$

And target the following conversion quantity:

$$o_t^T = \chi_t^o \omega_t^H \qquad (A53)$$

That is, firms redirect the balance sheet cost they expect to the retrofitting of their capital stock. Incumbents do not invest in low-carbon capital to make for natural depreciation of their retrofitted machines:

$$i^{L}_{IN_t} = \Delta_{IN^L_T} \qquad (A54)$$

Once conversion demand is formulated, the challenger invests in low-carbon capital by considering expected stranding and conversion demand:

$$\omega^{T}_{CH_t} = \omega^{T}_{x_t} - \left(\omega^{T}_{H} - o^{T}_{t} - (q^{e}_{t} - o^{T}_{t})\right) - \left(\omega^{L}_{CH_t} + o^{T}_{t}\right) \qquad (A55)$$

$$i^{L^T}_{CH\,t} = \omega^{T}_{CH_t} - \omega_{CH_t} + \Delta^{L}_{CH\,t} \qquad (A56)$$

These investment targets determined; we can define their nominal counterparts:

$$I^{H^T}_{IN_t} = p^{H}_{t} i^{H^T}_{IN_t} \qquad (A57)$$

$$O^{T}_{t} = p^{L}_{t} o_{t} \qquad (A58)$$

$$I^{L^T}_{IN\,t} = p^{L}_{t} i^{L^T}_{IN\,t} \qquad (A59)$$

$$I^{T}_{IN_t} = I^{H^T}_{IN_t} + O^{T}_{t} + I^{L^T}_{IN_t} \qquad (A60)$$

$$I^{L^T}_{CH\,t} = p^{L}_{t} i^{L^T}_{CH\,t} \qquad (A61)$$

A1.1.5. Funding and investment constraints

Investments are funded with past accumulated deposits, current retained earnings, loans and equity emissions.

I assume that firms fund a constant fraction of their planned investment expenses with bank loans:

$$NL^{d}_{\ell_t} = \psi_{\ell} I^{T}_{\ell_t} \qquad (A62)$$

With $\psi_{\ell} = \bar{\psi}\ \forall \ell$

Banks will only accommodate a fraction $\left(1 - \varpi_{\ell_t}\right)$ of this loan demand at each point in time:

$$NL_{\ell_t} = \left(1 - \varpi_{\ell_t}\right) NL^{d}_{\ell_t} \qquad (A63)$$

Firms will also emit equity under the constraint of not reducing their value on the market. That is, firms will emit the minimum amount of security between the one allowing them to target their expected equity price and the gap between desired investment, loan supply and available funds.

$$a_{\ell_t} = a_{\ell_{t-1}} + \max\left(0, min\left(\begin{array}{c} A_{\ell_t} - A_{\ell_{t-1}} - \left(p^e_{a_{\ell_t}} - p_{a_{\ell_{t-1}}}\right)\frac{a_{\ell_{t-1}}}{p^e_{a_{\ell_t}}}, \\ \frac{I^T_{\ell_t} - NL_{\ell_t} - \left(D_{\ell_{t-1}} + RE_{\ell_{t-1}}\right) - \Gamma_{\ell_{t-1}})}{p^e_{a_{\ell_t}}} \end{array}\right)\right) \quad (A64)$$

Where a_{i_t} is the real amount of equity issued by the firm, A_{i_t} the nominal demand for this firm's equity from NBFIs, $p^e_{A_{i_t}}$ expected prices and $p_{A_{i_t}}$ the actual price. Expected prices are determined through adaptive expectations:

$$p^e_{A_\ell} = p^e_{A_{\ell_{t-1}}} + \eta_e\left(p^e_{A_{\ell_{t-1}}} - p_{A_{\ell_{t-2}}}\right) \quad (A65)$$

As usual in SFC modelling, I assume that equity prices clear the market by balancing nominal demand for equity A_{ℓ_t} and real supply of equity a_{ℓ_t}

$$p_{a_{\ell_t}} = \frac{A_{\ell_t}}{a_{\ell_t}} \quad (A66)$$

This results in the following budget constraints:

$$I^c_{CH_t} = RE_{CH_t} + \Delta D_{CH_t} + \Delta a_{CH_t} p_{a_{CH_t}} + NL_{CH_t} - \Gamma_{CH_t} \quad (A67)$$

$$I^c_{IN_t} = RE_{IN_t} + \Delta D_{IN_t} + \Delta a_{IN_t} p_{a_{IN_t}} + NL_{IN_t} - \Gamma_{IN_t} \quad (A68)$$

Where c stands for "constrained" and indicates the maximum amount of investment expenses firms can afford given available internal and external funds. Actual sectoral investments thus write:

$$I_{\ell_t} = \min\left(I^c_{\ell_t}, I^T_\ell\right), \ell \in \{CH, IN\} \quad (A69)$$

If $I^T_{\ell_t} < I^c_{\ell_t}$, firms pocket the residual as deposits. In the case of the incumbent sector, which invests in three different items, constrained high-carbon and low-carbon investment and conversion write as follows:

$$I^H_{IN_t} = I^c_{IN_t}\frac{I^{H^c}_{IN_t}}{I^T_{IN_t}} \quad (A70)$$

$$O_t = I^c_{IN_t} \frac{O^T_t}{I^T_{IN_t}} \quad (A71)$$

$$I^L_{IN_t} = I^c_{IN_t} \frac{I^L_{IN_t}}{I^T_{IN_t}} \quad (A72)$$

Once actual nominal investment expenses are determined, real investment demand is determined by dividing by corresponding prices. Demanded capital I delivered in the next period and corresponds to an additional row in the capital vintage vector $b^j_{i_t}$. Real conversion entails a decrease in the stock of high-carbon capital and an increase in the stock of low-carbon capital of the incumbent sector. High-carbon vintages are converted based on their share in total high-carbon capital. Finally, natural depreciation is always comprised in newly added capital vintages.

Finally, when actual conversion o_t is determined, actual asset stranding can be computed as follows:

$$q_t = q^e_t - o_t \quad (A73)$$

I assume that asset stranding affects in priority the oldest capital vintages. The nominal value of stranded assets Q_t is removed from the balance sheet of the incumbent sector and is modelled as a balance sheet shock.

Total investment $I_t = I_{IN_t} + I_{CH_t}$ defines nominal value added in the investment good sector. Real value added is obtained by deflating with the corresponding price indices.

A1.2 Households

In the model, households consume and save. They hold three assets: bank deposits (D_H), cash (H_H) and NBFI units (U).

Household determine their consumption expenditures based on past consumption (C_{t-1}), expected available income (YD^e_t) and expected wealth, namely (V^e_{t-1}) :

$$C_t = C_{t-1} + \gamma_C(\alpha_{YD} YD^e_t + \beta_V V^e_{t-1}) \quad (A74)$$

With

$$YD_t^e = YD_{t-1}^e - \eta(YD_{t-2}^e - YD_{t-1}) \qquad (A75)$$

$$V_t^e = V_{t-1}^e - \eta(V_{t-2}^e - V_{t-1}) \qquad (A76)$$

Real consumption demand is determined by deflating total expenditures by the price of the consumption good:

$$c_t = \frac{C_t}{p_{x_t}} \qquad (A77)$$

Households hold a constant fractions of their wealth as high-powered money and NBFI units. Deposits are a buffer:

$$H_t = \alpha_{HPM} V_t^e \qquad (A78)$$
$$U_t = \alpha_{HPM} V_t^e \qquad (A79)$$

$$D_{H_t} = D_{H_{t-1}} + YD_t - C_t - \left(H_{H_t} - H_{H_{t-1}}\right) - (U_t - U_{t-1}) \qquad (A80)$$

With YD_t disposable income defined as:

$$YD_t = W_t + i_{D_{t-1}} D_{H\,t-1} + F_t + \Pi_{IG_t} + \Pi_{B_t} + \tau_{H_t} - T_{H_t} \qquad (A81)$$

Where W_t is the economy-wide wage bill equal to $W_{CH_t} + W_{IN_t} + W_{IG_t}$, F_t is financial incpme from non-bank financial institutions, Π_{B_t} bank profits, Π_{IG_t} profits from the investment good sector, τ_{H_t} government transfers to households and T_{H_t} household taxes.

A1.3 Financial sector

A1.3.1. Banks

Banks collect deposits, extend loans, buy government bonds and take on central bank advances to close their balance sheets. They also collect deposits from firms, households and NBFIs. They finally fix interest rates, performing price rationing and implement quantity rationing when faced with loan demand.

A.1.3.1.1 Interest rates, credit rationing and defaults

Interest rates consist in a mark-up on top of the risk-free interest rate, which is fixed by the central bank as usual in SFC modelling (Caiani et al., 2012; Dafermos et al., 2017b; Godley and Lavoie, 2007; Lavoie and Daigle, 2011):

$$r_{L_{\ell_t}} = r_{cb} + \mu_{\ell_t} \qquad (A82)$$

Mark-ups are sector-specific ($\ell = \{IN, CH\}$) and are composed of three components:

$$\mu_\ell = \bar{\mu}_{bank} + \sigma_\ell + \sigma_{lev}\left(lev_{\ell_t} - \overline{lev}\right) \qquad (A83)$$

With $\bar{\mu}$ a minimum profit mark-up on top of the risk-free interest rate and σ_i sector-specific markups, held constant. σ_{lev} is a reaction to observed leverage lev_{ℓ_t} relative to a "normal" leverage $\overline{lev}$ in each sector, defined as follows:

$$lev_{\ell_t} = \frac{L_i}{D_{\ell_t} + \Omega^H_{\ell_t} + \Omega^L_{\ell_t}} \qquad (A84)$$

Credit constraint is based on the financial health of banks and the borrowing firm:

$$\varpi_{\ell_t} = \frac{1}{1 + \varpi_0 \exp\left(\varpi_1 - \varpi_2 dsr_{\ell_t} + \varpi_3 (CAR_{t-1} - \overline{CAR})\right)} \qquad (A85)$$

Where:

$$dsr_{\ell_t} = \frac{Kcost_{\ell_t}}{\Pi_{\ell_t}} \qquad (A86)$$

And:

$$CAR = \frac{OF_t}{L_{IN_t} + L_{CH_t}} \qquad (A87)$$

With OF_t the Banks' own funds and L_{ℓ_t} the total loan stock outstanding for sector ℓ, defined below.

Default probabilities write as follows

$$\varphi_{NPL_{\ell_t}} = \frac{1}{1 + \varphi_0 \exp(\varphi_1 - \varphi_2 \iota_{\ell_t})} \quad (A88)$$

With ι_{ℓ_t} the ratio of all cash outflows to all cash inflows of a given sector:

$$\iota_{\ell_t} = \frac{\Xi_{\ell_t} + T_{\ell_t} + d_{\ell_t} + W_{\ell_t}}{X_{\ell_t} + NL_{\ell_t} + \tau_{\ell_t} + p_{A_{\ell_t}}(a_{\ell_t} - a_{\ell_{t-1}})} \quad A89$$

With Ξ_{ℓ_t} total capital cost. Logistic shapes for default probabilities and credit rationing probabilities are well-established functional forms in SFC and agent-based modelling (Dafermos et al., 2017b). Logistic shapes (under the form of logit econometric models) also have empirical validity, as they are widely used to estimate default propensities (Allen et al., 2020; Cathcart et al., 2020) and credit rationing (Becchetti et al., 2011; Rahji and Fakayode, 2009). To keep things simple, I limit the number of arguments for each function to those employed in Dafermos et al. (2017).

Symmetrically to capital stocks in the consumption good sectors, I model loan vintages, which allow for a realistic representation of principal repayment, capital costs and of loan maturity. Banks' loan assets on firm ℓ are represented as a vector Z_t writing:

$$Z_{\ell_t} = \begin{pmatrix} \max\left(0, l_\ell^0 - \sum_{n=1}^{t} \gamma_{\ell_n}^0\right)\left(1 - \varphi_{NPL_{\ell_t}}\right) \\ \max\left(0, l_\ell^1 - \sum_{n=2}^{t} \gamma_{\ell_n}^1\right)\left(1 - \varphi_{NPL_{\ell_t}}\right) \\ \dots \\ l_i^t \end{pmatrix} \quad A90$$

With l_ℓ^s, $s \in [|1, t|]$ the amount of the loan vintage at its time of extension to firm ℓ and $\gamma_{\ell_n}^s$ the principal repayment flow for loan vintage s to firm i paid at time $n \in [|s+1, t|]$ (loans being repaid from the period following their issuance onwards). I assume finally that defaults $\varphi_{NPL_{\ell_t}}$ are distributed homogenously amongst past loans. When the loan principal is repaid, it is erased from the bank's books.

The total loan stock for a given sector ℓ obtains by summing all components of the Z_{ℓ_t} vector at each time step. The total loan stock for the whole economy L_t is the sum over all sectors.

Loans of different vintages have the same maturity M. Following a well-established formula for loan repayment with constant annuity, the annual capital cost corresponding to the vintage taken at time s by firm ℓ, $\Xi_{i_t}^{s}$, which includes both repayment and interest:

$$\Xi_{\ell_t}^{s} = \frac{\left(r_{L_{\ell_s}}\left(1 + r_{L_{\ell_s}}\right)^{M}\right)}{\left(1 + r_{L_{\ell_s}}\right)^{M} - 1} l_{\ell}^{s} \qquad A91$$

With $l_{\ell}^{s} = NL_{\ell_s}$, that is the actual loan amount extended to firm ℓ at time s and $r_{L_{\ell_s}}$ the interest rate on this loan contract. The total capital cost is constant.

The interest paid on this precise vintage evolves with principal repayment and reaches zero when the loan reaches maturity. Correcting again for non-performing loans, it writes:

$$\rho_{i_t}^{s} = r_{L_{i_s}} \max\left(0, \left(l_i^{s} - \sum_{n=s+1}^{t} \gamma_{i_n}^{s}\right)\right)\left(1 - \varphi_{NPL_{i_t}}\right) \qquad A92$$

The principal repayment is the residual and writes:

$$\gamma_{i_t}^{s} = \Xi_{i_t}^{s} - \rho_{i_t}^{s} \qquad (A93)$$

Hence, the interest part of the capital cost decreasing with time and the repayment charge will increase. Bu accounting identity, total loan stocks follow the law of motion:

$$L_{\ell_t} = L_{\ell_t} + NL_{\ell_t} - \Gamma_{\ell_t} - NPL_{\ell_t} \qquad (A94)$$

With NPL_{ℓ_t} is the sum of all default loans on all vintages for sector ℓ.

A.1.3.1.2 Regulatory obligations

Banks must hold a certain fraction of their deposits as high-powered money:

$$HPM_{B_t} = \eta_{B_{Dep}} D_t \qquad (A95)$$

With $D_t = D_{H_t} + D_{NBFI_t} + D_{CH_t} + D_{IN_t}$ the total amount of deposits.

Banks balance sheet is closed by demanding advances central bank J_{CB}, like in Dafermos et al. (2017a):

$$J_{CB}^{d} = J_{CB_{t-1}} + L_t - L_{t-1} - HPM_{B_t} - HPM_{B_{t-1}} - (D_t - D_{t-1}) - RE_{B_t} + GB_{B_t} - GB_{B_{t-1}} \quad (A96)$$

Where D_t is the total loan stock at time t and GB_{B_t} the amount of government bonds held by banks.

Banks pay interests on advances.

I finally assume as in Dafermos et al. (2017b), that if banks fall below a minimum capital adequacy ratio CAR_{min}, the government steps in to bail banks out. The bailout Θ_{B_t}takes the form of a capital transfer directed to own funds.

A.1.3.1.3 Bank profits and retained earnings

Bank profits write as follows:

$$\Pi_{B_t} = R_{CH_t} + R_{IN_t} + r_{B_{t-1}} GB_{B_{t-1}} - r_{D_{t-1}} D_{t-1} - r_{CB} J_{CB_{t-1}} \quad (A97)$$

Where r_{CB} is the interest on central bank advances.

Dividends d_{B_t} are a constant fraction of profits:

$$d_{B_t} = \xi_B \Pi_{B_t} \quad (A98)$$

And retained earnings write:

$$RE_{B_t} = (1 - \xi_B)\Pi_{B_t} \quad (A99)$$

Banks will use part of their retained earnings to buy make for non-performing loans that harm their own funds and target a constant capital adequacy ratio. Own funds write as follows:

$$OF_t = OF_{t-1} - NPL_t + \alpha_{RE_{B_t}} RE_{B_t} + \Theta_{B_t} \quad (A100)$$

With

$$\alpha_{RE_{B_t}} = \min\left(1, \max\left(0, \frac{\overline{CAR} * L_t - OF_{t-1} + NPL_t}{RE_{B_t}}\right)\right) \quad (A101)$$

Which is defined to target $\overline{CAR}$, a normal capital adequacy ratio. Retained earnings that are not used to make for non-performing loans are used to purchase government bonds to avoid accumulating dormant capital, on top of a fraction of deposits:

$$GB_B^d = \alpha_D D_t + \left(1 - \alpha_{RE_{B_t}}\right) RE_{B_t} \tag{A102}$$

With such behavioural equations, banks always manage to reach their target capital adequacy ratio, except when retained earnings are insufficient.

A1.3.2. Non-bank financial institutions

The non-bank financial sector mimics funds providing firms with market finance. They plainly are financial intermediaries that take some of household savings to invest it into equities and government bonds, greatly inspired from Burgess et al.'s (2016) treatment of insurance and pension funds. Pension funds sell fund units U_t to households at a constant price and use the collected savings to three types of financial assets: government bonds (GB_{NBFI_t}), equity from incumbents (A_{IN_t}) and equity from challengers $\left(A_{CH_t}\right)$. They also hold deposits $\left(D_{NBFI_t}\right)$ on which they earn interest. If NBFI fall short of rolling funds, the government step in to fill the gap through a transfer Θ_{NBFI_t}. NBFI collect financial income from their assets (dividends and interests on government bonds), which constitute their profits:

$$\Pi_{NBFI_t} = r_{B_{t-1}} B_{NBFI_{t-1}} + d_{IN_t} + d_{CH_t} + r_{D_{t-1}} D_{NBFI_{t-1}} \tag{A103}$$

I assume that NBFIs modulate their retained earnings to target a constant deposit-to-profit ratio α_{NBFI}^{Π}, without accounting for a potential bailout. Retained earnings cannot go beyond the current profit flow. After some manipulation, the law of motion writes:

$$RE_{NBFI_t} = \min\left(\begin{matrix} \Pi_{NBFI_t}, \alpha_{NBFI}^{\Pi} \Pi_{NBFI_t} - D_{NBFI_{t-1}} - (U_t - U_{t-1}) + \\ \left(p_{A_{IN_t}}\left(a_{IN_t} - a_{IN_{t-1}}\right) + p_{A_{HCH}}\left(a_{CH_t} - a_{CH_{t-1}}\right) + B_{NBFI_t} - B_{NBFI_{(t-1)}}\right) \end{matrix}\right) \tag{A104}$$

With this formula, nothing forbids retained earnings to be negative. In that case, NBFIs dissave from their deposits to hand out a higher financial income F_t to households:

$$F_t = \Pi_{NBFI_t} - RE_{NBFI_t} \tag{A105}$$

Asset allocation is determined through a Tobin portfolio choice model (Godley and Lavoie, 2007):

$$\begin{pmatrix} GB_{NBFI_{t-1}} \\ A_{IN_t} \\ A_{CH_t} \end{pmatrix} = \left(\begin{pmatrix} \lambda_{0_t^{BG}} \\ \lambda_{0_t^{IN}} \\ \lambda_{0_t^{CH}} \end{pmatrix} + \begin{pmatrix} \lambda_{11} & \lambda_{12} & \lambda_{13} \\ \lambda_{21} & \lambda_{22} & \lambda_{23} \\ \lambda_{31} & \lambda_{32} & \lambda_{33} \end{pmatrix} \begin{pmatrix} h^e_{BG_t} \\ h^e_{IN_t} \\ h^e_{CH_t} \end{pmatrix} \right) \upsilon_t \qquad (A106)$$

Deposits are a buffer stock:

$$D_{NBFI_t} = D_{NBFI_{t-1}} + U_t - U_{t-1} - \left(p_{A_{IN_t}} \left(a_{IN_t} - a_{IN_{t-1}} \right) + p_{A_{HCH}} \left(a_{CH_t} - a_{CH_{t-1}} \right) + B_{NBFI_t} - B_{NBFI_{(t-1)}} \right) + \Theta_{NBFI_t} \qquad (A107)$$

υ_t stands for the total funds available for asset purchases, defined as:

$$\upsilon_t = \upsilon_{t-1} + U_t - U_{t-1} + \alpha_{D_{NBFI}} D_{NBFI_{t-1}} \qquad (A108)$$

NBFIs use the funds collected through the sale of Units to fund asset purchases, plus a constant fraction of their accumulated deposits α_{NBFI} to avoid accumulating unnecessarily dormant capital

h^e_{it}'s ($i \in \{BG, IN, CH\}$ are expected returns on assets, which depend on dividends and expected capital gains:

The $\lambda_{j,k}$, $(j,k) \in [|1,3|] \times [|1,3|]$ are reaction parameters respecting Tobin's condition (Godley and Lavoie, 2007). The basic Tobin model does not easily make for structural change through the assumption of constant equilibrium portfolio shares λ_0. I therefore give these parameters the following law of motions:

$$\lambda_{0_t^{BG}} = \overline{\lambda_0^{BG}} \qquad (A109)$$

$$\lambda_{0_t^{IN}} = \left(1 - \overline{\lambda_0^{BG}}\right) S_{IN_t} \qquad (A110)$$

$$\lambda_{0_t^{BG}} = \left(1 - \overline{\lambda_0^{BG}}\right) S_{CH_t} \qquad (A111)$$

Fixing the structure share of government bond, the structural share in NBFI portfolios of the two consumption-good sub-sectors evolves with their market share.

Finally, capital gains write:

$$CG_{NBFI_t} = A_{IN_{t-1}}\left(p_{A_{IN_t}} - p_{A_{IN_{t-1}}}\right) + a_{CH_{t-1}}\left(p_{A_{CH_t}} - p_{A_{CH_{t-1}}}\right) \quad (A112)$$

They are imputed to households' wealth, since who own the units that used to purchase assets

A1.4 Central bank

The central bank fixes the interest rate and charges it on advances. It is held fixed throughout:

$$r_{CB_t} = \overline{r_{CB}} \quad (A113)$$

The central bank provides advance on demand (which is a redundant equation, typical of SFC models (Godley & Lavoie, 2017):

$$A^s = A^d \quad (A114)$$

And the central bank purchases the residual amount of government bonds if it is positive, to ensure equality being bond supply and bond demand:

$$GB_{CB_t} = GB_{CB_{t-1}} + \begin{cases} GB^s_{G_t} - GB^s_{G_{t-1}} - GB^d_{B_t} - GB^d_{B_{t-1}} - GB^d_{G_{NBFI_t}} \\ -GB^d_{G_{NBFI_t}}\ if\ \Delta B^s_{G_t} - \Delta B^d_{G_{B_t}} - \Delta B^d_{G_{NBFI_t}} > 0 \\ 0\ otherwise \end{cases} \quad (A115)$$

Central bank profits write:

$$\Pi_{CB_t} = r_{CB_t} J_{CB_{t-1}} + i_{B_G} GB_{cb_{t-1}} \quad (A116)$$

The central bank pays them in full to the government

A1.5 Government

The government spends in consumption goods, manages taxes and transfers and rescues the banking sector through a contingent bailout. Along transition paths, the government levies a carbon tax, whose proceeds are not recycled.

I assume that the government spends a constant proportion of last-period nominal value-added:

$$G_t = \gamma_{Gov_t} VA_{t-1} \qquad (A117)$$

Real government consumption writes:

$$g_t = \frac{G_t}{p_{x_t}} \qquad (A118)$$

With:

$$\gamma_{Gov_t} = \gamma_{Gov_{t-1}} + \eta_{\gamma_{Gov}} \left(\frac{NLP_{Gov_{t-1}}}{VA_t} - \overline{\frac{NLP_{Gov}}{VA}} \right) \qquad (A119)$$

That is, the government targets a deficit as fraction of GDP, denoted by $\overline{\frac{NLP_{Gov}}{VA}}$.

The government levies other taxes on household available income and on the gross profits of the three non-financial firms of the model: investment good, challengers and incumbents.

$$T_{H_t} = \theta_H YD_t \qquad (A120)$$
$$T_{\ell_t} = \theta_\ell \Pi_{\ell_t}, \ell \in \{IG, CH\} \qquad (A121)$$
$$T_{HC_t} = \theta_{HC} \Pi_{HC_t} + \theta_{c_t} E_t \qquad (A122)$$

Incumbents also pay a carbon tax T_C proportional to emissions E_t at a rate θ_{c_t}.

$$T_t = T_{H_t} + T_{IG_t} + T_{CH_t} + T_{IN_t} + T_{C_t} \qquad (A123)$$

The tax receipt is split between subsidies to producers and households. I define total subsidies as:

$$\tau_t = \alpha_\tau VA_{t-1} \qquad (A124)$$

With $\alpha_\tau = 0.1$ and:

$$\tau_{H_t} = \frac{\alpha_\tau VA_{t-1}}{2} \qquad (A125)$$
$$\tau_{IG_t} = 0 \qquad (A126)$$

$$\tau_{IN_t} = S_{IN_t}\frac{\alpha_\tau VA_{t-1}}{2} \quad (A127)$$

$$\tau_{CH_t} = \left(1 - S_{IN_t}\right)\frac{\alpha_\tau VA_{t-1}}{2} \quad (A128)$$

The central bank pays all its profits Π_{CB_t} to the government.

Finally, if the capital adequacy ratio of banks falls below a threshold CAR_{min}, the government can optionally effectuate a capital transfer to the banking sector to avoid a financial crash.

The government funds its deficits by emitting bonds:

$$\Delta GB_t^s = G_t + \tau_t + i_{GB}GB_{t-1}^s - T_t - \Pi_{CB} + \Theta_{NBFI_t} + \Theta_{B_t} \quad (A129)$$

Where GB_t is the total amount outstanding of government bonds at time t. I assume, also to keep things simple, that government bonds are perpetuities, hence that there is no principal repayment. The interest rate on bonds is constant and so is their price.

I also restrict government debt B_G to be always positive. If $GB_t < 0$, I impose $GB_t = 0$ and assume that the government pays the excess to households as transfers.

A1.6 Accounting

I finish by presenting key accounting identities.

A1.6.1. Values-Added

$$\begin{aligned} VA_t &= C_t + I_t + O_t + G_t = VA_{IN_t} + VA_{CH_t} + VA_{IG_t} \\ &= WB_{IN_t} + WB_{CH_t} + WB_{IG_t} + \Pi_{IN_t} + \Pi_{CH_t} + \Pi_{IG_t} \end{aligned} \quad (A130)$$

$$va_t = c_t + i_t + g_t = va_{IN_t} + va_{CH_t} + va_{IG_t} \quad (A131)$$

A1.6.2. Net-lending positions

Households

$$NLP_{H_t} = YD_t - C_t = D_{H_t} - D_{H_{t-1}} + H_{H_t} - H_{H_{t-1}} + U_t - U_{t-1} \qquad (A132)$$

Challengers

$$NLP_{CH_t} = RE_{CH_t} - I_{CH_t} = \left(D_{CH_t} - D_{CH_{t-1}}\right) - \left(L_{CH_t} - L_{CH_{t-1}}\right) - p_{A_{CH_t}}\left(a_{CH_t} - a_{CH_{t-1}}\right) \qquad (A133)$$

Incumbents

$$NLP_{CH_t} = RE_{IN_t} - I_{IN_t} = \left(D_{IN_t} - D_{IN_{t-1}}\right) - \left(L_{IN} - L_{IN_{t-1}}\right) - p_{A_{IN_t}}\left(a_{IN_t} - a_{IN}\right) \qquad (A134)$$

Banks

$$\begin{aligned} NLP_{B_t} &= RE_{B_t} + \Theta_B \\ &= (L_t - L_{t-1}) + \left(GB_{B_t} - GB_{B_{t-1}}\right) + \left(H_{B_t} - H_{B_{t-1}}\right) - \left(J_{CB_t} - J_{CB_{t-1}}\right) - (D_t - D_{t-1}) \end{aligned} \qquad (A135)$$

NBFI

$$\begin{aligned} NLP_{NBFI_t} &= RE_{NBFI_t} + \Theta_{NBFI} \\ &= U_t - U_{t-1} - \begin{pmatrix} D_{NBFI_t} - D_{NBFI_{t-1}} + p_{A_{IN_t}}\left(a_{IN_t} - a_{IN}\right) \\ + p_{A_{CH_t}}\left(a_{CH_t} - a_{CH_{t-1}}\right) + GB_{NBFI_t} - GB_{NBFI_{t-1}} \end{pmatrix} \end{aligned} \qquad (A136)$$

Government

$$NLP_{G_t} = T_t + \Pi_{CB_t} - G_t - \tau_t - r_{GB} GB_{t-1} - \Theta_{NBFI_t} - \Theta_{B_t} = GB_t - GB_{t-1} \qquad (A137)$$

Central Bank

$$\begin{aligned} NLP_{CB_t} &= 0 = r_{GB} GB_{CB_{t-1}} + i_{CB} J_{CB_{t-1}} - \Pi_{CB_t} \\ &= \left(GB_{CB_t} - GB_{CB_{t-1}}\right) + \left(J_{CB_t} - J_{CB_{t-1}}\right) - (H_t - H_{t-1}) \end{aligned} \qquad (A138)$$

By virtue of stock-flow consistencies, all net lending positions sum up to zero.

A1.6.3. Wealth

Households

$$V_{H_t} = D_{H_t} + H_{H_t} + U_t + OF_t = D_{H_{t-1}} + OF_t - OF_{t-1} + YD_t - C_t \qquad (A139)$$

Incumbents

$$V_{IN_t} = D_{IN_t} + \Omega_{IN_t} - L_{IN_t} - A_{IN_t} \qquad (A140)$$

Challengers

$$V_{CH_t} = D_{CH_t} + \Omega_{CH} - L_{CH_t} - A_{CH_t} \qquad (A141)$$

NBFIs

$$V_{NBFI_t} = D_{NBFI_t} + A_{IN_t} + A_{CH} - U_t \qquad (A142)$$

A1.7 Stock-Flow Consistency Tables

A1.7.1. Transaction-Flow Matrix

		Households	Incumbent Firms		Challenger Firms		Investment Good Firms	Banks		NBFI		Government	Central Bank	Sum
	Flow	Current	Current	Capital	Current	Capital	Current	Current	Capital	Current	Capital	Current	Current	
Transactions	Consumption													0
	Households	$-C$	$+C_{IN}$		$+C_{CH}$									0
	Government		$+G_{IN}$		$+G_{IN}$							$-G$		0
	Investment			$-I_{IN}$		$-I_{CH}$	$+I$							0
	Conversion			$-O$			$+O$							0
Value-Added			$[VA_{IN}]$		$[VA_{CH}]$		$[VA_{IG}]$							
Primary Income Distribution	Wages	$+WB$	$-WB_{IN}$		$-WB_{CH}$		$-WB_{IG}$							0
	Gross Profits		$[\Pi_{IN}]$		$[\Pi_{CH}]$		$[\Pi_{IG}]$							0
Secondary Income Distribution	Taxes	$-T_H$	$-T_{IN}-T_C$		$-T_{CH}$		$-T_{IG}$					$+T$		0
	Transfers	$+\tau_H$	$+\tau_{IN}$		$+\tau_{CH}$		$+\tau_{IG}$					$-\tau$		0
Financial payments	Interests													
	Deposits	$+r_D D_{H_{-1}}$	$+r_D D_{IN_{-1}}$		$+r_D D_{CH_{-1}}$			$+r_D D_{-1}$		$+r_D D_{NBFI_{-1}}$				0
	Loans		$-R_{IN}$		$-R_{CH}$			$+R$						0
	Bonds							$+r_{GB} GB_{B_{-1}}$		$+r_{GB} GB_{NBFI_{-1}}$		$-r_{GB} GB_{-1}$	$+r_{GB} GB_{BC_{-1}}$	0
	Advances							$-J_{CB_{-1}}$					$+r_{J_{CB}} J_{CB_{-1}}$	0
	Dividends	$+d_{IG}+d_B$	$-d_{IN}$		$-d_{CH}$		$-d_{IG}$	$-d_B$		$+d_{IN}+d_{CH}$				0
	Financial Income	$+F$								$-F$				0
	Contingent Bailouts								$+\Theta_B$		$+\Theta_{NBFI}$	$-\Theta_B-\Theta_{NBFI}$		0
Disposable income		$[YD]$												
Retained Earnings			$-RE_{IN}$	$+RE_{IN}$	$-RE_{CH}$	$+RE_{CH}$		$-RE_B$	$+RE_B$	$-RE_{NBFI}$	$+RE_{NBFI}$			
Net lending position		$-NLP_H$		$-NLP_{IN}$		$-NLP_{CH}$			$-NLP_B$		$-NLP_{NBFI}$	$-NLP_G$	$-NLP_{CB}$	
Flow-of-Funds	High-Powered Money	$+(H_H-H_{H_{-1}})$							$+(H_B-H_{B_{-1}})$				$-\ H-H_{-1}$	0
	Deposits	$-(D_H-D_{H_{-1}})$		$-(D_{IN}-D_{IN_{-1}})$		$-(D_{CH}-D_{CH_{-1}})$			$+\ D-D_{-1}$		$-(D_{NFBI}-D_{NBFI_{-1}})$			
	New Loans			$+NL_{IN}$		$+NL_{CH}$			$-NL$					0
	Principal Repayment			$-\Gamma_{IN}$		$-\Gamma_{CH}$			$+\Gamma$					0
	Bonds								$-(GB_H-GB_{H_{-1}})$		$-(GB_H-GB_{H_{-1}})$	$+\ GB-GB_{-1}$	$-(GB_{CB}$ $-GB_{CB_{-1}})$	0
	Equity			$+p_{A_{IN}}(a_{IN}-a_{IN_{-1}})$		$+p_{A_{IN}}(a_{IN}$ $-a_{IN_{-1}})$					$-p_{A_{CH}}\ a_{CH}-a_{ICH}$ $-\ +p_{A_{IN}}(a_{IN}-a_{IN_{-1}})$			0
	Advances								$+(J_{CB}-J_{CB_{-1}})$				$-(J_{CB}-J_{CB_{-1}})$	0
Sum		0	0	0	0	0	0	0	0	0	0	0	0	0

A1.7.2. Balance sheet matrix

	Asset	Households	Incumbents	Challengers	Investment good	Banks	NBFIs	Government	Central Banks	Sum
Balance sheet	High-carbon capital		$+\Omega_{IN}^{HC}$							$+\Omega_{IN}^{HC}$
	Low-carbon capital		$+\Omega_{IN}^{LC}$	$+\Omega_{CH}^{LC}$						$+\Omega_{IN}^{LC}+\Omega_{CH}^{LC}$
	High-Powered Money	$+H_H$				$+H_B$			$-H$	0
	Units	$+U$					$-U$			0
	Deposits	$+D_H$	$+D_{IN}$	$+D_{CH}$		$-D$	$+D_{NBFI}$			0
	Loans		$-L_{IN}$	$-L_{CH}$		$+L$				0
	Bonds					$+GB_B$	$+GB_{NBFI}$	$-GB$	$+GB_{CB}$	0
	Advances					$-J_{CB}$			$+J_{CB}$	0
	Equity		$-A_{IN}$	$-A_{CH}$			$+A_{IN}+A_{CH}$			0
	Own Funds	$+OF$				$-OF$				0
Revaluation Matrix	Non-performing loans		$+NPL_{IN}$	$+NPL_{CH}$		$-NPL$				0
	Equity		$+a_{IN}\left(p_{A_{IN}}-p_{A_{IN_{t-1}}}\right)$	$+a_{CH}\left(p_{A_{CH}}-p_{A_{CHN_{t-1}}}\right)$			$-a_{IN}\left(p_{A_{IN}}-p_{A_{IN_{t-1}}}\right)$- $a_{CH}\left(p_{A_{CH}}-p_{A_{CHN_{t-1}}}\right)$			0
	Asset Stranding		$-Q$							$-Q$
	Own funds	$+OF-OF_{-1}$				$-OF-OF_{-1}$				0
Net Worth		$-V_H$	$-V_{IN}$	$-V_{CH}$	0	0	$-V_{NBFI}$	0	0	$+\Omega_{IN}^{LC}+\Omega_{CH}^{LC}++\Omega_{IN}^{HC}-Q$

A2. NGFS 2021 Vintage

Starting with a description of the scenarios, I follow by a display of the results for the NGFS's 2021 scenario vintage for the same metrics as in the body of the article (Incumbents' default probability and equity price, Banks' CAR and NBFI deposits). As can be seen, results are in line with those of the 2020 scenario.

Figure A2-1 – NGFS 2021 Scenario Description

		Physical risk	Transition risk			
Category	**Scenario**	**Policy ambition**	**Policy reaction**	**Technology change**	**Carbon dioxide removal**	**Regional policy variation+**
Orderly	Net Zero 2050	1.5°C	Immediate and smooth	Fast change	Medium use	Medium variation
	Below 2°C	1.7°C	Immediate and smooth	Moderate change	Medium use	Low variation
Disorderly	Divergent Net Zero	1.5°C	Immediate but divergent	Fast change	Low use	Medium variation
	Delayed transition	1.8°C	Delayed	Slow/Fast change	Low use	High variation
Hot House World	Nationally Determined Contributions (NDCs)	~2.5°C	NDCs	Slow change	Low use	Low variation
	Current Policies	3°C+	None – current policies	Slow change	Low use	Low variation

Colour coding indicates whether the characteristic makes the scenario more or less severe from a macro-financial risk perspective^

- Lower risk (blue)
- Moderate risk (yellow)
- Higher risk (pink)

Borrowed from NGFS (2021). NB: The Delayed-Action scenario introduces a brisk shift in climate policy from the Current Policy Scenario, as opposed to that of the 2020 vintage, which introduced climate policies from the NDC scenarios.

Figure A2-2 – 2021 Vintage – Transition risk realisations

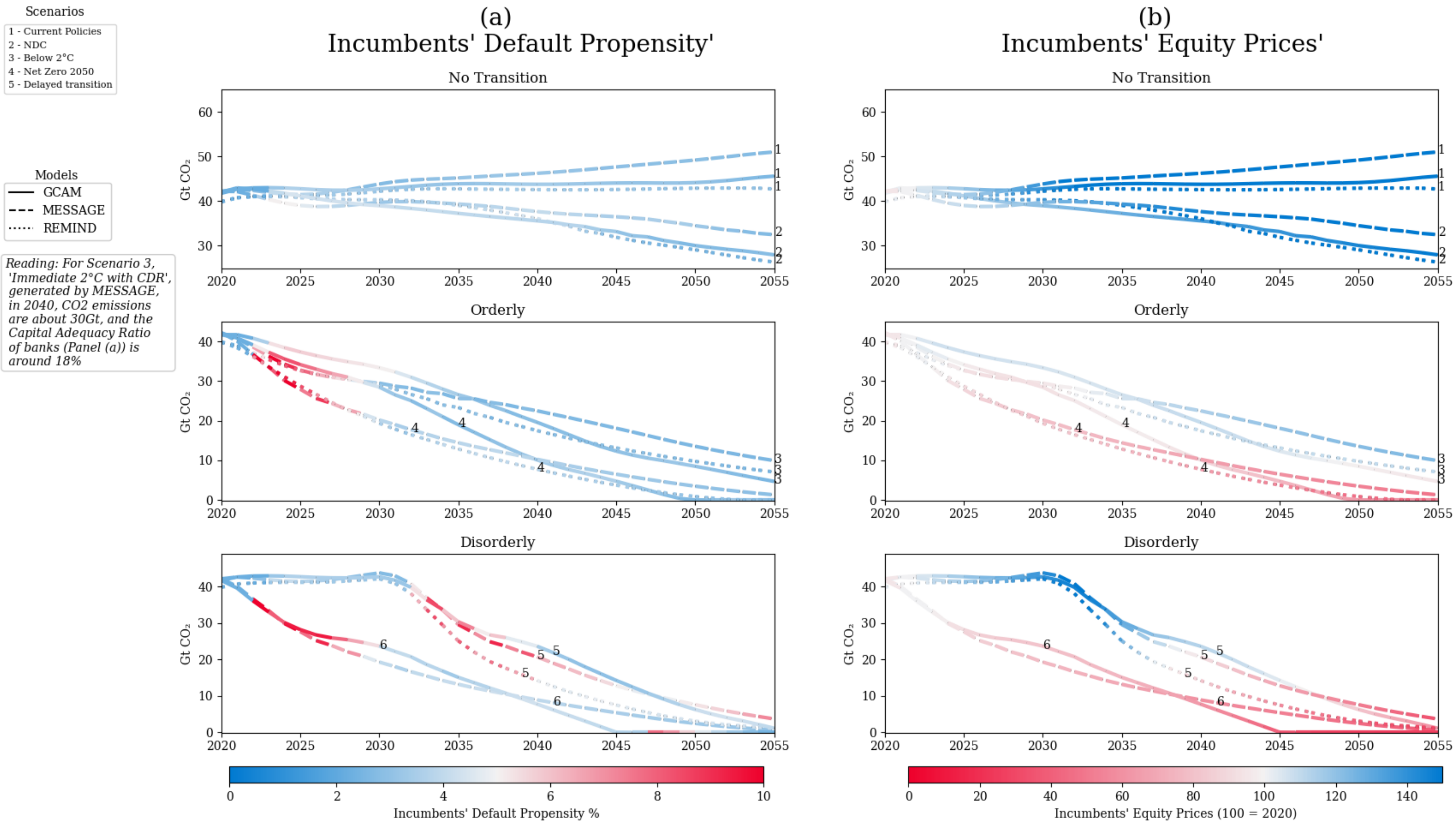
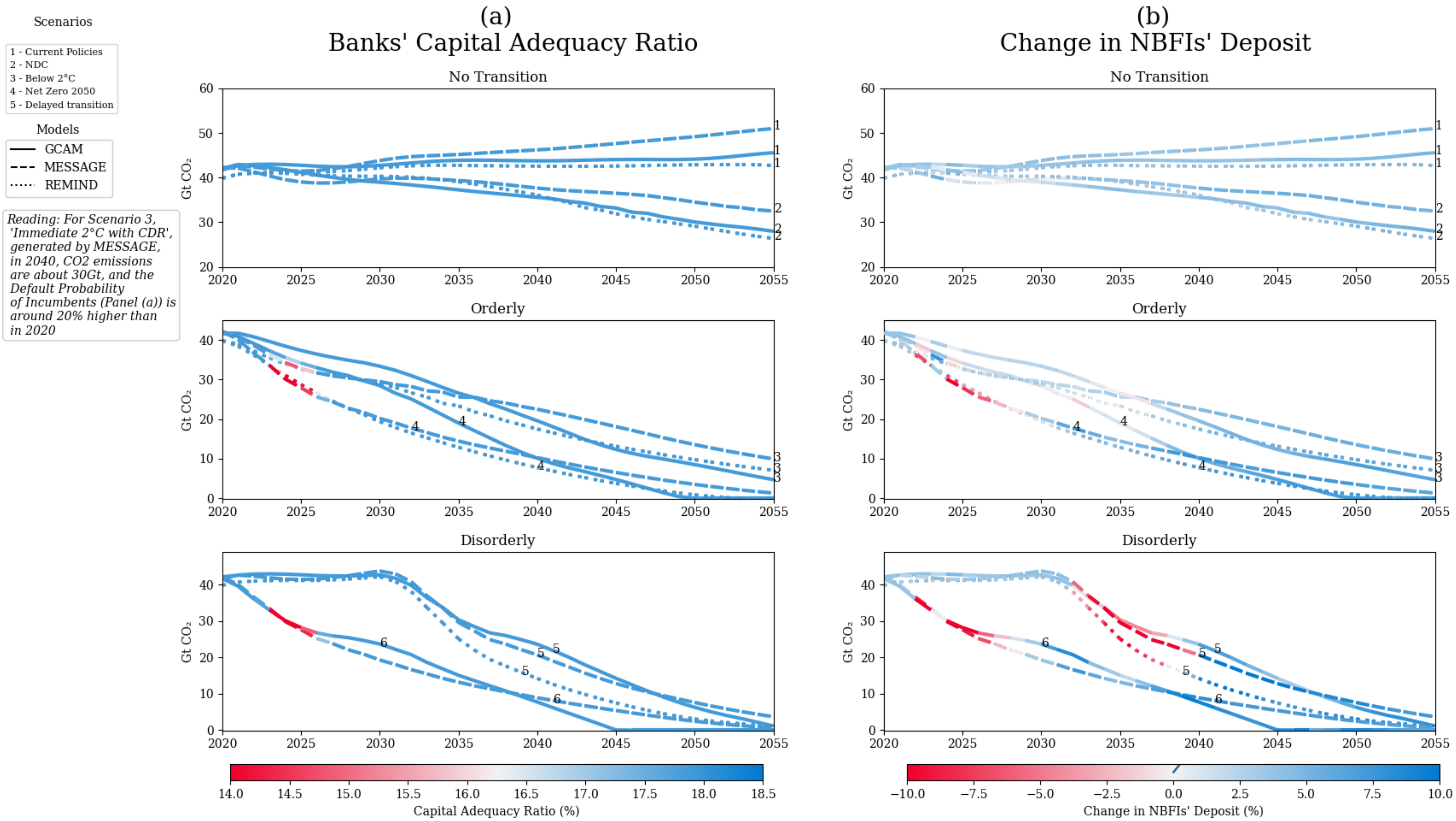


Figure A2-4 – 2021 Vintage – Impact on Financial Companies (Vulnerability)



A3. Calibration Tables

Table A3.1 – Target values for endogenous before the start of the transition

220	Description	Target Value	Reached Value
VA	Nominal GDP	8761 (World Bank, 2022)	8737
ω_{HC}	High-Carbon capital stock (total capital stock in 2019)	22632* (WIOD, 2016)	21907
g_{va}	Real value-added growth	Around 2.4% (World Bank, 2022)	2.36%
g_{p_x}	Inflation Rate	Around 2% (World Bank, 2022)	1.95%
$\frac{WB}{VA}$	Wage Share	49% (WIOD ,2016)	49.1%
CAR	Bank's Capital Adequacy Ratio	18% (ECB, 2020)	18%
lev_{IN}	Leverage Ratio of Incumbents (Whole Economy in 2020)	45% (Consistent with US and European data (Ferrari and Antonecchia, 2018; Graham et al., 2014))	46%
φ_{NPL}	Average default propensity	2.48% (World Bank, 2022)	2.28%

ϖ_{IN_t}	Credit constraint on incumbents	1-3% (Reasonable values)	2.68%
$\lambda_{i,i} \in \{IN, CH, K_H, L_H\}$	Labour productivities except conversion	4 (WIOD, 2016)	4.32
λ_o	Labour productivity for conversion	7 (Reasonable range of values)	7.21
$\frac{NLP_G}{VA}$	Government deficit (% GDP)	1.8% (Word Bank, 2022)	1.6%

*

Table A3-2 – Parameters

Parameter	Description	Value	Justification/Source
ν_{w_1}	Sensitivity of nominal wage growth to past CPI inflation	0.665	Calibrated to reach inflation around 2% in baseline (OECD, 2022)
ν_{w_2}	Sensitivity of nominal wage growth to past growth	1.1	Calibrated to reach inflation around 2% in baseline (OECD, 2022)
ν_{λ}	Sensitivity of productivity growth value-added growth	0.825	Calibrated based on Dafermos et al.'s (2017) estimate
ν_{u}	Sensitivity of markup to drift from target utilisation rate	0.04	Calibrated to reach a 2% inflation rate on average over baseline (OECD, 2022)
δ_L	Depreciation rate – Low-carbon capital	0.05	Reasonable range of values
δ_H	Depreciation rate – High-carbon capital	0.05	Reasonable range of values
r_{GB}	Interest rate on government bonds	0.02	Average on country data (World Bank)
r_D	Interest rate on deposits	0.02	Average on country data (World Bank)
r_{CB}	Interest rate on central bank advances	0.01	Early-2020 Fed rate (FRED, 2022)
γ_C	Sensitivity of consumption to available funds	0.054	Calibrated to yield a growth rate close to 2% on average over baseline

α_{YD}	Specific sensitivity coefficient – Expected Available income	0.85	
β_V	Specific sensitivity coefficient - Expected Wealth	0.02	
θ_H	Tax rate on available income	29%	Global average effective personal income tax rate (Global Economy, 2020)
θ_{IN}	Tax rate on incumbent profits	23.54%	Global corporate income tax rate (Bray, 2021)
θ_{LC}	Tax rate on challenger profits		
θ_{IG}	Tax rate on investment good profits		
u_X^T	Target utilisation rate in the consumption good sector	0.75	Botte (2017)
$\kappa_{IN} = \kappa_{CH} = \kappa_L = \kappa_H$	Capital intensity	1.279203217	WIOD (2014)
η	Parameter ruling adaptive expectations	0.1	Calibrated to yield an average 2% growth rate in baseline (Riahi et al., 2017)
M	Maturity of loans	8	World Bank (2022)
σ_{lev}	Sensitivity of interest to observed leverage	0.025	Calibrated to match a weighted average on commercial rates of 5-7% (World Bank, 2022)
$\bar{\mu}$	Markup on base rate	0.055	

φ_1	Parameter ruling minimum default probability	10.06	Calibrated to yield a 2.48% average default probability in baseline (World Bank, 2022)
φ_1	Parameter ruling sensitivity of default probability to liquidity ratio	7.7	
γ_D	Fraction of deposits held in government bonds by banks	0.05	Chosen within a reasonable range of values
γ_H	Fraction of deposits held in cash by banks	0.05	
ϖ_1	Parameter ruling maximum credit rationing	4.5	Calibrated to yield a 2-3% credit rationing over baseline on average
ϖ_2	Parameter ruling sensitivity of credit rationing to debt service ratio	1	
ϖ_3	Parameter ruling sensitivity of credit rationing to deviation from target capital adequacy ratio	6	
CAR_{min}	Prudential threshold for government bailout of banks	0.08	Prudential ratio retained by Basel III (BIS, 2022)
$\alpha_{D_{NBFI}}$	Proportion of deposits reinvested by NBFIs	0.1	Calibrated to ensure a positive trend in equity price in baseline
α^{Π}_{NBFI}	Target deposits to profit ratio of NBFIs	0.01	Calibrated to ensure sufficient financial income for households

$\lambda_{i,j}, i, j \in [\|1,3\|]$	Diagonal Tobin Portfolio coefficients	0.05 if $i = j$ -0.025 otherwise	Chosen within a range of reasonable values
ξ_B	Dividend-payout ratio of banks	0.4	Chosen conservatively from the minimum payout ratio of EU banks since 2000 (Muñoz, 2020)
ξ_{CH}, ξ_{IN}	Dividend-payout ratio of firms	0.5	Average across world regions from various sources (Factset, Datastream, Citi Research ; McCrum, 2018)
$\overline{lev}$	Normal leverage	0.5	Benchmark value for a sustainable leverage on financial market (Kurt, 2021)
$\frac{\overline{NLP_G}}{VA}$	Target government deficit	1.7%	World Bank (2022)
α_τ	Coefficient ruling subsidies	0.1	World Bank (2022)
ζ	Parameter ruling technological penetration	0.85	Calibrated to follow decarbonisation pathways
ψ_{LC}, ψ_{HC}	Investment-to-debt ratio	0.5	Chosen within a reasonable range of values

A4. Emission and carbon prices (2021 Vintage)

Figure A4-3 – Emissions and carbon prices (2021 Vintage)

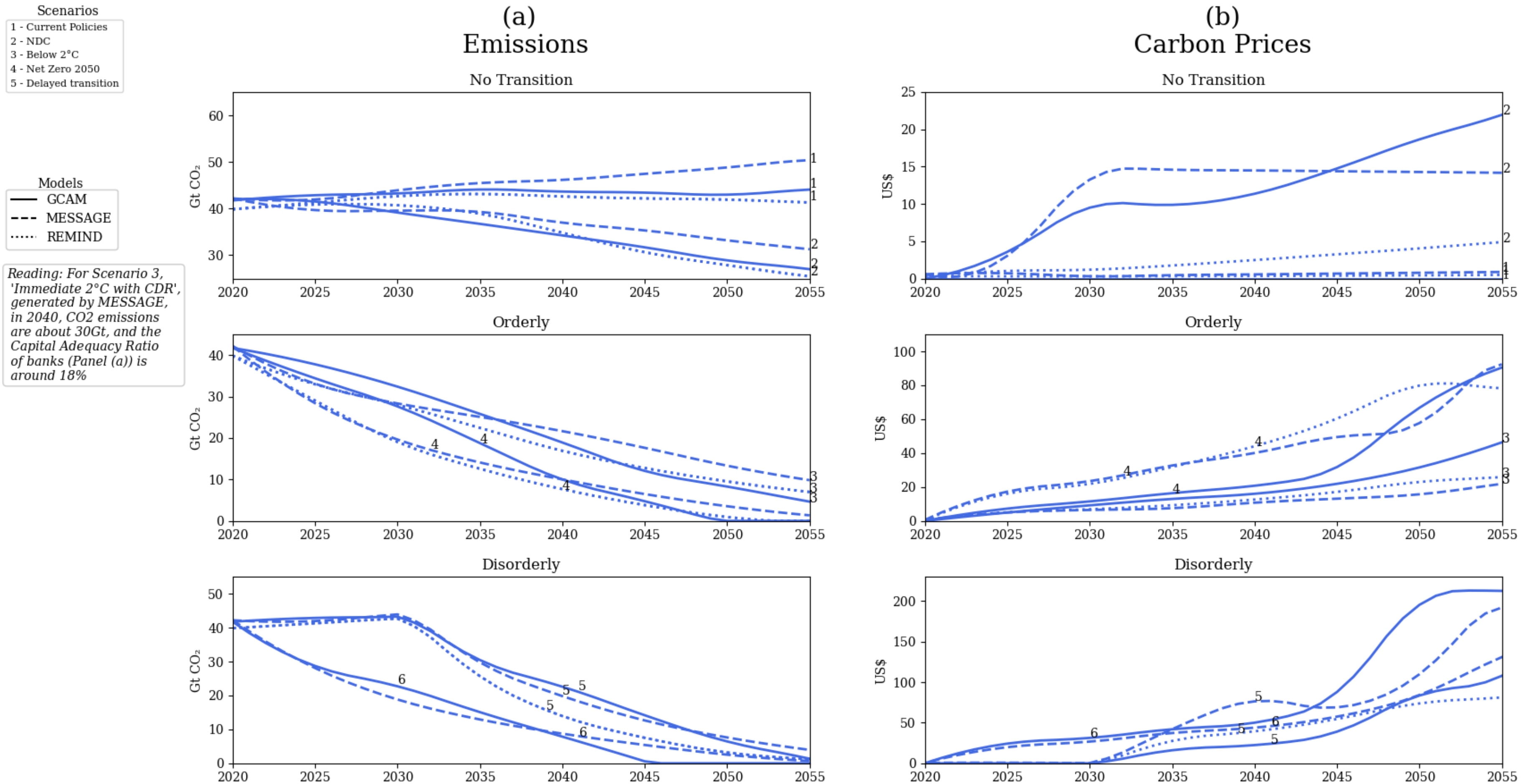


Table A4-1 – Target values for key variables in baseline

Variable	Description	Target Value	Average over baseline - GCAM	Average over baseline - MESSAGE	Average over baseline - REMIND
g_{va}	Real value-added growth	Around 2% (Riahi, 2017)	1.98%	2%	1.97%
g_{p_x}	Inflation Rate	Around 2% (World Bank, 2022)	2.3%	2.3%	2.3%
$\frac{WB}{VA}$	Wage Share	49% (WIOD ,2016)	47.6%	47.6%	47.6%
φ_{NPL}	Average default propensity	2.48% (World Bank, 2022)	2.57%	2.57%	2.6%
ϖ_{IN_t}	Credit constraint on incumbents	1-3% (Reasonable values)	2%	2%	2%
$\frac{NLP_G}{VA}$	Government deficit	1.8% (Global Economy, 2022)	2%	2%	2%

A5. Demonstrations

A5.1 Link between NBFI deposits and asset prices

To see it, let us first recall that:

$$D_{NBFI_t} = D_{NBFI_{t-1}} + RE_{NBFI_t} + U_t - U_{t-1} + p_{A_{IN_t}}(a_{IN_t} - a_{IN\,t-1}) \\ + p_{A_{HCH}}(a_{CH_t} - a_{CH\,t-1}) + B_{NBFI_t} - B\_NBFI_{\,t-1}$$

We can then easily show that:

$$A_{\ell_t} - A_{\ell_{t-1}} = \left(p_{A_{\ell_t}} - p_{A_{\ell_t}}\right) a_{\ell_{t-1}} + (a_{\ell_t} - a_{\ell_{t-1}}) p_{A_{\ell_t}}$$

Rearranging, we have:

$$(a_{\ell_t} - a_{\ell_{t-1}}) p_{A_{\ell_t}} = (A_{\ell_t} - A_{\ell_{t-1}}) - \left(p_{A_{\ell_t}} - p_{A_{\ell_t}}\right) a_{\ell_{t-1}}$$

As a result, with a given change in nominal equity demand $\left(A_{\ell_t} - A_{\ell_{t-1}}\right)$, a decrease in the price of equity $\left(p_{A_{\ell_t}} - p_{A_{\ell_t}}\right) < 0$ will mechanically increase $(a_{\ell_t} - a_{\ell_{t-1}}) p_{A_{\ell_t}}$. This arises because NBFIs buy an important amount of real equity at a low price to compensate for the drop in asset prices. To fund this purchase, they must draw on their rolling funds. This feature figures the balance-sheet shock incurred by equity holders when prices go down.

A5.2 Technological penetration

Let us start from the identity:

$$E = x_{IN_t} \varepsilon \frac{\omega_{IN}^{H}}{\omega_{IN_t}}$$

Recalling that the incumbent sector is the only holder of carbon-intensive capital and that capital shares correspond to market approximate market shares, we can write:

$$E_t \approx x_{IN_t}\varepsilon \frac{(1 - S_{L_t})(\omega_{IN_t} + \omega_{CH_t})}{(1 - S_{IN_t})(\omega_{IN_t} + \omega_{CH_t})} = x_{IN_t}\varepsilon \frac{(1 - S_{L_t})}{(1 - S_{IN_t})}$$

Which, after rearranging, yields:

$$\frac{E_t}{x_{IN_t}\varepsilon}(1 - S_{IN_t}) \approx (1 - S_{L_t})$$

$$\Leftrightarrow S_{L_t} \approx 1 - \frac{E_t}{x_{IN_t}\varepsilon}(1 - S_{IN_t})$$

Replacing S_{L_t} by $S_{L_t}^d$ the desired share of low-carbon capital and E_t by the desired emissions in $t + 1$ E_{t+1}^d, we get:

$$S_{L_t}^T \approx 1 - \frac{E_{t+1}^d}{x_{IN_t}\varepsilon}(1 - S_{IN_t})$$

To make for the approximation, I add a ζ term to make the function more concave and define $S_{L_t}^d$ as

$$S_{L_t}^T = \left(1 - \frac{E}{x_{IN_t}\varepsilon}(1 - S_{IN_t})\right)^{\zeta}$$