Climate Minsky Moments and Endogenous Financial Crises*

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Abstract

Does a shift to ambitious climate policy increase financial fragility? In this paper, we develop a quantitative macroeconomic model with carbon taxes and endogenous financial crises to study such "Climate Minsky Moments". By reducing asset returns, an accelerated transition to net zero exerts deleveraging pressure on the financial sector, initially elevating the financial crisis probability substantially. However, carbon taxes improve long-run financial stability since permanently lower asset returns reduce the buildup of excessive leverage. Quantitatively, we find that the net financial stability effect of ambitious climate policy is positive for low but empirically plausible social discount rates.

Keywords: Climate Policy, Financial Stability, Financial Crises, Transition Risk, Non-Linearities.

JEL classification: E32, E44, G20, Q52, Q58

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1 Introduction

Does the net zero transition increase financial fragility and, if so, by how much? Answering these questions is crucial for financial regulation over the next decades, which will be characterized by a large shift away from emission-intensive technologies. Ambitious taxes on carbon emissions negatively affect the macroeconomy and asset prices by triggering a sharp and permanent drop in the productivity of emission-intensive assets. Climate policy can then give rise to "Climate Minsky Moments", in which a sudden reduction in asset prices raises the concern that financial intermediaries are unable to repay depositors, triggering a financial crisis.[1] However, as no country has yet introduced sufficiently stringent climate policies, evaluating the empirical relevance of "Climate Minsky Moments" using historical data is practically impossible.

To assess the threat of "Climate Minsky Moments", we therefore develop a nonlinear quantitative macroeconomic model with endogenous financial crises and carbon taxes. Our model is centered on the notion that financial intermediaries are run-prone in the spirit of Diamond and Dybvig (1983). Specifically, the possibility of a systemic run on the financial system is fully endogenous and depends on the macro-financial environment. Based on the seminal work by Nordhaus (2008), we incorporate carbon emissions into the production process, carbon taxes, and endogenous emission abatement. Using our macro-finance-climate model, we evaluate how climate policy consistent with net zero emissions affects financial stability, both in the short- and long-run. Specifically, our nonlinear DSGE framework allows us to examine how climate policy impacts the endogenous build-up of financial instability and the possibility of "Climate Minsky Moments". Thus, we provide a new element to the ongoing debate on financial stability in the context of climate policy.[2]

The two key building blocks of our framework are the financial sector with endogenous financial crises and firms' emission abatement that depends on climate policy. Financial intermediaries are subject to an endogenous time-varying leverage constraint based on Adrian and Shin (2014) and Nuño and Thomas (2017). Importantly, the financial sector faces occasional runs, which depend on the state-dependent willingness of depositors to roll over intermediaries' liabilities, similar to Gertler et al. (2020). The probability of such a self-fulfilling run depends on the financial sector's leverage and the price of capital, which is directly affected by climate policy.

Climate policy enters the model through the production sector. Firms emit greenhouse gases during the production process. Unabated emissions are taxed by the fiscal authority, but we allow for costly abatement to reduce their emission intensity (Nordhaus, 2008).

[1]The term "Climate Minsky Moments" was coined by Carney (2016).

[2]The current debate on financial stability implications of climate policies centers around negative credit supply effects operating through the net worth of intermediaries, while abstracting from its effect on the endogenous build-up on leverage and on systemic financial crises.

The tax bill is given by the amount of unabated emissions times the carbon tax. Emission abatement costs and the carbon tax bill jointly drive a wedge in the marginal product of capital that monotonically increases with the carbon tax (Heutel, 2012). We embed this framework in a New Keynesian general equilibrium setup.

Climate policy affects financial stability through two opposing mechanisms. Increasing the carbon tax reduces the marginal product of capital. This reduces the market value of assets held by the financial sector, which endogenously tightens the financial sector's leverage constraint.[3] Since net worth only moves slowly into the financial sector, this puts downward pressure on the price of capital and increases the partition of the state space supporting a run on the financial sector: the probability of "Climate Minsky Moments" increases. On the other hand, by reducing the marginal product of capital, higher carbon taxes reduce the incentives to accumulate capital.[4] This requires households to absorb less capital during downturns and has a positive effect on the price of capital. Downturns are less likely to result in a systemic financial crisis: the probability of "Climate Minsky Moments" decreases.

Which of these opposing mechanisms dominates is, therefore, a quantitative question. To answer this problem, we match the model to salient features of financial cycles and the macroeconomic effects of climate policy. Solving our model in its nonlinear specification with global methods allows us to calculate the crisis probability during the transition to net zero. Our quantitative analysis reveals that both mechanisms matter, but at different time horizons.

As a first result, we show that permanently higher carbon taxes enhance financial stability in the long-run. The reason behind this perhaps surprising result is that the capital-to-GDP ratio is smaller in the long-run for an economy with high taxes. The social value of financial intermediation is smaller since households are willing to hold a larger share of the capital stock. Consequently, the financial sector is smaller and less leveraged: intermediaries can deleverage more easily in a downturn without having to sell capital at fire sale prices that would justify the existence of the run equilibrium. The probability of financial crises declines from around 2% in the long-run equilibrium without climate policy to 1.5% in the long-run equilibrium with full abatement.

Second, the long-run financial stability gain comes at the cost of an elevated crisis probability in the early stages of the transition to higher carbon taxes. To appropriately quantify the adverse financial stability effects of the transition in the short-run, we first define a reference scenario, to which we refer to as *business-as-usual*. In this scenario, we extrapolate the European Union's emission reduction path from 1990 to 2023. Emissions

[3]Jung et al. (2024) show that ambitious climate policy induces loan portfolio losses between 1 and 6% for US banks. More generally, institutional investors are aware that a shift towards ambitious climate policy has detrimental effects on asset values (Krueger et al., 2020).

[4]Kaenzig (2023) provides evidence that positive carbon tax shocks decrease aggregate investment. Berthold et al. (2023) show that such positive carbon shocks also tighten financing conditions.

declined almost linearly by one percentage point per year over this period. Linearly extrapolating this path implies that net zero would be reached in 2090 under the *business-as-usual* scenario. Full abatement is reached for a carbon tax of 143 dollars per ton of carbon ($/ToC) in our baseline calibration.

The *ambitious policy* scenario assumes that, in 2025, the economy suddenly shifts to a carbon tax path that increases linearly to the full abatement level in 2050. This carbon tax path is consistent with the Paris Agreement and with recently announced transition plans by the European Union. The implied emission reduction under the ambitious path is around three percent annually, which is a considerable increase compared to the *business-as-usual* path.[5] The gradual but permanent increase of carbon taxes renders the pre-transition financial sector leverage unsustainable: the (annualized) crisis probability increases to slightly more than 2.6% before slowly declining to its long-run level of 1.5%. Our non-linear model reveals that a monotonic transition path can have non-monotonic financial stability effects. The net financial stability effect is, therefore, ambiguous.[6]

To jointly measure the financial stability net effect of ambitious climate policy, we introduce a metric of financial stability along different transition paths. The *excess crisis probability* is defined as the average difference between the crisis probability under an *ambitious policy* path and under the *business-as-usual* path. This average is computed from the initial period (2025) to some cut-off period, which we vary in a robustness test. Our baseline model predicts an *excess crisis probability* close to zero over the period 2025 to 2070 for the carbon tax path consistent with net zero by 2050. The inflection period - the point in time in which the *excess crisis probability* turns negative - corresponds to 2069.

We then analyze how changing the *speed* and *shape* of the *ambitious policy* path affects the occurrence of "Climate Minsky Moments". First, we assume that net zero carbon taxes are implemented in 2045, i.e., we increase the *speed* of the transition. This improves short-run financial stability by allowing intermediaries to deleverage over a longer period. At the same time, the lower long-run crisis probability is reached at a later point in time. Quantitatively, these opposing effects offset each other, such that the *excess crisis probability* from 2025 to 2070 is effectively independent of variations in the transition speed. The implications for climate policy sharply contrast the approximate irrelevance for financial stability since slow transition paths are characterized by substantially elevated levels of atmospheric carbon in 2070, i.e., 45 years after the shift onto the *ambitious policy* path and 20 years after net zero emissions are reached.

[5]The EU transition plans represent a reasonable upper bound for the speed of the net zero transition, such that our results for the initial increase in financial fragility represent an upper bound.

[6]Throughout the analysis, we abstract from adverse financial stability consequences of delayed climate policy associated with elevated physical risks. Partialling out such additional channels allows us to cleanly attribute all financial stability consequences to the time path of abatement costs. However, our framework can be augmented by physical climate risks in a conceptually straightforward way.

While our baseline *ambitious policy* path imposes a linear increase of carbon taxes, we also consider differently shaped carbon tax paths, i.e., we allow for front- or back-loading climate action. In the case of front-loading, the crisis probability spikes early but at a higher level before rapidly converging to lower levels. Consequently, the *excess crisis probability* turns negative in 2066 already. In contrast, if ambitious climate policy is deferred to the future, but still committed to reaching net zero by 2050, the crisis probability peaks later, but remains elevated essentially for the entire transition path. The inflection period at which the *excess crisis probability* turns negative increases to 2073.

Our quantitative results soften frequently articulated concerns about a trade-off between financial stability and ambitious climate policy - provided that policymakers place a sufficiently high weight on future periods. Crisis probabilities peak early and at comparatively high levels if climate policy is ambitious and front-loaded, before converging rapidly to their lower long-run level. Under sufficiently small time discount rates, ambitious climate policy has a positive net financial stability effect. In contrast, a present bias by the regulator might imply that delayed action is preferred. For example, an annualized time preference rate exceeding 2.5% renders a back-loaded transition optimal. The time pattern of crisis probabilities implied by our model bears a striking resemblance to the time pattern of costs and benefits of ambitious climate policy action more generally.[7]

Lastly, we also allow for the possibility of abatement subsidies. We assume that all carbon tax revenues are rebated to firms as a subsidy for their abatement costs. Since the subsidy has to be financed entirely by carbon tax revenues, the long-run equilibrium is not affected because the carbon tax base is zero under full abatement. While emissions are substantially smaller if abatement subsidies are in place, they turn out to be detrimental to financial stability along the transition. The subsidy initially cushions the financial sector from losses, consistent with empirical evidence by Bauer et al. (2023). But, the subsidy also sustains a large incentive to accumulate physical capital, such that it merely shifts the deleveraging pressure into future periods. Once a tight climate policy is in place and carbon tax revenues start to fall, the subsidy declines quickly, which forces intermediaries to sell assets, while households still incur a large cost from managing them. “Climate Minsky Moments” are particularly likely towards the end of the transition such that the inflection point increases to 2081. Again, taking a general equilibrium perspective allows us to cleanly assess the implications of different policy options. Even though subsidies may address the adverse side effects of climate policy on the financial sector by stabilizing asset returns, they do not fundamentally solve the problem that the costs of the net zero transition have to be borne eventually.

[7]The horizon of policymakers in the context of climate policy and financial risks of breaking the ”Tragedy of the Horizon” were brought into the discussion by Carney (2015).

Related Literature. Our paper is connected to the fast-growing literature that uses fully-fledged DSGE models with climate policy and frictions in the financial sector (e.g., Diluiso et al., 2021; Annicchiarico et al., 2023; Carattini et al., 2023a; Comerford and Spiganti, 2023; Frankovic and Kolb, 2024; Nakov and Thomas, 2023; Airaudo et al., 2024). Closely related, Carattini et al. (2023b) demonstrate that carbon taxes can negatively affect financial intermediaries' net worth and induce a credit crunch. Barnett (2023) shows how financial frictions can give rise to fire sales of carbon-intensive assets. In contrast, our paper explicitly considers the systemic dimension of climate policy, i.e. implications for financial stability at the aggregate level. Giovanardi et al. (2023) and Giovanardi and Kaldorf (2023) model idiosyncratic default and risk-taking in the firm and banking sector. Our paper differs from these studies as we incorporate the possibility of runs into an climate DSGE model. As a result, we can study the impact of climate policy on the endogenous buildup of financial leverage, and on financial crises.

To incorporate the possibility of "Climate Minsky Moments", we build on the recent advancements in the macro-finance literature that incorporated endogenous financial crises in macroeconomic models, as in Brunnermeier and Sannikov (2014), Gertler and Kiyotaki (2015), Boissay et al. (2016), Moreira and Savov (2017), and Amador and Bianchi (2024). Our macro-finance model block builds upon Rottner (2023), which combines pro-cyclical leverage dynamics with self-fulfilling runs, as in Gertler et al. (2020) to reconcile key features of financial cycles.[8] Our paper contributes to this literature by incorporating the role of climate policy in this type of model.

We also relate to the literature on the interactions between financial stability and climate policy that uses analytically tractable models. Jondeau et al. (2021) address the risk of fire sales of emission-intensive assets. Döttling and Rola-Janicka (2022) analyze jointly optimal climate and financial policy in the context of our paper. Our contribution is to build a quantitative model, which opens up the possibility to analyze the impact of different climate policies on financial stability through a quantitative lens.

An alternative approach is taken by several regulators are climate stress tests. Acharya et al. (2023) provide a summary and outlook for climate change stress tests. Specific examples are Jung et al. (2024) and IMF (2022a), who evaluate the effects of specific climate change scenarios on the loan portfolio for the US and UK, respectively. Brunetti et al. (2022) review the results of climate stress tests conducted in several jurisdictions. By design, stress tests are not able to uncover positive financial stability effects of the transition, as they abstract from the financial sector's deleveraging incentives along the net zero transition. In contrast, by taking a general equilibrium perspective, our paper allows us to fully endogeneize the responses of the different economic agents during the transition to net zero.

[8]The framework features, for instance, "credit booms gone bust" dynamics (Schularick and Taylor, 2012) and the volatility paradox (Brunnermeier and Sannikov, 2014).

2 Model

The model consists of three building blocks related to the financial sector, climate policy, and the macroeconomy, respectively. The financial sector follows largely the setup of Rottner (2023), which embeds an endogenous leverage constraint (Adrian and Shin, 2014; Nuño and Thomas, 2017) in a model with endogenous financial crises as in Gertler et al. (2020). The climate block follows the framework of Heutel (2012), in which firms emit greenhouse gases during the production process. Unabated emissions are subject to a carbon tax, but firms can undertake a costly abatement effort to reduce their emissions. This representation of financial fragility and climate policy is embedded into an otherwise standard New Keynesian setup.

Time is discrete and denoted by $t = 1, 2, ...$, there is a representative household and a representative financial intermediary that is funded by runnable deposits. Households and intermediaries can invest in claims on manufacturing firms. Nominal rigidities enter the model through monopolistically competitive retail firms that differentiate and sell the output of manufacturers to households. The model is closed by a monetary policy rule and the assumption that carbon tax taxes are rebated to households in lump sump fashion.

Household The representative household consists of workers and managers that have perfect insurance for their consumption C_t. Workers supply labor L_t and earn the wage W_t. Mangers run financial intermediaries which return their net worth to the household with a probability of $1 - \theta$. New intermediaries enter each period and receive a transfer from the household, who owns non-financial firms and receives their profits. The variable T_t captures all transfers from the public sector.

Households save in terms of one-period deposits D_t which promise to pay the gross interest rate of $\overline{R}_t^D$ next period. However, in case of a run, households receive then only the fraction $x_t^\star$ of the promised return, to which we refer as the recovery ratio. The realized gross return R_t^D depends on the realization of a run in period t:

$$R_t^D = \begin{cases} \overline{R}_{t-1}^D & \text{if no run takes place in period } t \text{ ,} \\ x_t^\star \overline{R}_{t-1}^D & \text{if a run takes place in period } t \text{ ,} \end{cases} \tag{1}$$

where x_t^* is the recovery rate on deposits which we derive below. Additionally, households and intermediaries can invest in the production sector by purchasing capital K_t^H and K_t^B, respectively, that give them ownership in the intermediate good firm. The rental rate on capital is denoted by Z_t, while its market price is denoted by Q_t. Total end-of-period securities are given by $K_t = K_t^H + K_t^B$. Households maximize utility subject to the following period budget constraint:

$$C_t = W_t L_t + D_{t-1} R_t^D - D_t + \tau_t - Q_t K_t^H + \big(Z_t + (1-\delta) Q_t\big) K_{t-1}^H \ . \tag{2}$$

Capital Management Costs for Households We assume that households are less efficient in managing securities than intermediaries (Brunnermeier and Sannikov, 2014). As in Gertler et al. (2020), households incur a utility cost from managing capital. The otherwise standard period utility function is given by:

$$u(C_t, L_t, K_t^H) = \frac{C_t^{1-\gamma_C}}{1-\gamma_C} - \frac{L_t^{1+\gamma_L}}{1+\gamma_L} - \frac{\omega_F}{2}\Big(\frac{K_t^H}{K_t} - \gamma^F\Big)^2 K_t \ . \tag{3}$$

Inspecting the capital management cost function $\frac{\omega_F}{2}\Big(\frac{K_t^H}{K_t} - \gamma^F\Big)^2 K_t$, we observe that:

$$\frac{\partial cost_t}{\partial K_t^H} = \omega_F \Big(\frac{K_t^H}{K_t} - \gamma^F\Big) \quad \text{and} \quad \frac{\partial cost_t}{\partial K_t} = \frac{\omega_F}{2}\Big(\gamma^F - \frac{K_t^H}{K_t}\Big)\Big(\gamma^F + \frac{K_t^H}{K_t}\Big) \ .$$

Holding aggregate capital K_t constant, management costs increase in K_t^H as soon as household capital holdings exceed the target share ($\frac{K_t^H}{K_t} > \gamma^F$), up to a certain cost level $\frac{\omega_F}{2}(1-\gamma^F)^2 K_t$ at which households manage the entire capital stock. Furthermore, for any $\frac{K_t^H}{K_t} > \gamma^F$, management costs decrease in aggregate capital K_t. This reflects the notion that investing a large amount of assets is easier for households in deep financial markets, which allow for diversification and trade on comparatively liquid financial markets.

To provide intuition on the financial stability effects of climate policy, it is also helpful to consider the cross-derivative of the cost function with respect to the total capital stock K_t and the household capital share $\frac{K_t^H}{K_t}$:

$$\frac{\partial^2 cost_t}{\partial \frac{K_t^H}{K_t} \partial K_t} = \omega^F \Big(\frac{K_t^H}{K_t} - \gamma^F\Big) > 0 \quad \text{if} \quad \frac{K_t^H}{K_t} > \gamma_F \ , \tag{4}$$

The cross-derivative is positive if the share managed by households $\frac{K_t^H}{K_t}$ is larger than γ^F, which holds throughout our numerical simulations. This implies that the capital management cost increases by more if the economy has accumulated a large amount of capital. Consequently, the capital demand function is steeper, such that the associated capital price drop is larger when households have to acquire capital from financial intermediaries.

Financial Intermediaries and Risk-Shifting Incentives Financial intermediaries convert their capital holdings into ω_t efficiency units, either using a safe or a risky technology. While the safe technology converts capital into one efficiency unit ($\omega_t = 1$), the risky technology is subject to idiosyncratic productivity shocks $\widetilde{\omega}$. The shock is i.i.d. over time and intermediaries and follows a log-normally distribution:

$$\log \widetilde{\omega}_t \overset{iid}{\sim} N\left(\frac{-\xi_t^2 - \psi}{2}, \xi_t\right) , \tag{5}$$

where $\psi < 1$. The good technology is superior as it has a higher mean and a lower variance due to $\psi < 1$ (see also Adrian and Shin, 2014 and Nuño and Thomas, 2017). The risky technology is characterized by higher upside risk due to the possibility of a large idiosyncratic shock realization $\widetilde{\omega}$. The volatility of idiosyncratic productivity shock ξ_t is an exogenous driver of financial cycles and an important trigger of financial crises in this model. In the spirit of Christiano et al. (2014), ξ_t is exogenous and follows an AR(1) process:

$$\xi_t = (1-\rho^\xi)\xi + \rho^\xi \xi_{t-1} + \sigma^\xi \epsilon_t^\xi, \quad \text{where } \epsilon_t^\xi \sim N(0,1). \tag{6}$$

The intermediary earns the return $R_t^{K,j}$ which depends on the stochastic aggregate return R_t^K and (potentially) also on the realized idiosyncratic shock realization if the intermediary invested into the risky technology $\widetilde{\omega}_t^j R_t^K$. The aggregate return depends on the price of capital Q_t and the profits per unit of capital $R_t^K = [(1-\delta)Q_t + Z_t]/Q_{t-1}$. The threshold realization $\overline{\omega}_t^j$ where the intermediary can exactly cover the face value of the deposits is given by

$$\overline{\omega}_t^j = \frac{\overline{R}_{t-1}^D D_{t-1}^j}{R_t^K Q_{t-1} K_{t-1}^{Bj}} . \tag{7}$$

Limited liability protects the intermediary in case of default, which distorts the intermediary's technology choice. If the productivity shock realization is below $\overline{\omega}_t^j$, the intermediary declares bankruptcy. In this case, households seize the intermediaries' assets instead of receiving the promised deposit value. For this reason, the intermediary has an incentive to invest in the risky technology. Intermediaries profit fully from the upside risk, while limited liability eliminates the downside risk. The gain from limited liability for the risky technology is:

$$\Omega_t^j = \int_{-\infty}^{\overline{\omega}_{t+1}^j} (\overline{\omega}_{t+1}^j - \widetilde{\omega}) dF_t(\widetilde{\omega}) > 0. \tag{8}$$

In contrast to this, the gain from limited liability due to idiosyncratic risk is zero for the good technology. This creates a trade-off between the good technologies' higher mean return versus the gains from limited liability for the risky technology.

This results in an maximization problem, in which the financial intermediary maximizes the franchise value subject to an incentive and participation constraint. While we summarize the problem here, the full derivation is relegated to Appendix A. The incentive constraint ensuring that intermediaries only invest in the good technology enters as an additional equilibrium condition:

$$(1-\pi_t)\mathbb{E}_t^N\left[\Lambda_{t,t+1}R_{t+1}^K(\theta\lambda_{t+1}^j+(1-\theta))\left(1-e^{\frac{-\psi}{2}}-\Omega_{t+1}^j\right)\right]=\pi_t\mathbb{E}_t^R\left[\Lambda_{t,t+1}R_{t+1}^K\left(e^{-\frac{\psi}{2}}-\overline{\omega}_{t+1}^j+\Omega_{t+1}^j\right)\right]. \tag{9}$$

where π_t is the probability of a run in period $t+1$. The expectation operators $\mathbb{E}_t^N[\cdot]$ and $\mathbb{E}_t^R[\cdot]$ are conditioned on the absence of a run and the occurrence of a run in period $t+1$, respectively. The trade-off between a higher mean return $(1-e^{\frac{-\psi}{2}})$ and the upside risk Ω_{t+1}^j can be seen on the LHS. In case of a run, there is an additional gain of investing in the risky technology, as displayed on the RHS. The risky technology offers the possibility of having positive net worth despite a run if the idiosyncratic shock exceeds $\widetilde{\omega}_t^i > \overline{\omega}_t$.

λ_t^j on the LHS of eq. (9) is the multiplier on intermediaries' participation constraint, which we derive next. The return on deposits needs to be sufficient such that households are willing to provide deposits to intermediaries. While households earn the predetermined interest rate $\overline{R}_t^D$ in normal times, households recover the gross return on capital if a run takes place. As the return on deposits in a run is lower, an increase in the run probability π_t increases intermediaries' funding costs. The participation constraint can be written as:

$$(1-\pi_t)\mathbb{E}_t^N\left[\beta\Lambda_{t,t+1}\overline{R}_t^D D_t^j\right]+\pi_t\mathbb{E}_t^R\left[\beta\Lambda_{t,t+1}R_{t+1}^K Q_t K_t^{Bj}\right]=D_t^j\ . \tag{10}$$

Note that it turns out that the incentive constraint and the participation constraint do not depend on intermediary j specific values, so that we can drop the subscript j. Thus, we can just sum up over the intermediaries to obtain aggregate values.

Runs and Equilibrium Selection In our model, a systemic financial crisis corresponds to a state in which households are not willing to roll over deposits. Runs are self-fulfilling in the sense that households' expectations about a low liquidation value of financial intermediaries' assets induce them to withdraw deposits, which forces intermediaries to sell assets at fire sale prices, justifying households' expectations. The systemic nature of runs in our model is reflected by the idea that it destroys the entire net worth of the financial system, i.e. $N_{S,t}=0$. Newly entering intermediaries and households are the only agents left to acquire assets, which induces the price of capital to fall dramatically. We denote the fire sale price of capital by Q_t^* to determine whether a self-fulfilling run is supported and define the recovery ratio

$$x_{t+1}^* \equiv \frac{\left((1-\delta)Q_t^*+Z_t\right)K_{t-1}^B}{\overline{R}_{t-1}D_{t-1}}\ . \tag{11}$$

Runs are possible if $x_{t+1}^* < 1$ (Gertler and Kiyotaki, 2015). If the run equilibrium is possible, we select equilibria using a sunspot shock ϵ_t^π, following Cole and Kehoe (2000). The sunspot shock takes the value one with probability Υ and zero otherwise. The run probability follows as

$$\pi_t = \text{prob}(x_{t+1}^* < 1) \cdot \Upsilon \ . \tag{12}$$

Intermediate Good Producers and Climate Policy Emissions enter the model at the stage of intermediate good producers, who emit greenhouse gases during the production process. All firms use a Cobb-Douglas technology $Y_t = AK_{t-1}^\alpha L_t^{1-\alpha}$ and are subject to emission taxes τ_t. We follow Heutel (2012) in assuming that emissions are proportional to production Y_t, but can be abated at a cost.[9] Denoting the abatement share by η_t, total emissions are therefore given by $(1-\eta_t)Y_t$ while the total carbon tax paid in period t is given by $\tau_t^c(1-\eta_t)Y_t$. In most policy experiments, we assume that carbon tax revenues are rebated to households in a lump sum fashion. In Section 4.5, we also consider a policy in which carbon tax revenues are used to subsidize firms' abatement costs.

Following Heutel (2012), abatement costs are proportional to output:

$$B(\eta_t, Y_t) = \frac{b_1}{b_2+1}\eta_t^{b_2+1} Y_t \ , \tag{13}$$

with b_1, $b_2 > 0$. Since emission and abatement costs are proportional to output by assumption, the optimal abatement effort solves the following per-unit cost minimization problem

$$\min_{\eta_t} \quad (1-\eta_t)\tau_t^c + \frac{b_1}{b_2+1}\eta_t^{b_2+1}$$

The optimal abatement effort η_t^* is given by

$$\eta_t^* = \min\left\{ \left(\frac{\tau_t^c}{b_1}\right)^{\frac{1}{b_2}}, 1 \right\} \ . \tag{14}$$

The abatement effort is increasing in the current carbon tax and capped by one, i.e. we do not allow for the possibility of net negative emissions.[10] Since climate policy directly affects the accumulation and pricing of capital in our model economy, it is helpful to define

[9] Golosov et al. (2014) explicitly model energy usage in the aggregate production function. Since ambitious climate policy yields to an increase in the cost of energy in the medium-run, this framework would yield a comparable decline in the aggregate return on capital.

[10] An alternative interpretation is that firms switch to an emission-free but less productive technology (see also Comerford and Spiganti (2023) and the references therein). Under this interpretation, it is reasonable to assume that some technologies, such as aviation, cement, or steel production are very costly to substitute, justifying the convex functional form assumption on abatement costs and also implies a decline in the aggregate return on assets.

the policy-induced wedge into the return on capital. Plugging-in the optimal abatement effort η_t^* into the abatement cost function, ξ_{t+1} summarizes all expenses per unit of capital from carbon taxation and abatement:

$$\xi_{t+1} \equiv \tau_{t+1}^c \left(1 - \eta_{t+1}^*\right) + \frac{b_1}{b_2 + 1} \left(\eta_{t+1}^*\right)^{b_2+1} \ . \tag{15}$$

The realized return on investment is given by $R_t^K = [(1-\delta)Q_t + Z_t]/Q_{t-1}$ and we can write the maximization problem as

$$\max_{K_{t-1}, L_t} \mathbb{E}_t \sum_{s=0}^{\infty} \Lambda_{t,t+s} \left((p_{t+s} - \xi_{t+s})Y_{t+s} + Q_{t+s}(1-\delta)K_{t+s-1} - R_{t+s}^K Q_{t+s-1} K_{t+s-1} - W_{t+s} L_{t+s}\right)$$

Taking the price of the intermediate good p_t as given, the first-order conditions for capital and labor are:

$$Z_t = (p_t - \xi_t)\alpha \frac{Y_t}{K_{t-1}}, \qquad \text{and} \qquad W_t = (p_t - \xi_t)(1-\alpha)\frac{Y_t}{L_t} \ , \tag{16}$$

Since emissions and abatement costs are proportional to total output, the carbon tax does not affect the optimal capital share in the production function but instead depresses total factor productivity.

Retailers Monopolistically competitive retail good firms buy the intermediate goods and transform them into a differentiated final good Y_t^j. Households' final good bundle Y_t, which is given by a CES-aggregate over all final goods varieties, and the price index are:

$$Y_t = \left[\int_0^1 (Y_t^j)^{\frac{\epsilon-1}{\epsilon}} dj\right]^{\frac{\epsilon}{\epsilon-1}}, \qquad \text{and} \qquad P_t = \left[\int_0^1 (P_t^j)^{1-\epsilon} dj\right]^{\frac{1}{1-\epsilon}} \ , \tag{17}$$

where the demand for the final good variety j negatively depends on its relative price:

$$Y_t^j = \left(P_t^j / P_t\right)^{-\epsilon} Y_t \ . \tag{18}$$

Retailers set prices to maximize profits subject to Rotemberg price adjustment costs:

$$\mathbb{E}_t \sum_{s=0}^{\infty} \Lambda_{t,t+s} \left[\left(\frac{P_{t+s}^j}{P_{t+s}} - \overline{p}_{t+s}\right) Y_{t+s}^j - \frac{\rho^r}{2} Y_{t+s}^j \left(\frac{P_{t+s}^j}{\Pi P_{t+s-1}^j} - 1\right)^2\right] \ , \tag{19}$$

where Π is the inflation target set by the central bank. Since their production function is linear in the intermediate good, retailers' marginal cost are simply given by the price of the intermediate good $MC_t = \overline{p}_t$. The New Keynesian Phillips curve follows as:

$$\left(\frac{\Pi_t}{\Pi} - 1\right)\frac{\Pi_t}{\Pi} = \frac{\epsilon}{\rho^r}\Big(MC_t - \frac{\epsilon - 1}{\epsilon}\Big) + \Lambda_{t,t+1}\left(\frac{\Pi_{t+1}}{\Pi} - 1\right)\frac{\Pi_{t+1}}{\Pi}\frac{Y_{t+1}}{Y_t} \ . \tag{20}$$

Investment Good Producers Investment good producers transform I_t units of the final good into $\left(a_1(I_t/K_{t-1})^{1-a_2} + a_0\right) K_{t-1}$ units of the investment good, which they sell at price Q_t. Solving the maximization problem

$$\max_{I_t} \ Q_t \left(a_1(I_t/K_{t-1})^{1-a_2} + a_0\right) K_{t-1} - I_t \ , \tag{21}$$

yields an investment good supply function. The law of motion for capital is given by $K_t = (1-\delta)K_{t-1} + \Gamma\left(I_t/K_{t-1}\right) K_{t-1}$.

Monetary Policy and Resource Constraint The monetary authority sets the interest rate R_t^I using a Taylor Rule subject to the zero lower bound:

$$R_t^I = \max\left\{R^I\left(\frac{\Pi_t}{\Pi}\right)^{\kappa_\Pi}\left(\frac{MC_t}{MC}\right)^{\kappa_y}, 1\right\} \ , \tag{22}$$

where deviations of marginal costs from its deterministic steady state MC reflect the output gap. To connect this rate to the household, there exists one-period bond in zero net supply that pays the riskless nominal rate R_t^I. The associated Euler equation governs the pass-through from the monetary policy rate to the macroeconomy:

$$\mathbb{E}_t\left[\Lambda_{t,t+1}R_t^I/\Pi_{t+1}\right] = 1 \ . \tag{23}$$

The resource constraint includes the price adjustment and abatement costs:

$$Y_t = C_t + I_t + G + \frac{\rho^r}{2}\Big(\frac{\Pi_t}{\Pi} - 1\Big)^2 Y_t + \frac{b_1}{b_2+1}\left(\frac{\tau_t^c}{b_1}\right)^{\frac{b_2+1}{b_2}} Y_t \ , \tag{24}$$

where G is government spending. From (24), we observe that resources spent on abatement reduce GDP, similar to a negative shock total factor productivity.

Lastly, carbon emissions $(1-\eta_t)Y_t$ accumulate into a stock of atmospheric carbon according to

$$E_t = \delta_E E_{t-1} + (1-\eta_t)Y_t \ , \tag{25}$$

where $\delta_E < 1$ is the decay factor of atmospheric carbon. Even though or model does not feature a climate block linking emissions to economic damages through increases in global temperatures, the stock of atmospheric carbon is a key metric for climate policy. In the quantitative analysis, we will show its evolution along different transition paths.

3 Calibration and Solution

3.1 Parameter Choices

We parameterize our model to match salient features of the macroeconomy, the financial sector, and climate policy. This results in a general calibration strategy that can easily adapted to potential country use cases. When we target specific non-climate related moments, we use the economy without a carbon tax, e.g. $\tau^c = 0$. An overview of the parameterization is given in Table 1.

The discount factor β is chosen to account for a risk-free rate of 1.0%. The Frisch labor elasticity is set to γ_L following Chetty et al. (2011), while we use log utility for consumption ($\gamma^C = 1$). We normalize output via the long-run TFP level A and target a government spending-to-output ratio of 20%. The capital share α is set to 0.33 and the deprecation rate δ to 0.025. Our Rotemberg pricing parameter ρ^r is set to 178, which would imply a duration of 5 quarters in the related Calvo framework. The investment adjustment cost parameters a_0 and a_1 are set to normalize the asset price and investment output. The curvature of the investment adjustment cost parameter is set in line with Bernanke et al. (1999). The central bank targets an inflation rate of 2%, while the response to the output gap $\kappa_y = 0.125$ and inflation $\kappa_\pi = 2.0$ are set to conventional choices.

The parameters related to the climate policy block of the model are set to match key properties of carbon emissions and the macroeconomic impact of carbon taxes. The functional forms follow the DICE model of Nordhaus (2008). The curvature is set to $\theta_2 = 1.6$ (Ferrari and Nispi Landi, 2023) and the slope to $\theta_1 = 0.05$, which is in line with Heutel (2012). The abatement costs parameter are subject to considerable uncertainty. For this reason, we consider for robustness reasons also different values for the slope and curvature parameters of the abatement cost function (13) in Appendix C. We set the quarterly decay rate of atmospheric carbon to 0.0021, implying that $\delta_E = 0.9979$.

Since the carbon tax is expressed in terms of abstract model units, which are hard to interpret, we transform the tax rate into carbon prices. To do so, we relate output y_t and emissions e_t in our model's initial stationary (i.e. without abatement) to current world GDP ($y^{world} = 105$ trillion USD in 2022, at PPP, see IMF, 2022b) and current global carbon emissions ($e^{world} = 33$ gigatons in 2022), respectively. Since output and emissions are normalized to one in the model, the carbon price in dollars per tonne of carbon (\$/ToC) associated with a given tax τ_t^c is then given by $\frac{y^{\text{world}}}{e^{\text{world}}}\tau_t^c$. Under our baseline value for θ_1, we obtain a full abatement tax of $\tau_t^c = 0.05$ which corresponds to a carbon price of 143\$/ToC. While this tax appears quite small compared to currently observed emission permit prices in the EU emission trading scheme, it has to be noted that *all* emissions are taxed in our macroeconomic model, while only a limited share of emissions is subject to emission trading or carbon taxes and firms receive a considerable amount of free allowances in practice.

The financial sector parameters are set to target salient features of financial cycles and systemic financial crises. We target an intermediary asset share of 1/3, implying that one-third of securities are funded by runnable deposits. For this reason, we set the target share of the household's asset holdings to $\gamma^F = 0.38$. The leverage of the financial intermediaries is set to 15, in line with equity to capital holdings in the financial sector of 6.67%. This value is obtained by setting households' intermediation cost to $\omega_F = 0.045$. The parameter controlling the mean return of the risky of technology follows Rottner (2023). The intermediary survival probability is set to a rather low value of $\zeta = 0.885$, which is helpful to incorporate runs in this type of model and is in line with the credit spread of 90 basis points over the risk-free rate (Gertler and Kiyotaki, 2015). The parameter that governs the initial endowment to new intermediaries is implied by the other parameters of the model. We set the standard deviation of our volatility shock to match an annual run frequency of 2%, a value that is well in line with the evidence on financial crises in the macrohistory database of Jordà et al. (2017). The persistence of the shock follows Rottner (2023). The probability governing the sunspot shock is normalized to $\Upsilon = 0.5$, so that we attribute to both equilibria the same likelihood, conditional on their existence.

3.2 Global Solution Method

We solve the model using global solution methods. This is paramount to capture the nonlinear effects of financial crises on the macroeconomy and to allow for non-monotonic effects of climate policy on the likelihood of financial crises. Specifically, we use time iteration with linear interpolation on a discretized state space. The model has two endogenous state variables, total capital K_t and financial sector net worth N_t, and one exogenous state, the exogenous risk affecting the payoff profile from the risky technology ϵ_t^{ξ}.

Transition paths are solved by backward induction starting from the terminal long-run equilibrium under full abatement. While the initial change in the transition speed is an unexpected shock, we account for uncertainty along the transition path as agents are aware of the materialization of shocks. Our solution method in principle allows us to solve the equilibrium for any non-linear carbon tax path, although we restrict our attention to monotonic tax paths in the quantitative analysis. For details on the numerical solution method, we refer to Appendix B.

Table 1: **Calibration**

a) Conventional parameters		Value	Target / Source
Discount factor	β	0.9975	Risk free rate of 1.0% p.a.
Frisch labor elasticity	$1/\gamma_L$	0.75	Chetty et al. (2011)
Risk aversion	γ_C	1	Log utility for consumption
TFP level	A	0.407	Output normalization
Government spending	G	0.2	Govt. spending to output ratio of 20%
Capital share	α	0.33	Capital income share of 33%
Capital depreciation	δ	0.025	Depreciation rate of 10% p.a.
Price elasticity of demand	ϵ	10	Markup of 11%
Rotemberg adjustment costs	ρ^r	178	Calvo duration of 5 quarters
Investment cost intercept	a_0	-.008	Normalization of $\Gamma(I/K) = I$
Investment cost slope	a_1	0.530	Asset price normalized to 1
Investment cost curvature	a_2	0.25	Bernanke et al. (1999)
Target inflation	Π	1.005	Inflation target of 2%
MP response to inflation	κ_Π	2.0	Conventional value
MP response to output	κ_y	0.125	Conventional value
b) Climate policy parameters		**Value**	**Target / Source**
Abatement cost slope	θ_1	0.05	In line with Nordhaus (2008)
Abatement cost curvature	θ_2	1.6	In line with Nordhaus (2008)
Pollution decay rate	δ_E	0.9979	In line with Nordhaus (2008)
c) Financial sector and shock parameters		**Value**	**Target / Source**
Slope intermediation cost HH	γ^F	0.38	Share financial sector
Target intermediation cost HH	ω_F	0.04	Leverage multiple of 15
Mean risky technology	ψ	0.01	Rottner (2023)
Survival rate	ζ	0.885	Credit spread of 90bp
Persistence risk	ρ^ξ	0.96	Rottner (2023)
Std. dev. risk shock	σ^ξ	0.0031	Financial crisis probability = 2%
Sunspot shock probability	Υ	0.5	Normalization

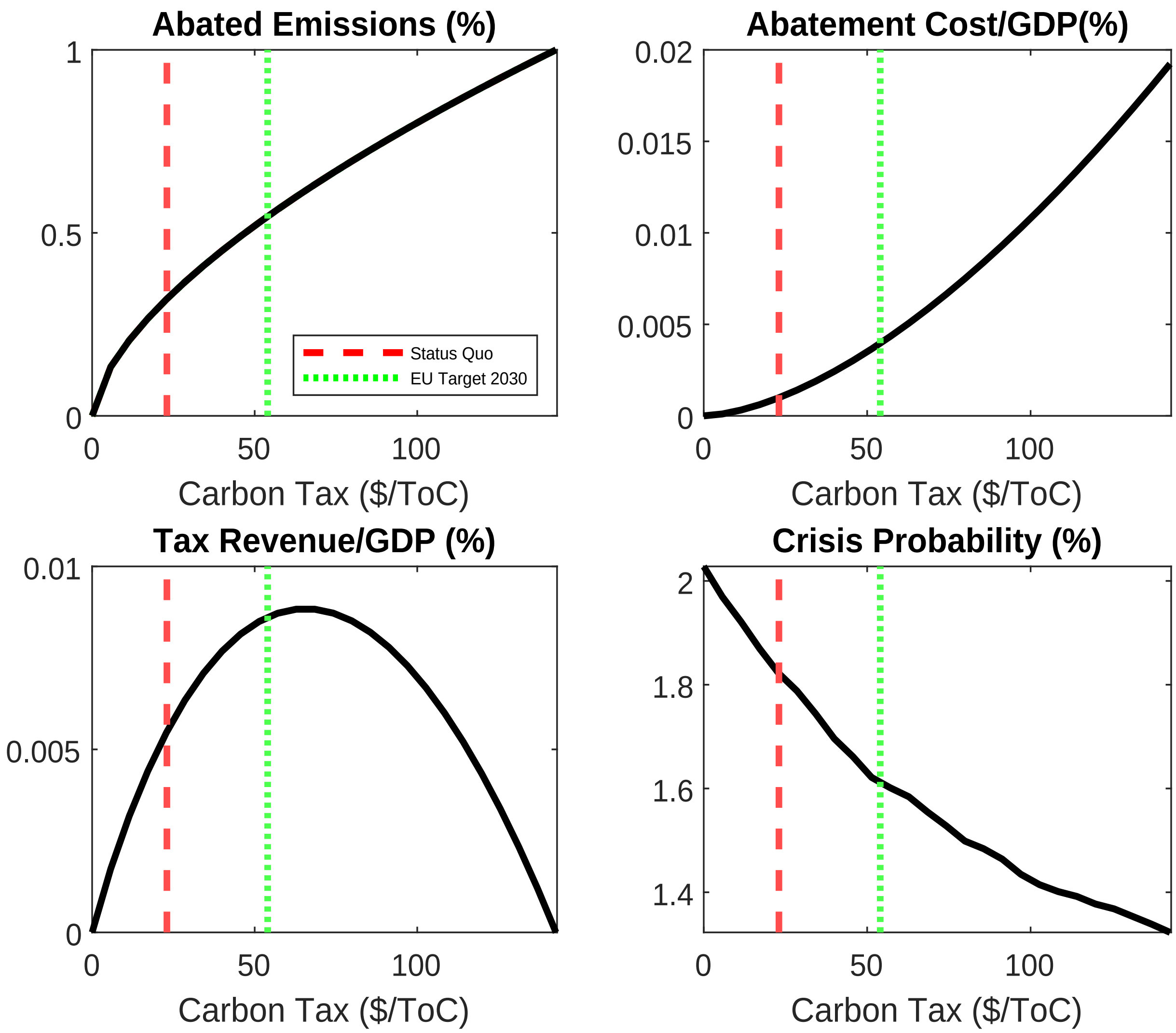
4 Quantitative Analysis

In this section, we use our calibrated model to study the financial stability implications of climate policy, proceeding in two steps. First, we demonstrate how carbon taxes affect financial stability in the long-run. Second, we study the transition dynamics from a slow transition path (*business-as-usual*) to an *ambitious climate policy* path, which is consistent with emission reduction goals specified in the Paris Agreement.

4.1 Carbon Taxes: Long-Run Effects

Figure 1 demonstrates how varying carbon taxes affects the macroeconomy and financial stability in the long-run. We solve the model economy for different time-invariant carbon tax levels, ranging from zero to 143$/ToC, which implies full abatement in our baseline calibration. The share of abated emissions implied by a given long-run tax is shown

Figure 1: **Carbon Taxes and Financial Stability in the Long-Run**



Notes: The crisis probability is computed based on a simulation with 100.000 periods with 10.000 burn-in periods.

in the upper left panel. The dashed red line indicates a value of 27$/ToC. This tax implies an abatement share of 33%, corresponding to the empirically observed emission reduction from 1990 to 2023. As an additional reference point, the dotted green line refers to a value of 54$/ToC, which implies an abatement share of 55%, consistent with the European Union's emission reduction target in 2030.[11]

The upper right panel shows that abatement costs increase in a concave fashion towards full abatement. In the bottom left panel, we demonstrate how the carbon tax bill per unit of capital is affected. Consistent with standard public finance theory, tax revenues exhibit a concave Laffer curve shape. Revenues vanish once full abatement is reached

[11]Under an array of climate policy measures, labeled "Fit for 55", announced in 2021, the European Union aims to reduce emissions by 55% relative to 1990. For details on the "Fit for 55" legislation, we refer to this link. Reports on the European Union's progress in achieving climate policy objectives are available under this link.

since the tax base is zero in this case. Note that abatement costs are convex, which implies that the decline in the tax bill does not compensate the increase of abatement costs. Consequently, the wedge ξ_{t+1} in the marginal product of capital is an increasing function of the carbon tax.

The bottom right panel of Figure 1 reveals that the annualized crisis probability declines from around 2% to less than 1.5% under the 143%/ToC tax consistent with full abatement. It has to be stressed that the positive effect on financial stability does *not* follow from a reduction in emission damages form which we abstract throughout the analysis. Instead, they stem from an equilibrium effect operating through the relative size of the financial sector. Since carbon taxes reduce average productivity of the economy, aggregate capital is smaller in the long-run. Consequently, households have to manage fewer assets and incur a smaller utility loss from doing so. Put differently, the social value of the financial system declines.

A smaller financial system affects the crisis probability in the long-run: households have to acquire less capital if financial intermediaries need to sell assets in order to reduce their leverage ratio. It follows from their period utility function (3) that they are willing to pay a higher price for holding capital, ceteris paribus. Thus, intermediaries are more likely to be able to service depositors even at the fire sale price. This reduces the partition of the state space supporting the run equilibrium and, thereby, reduces the run frequency.

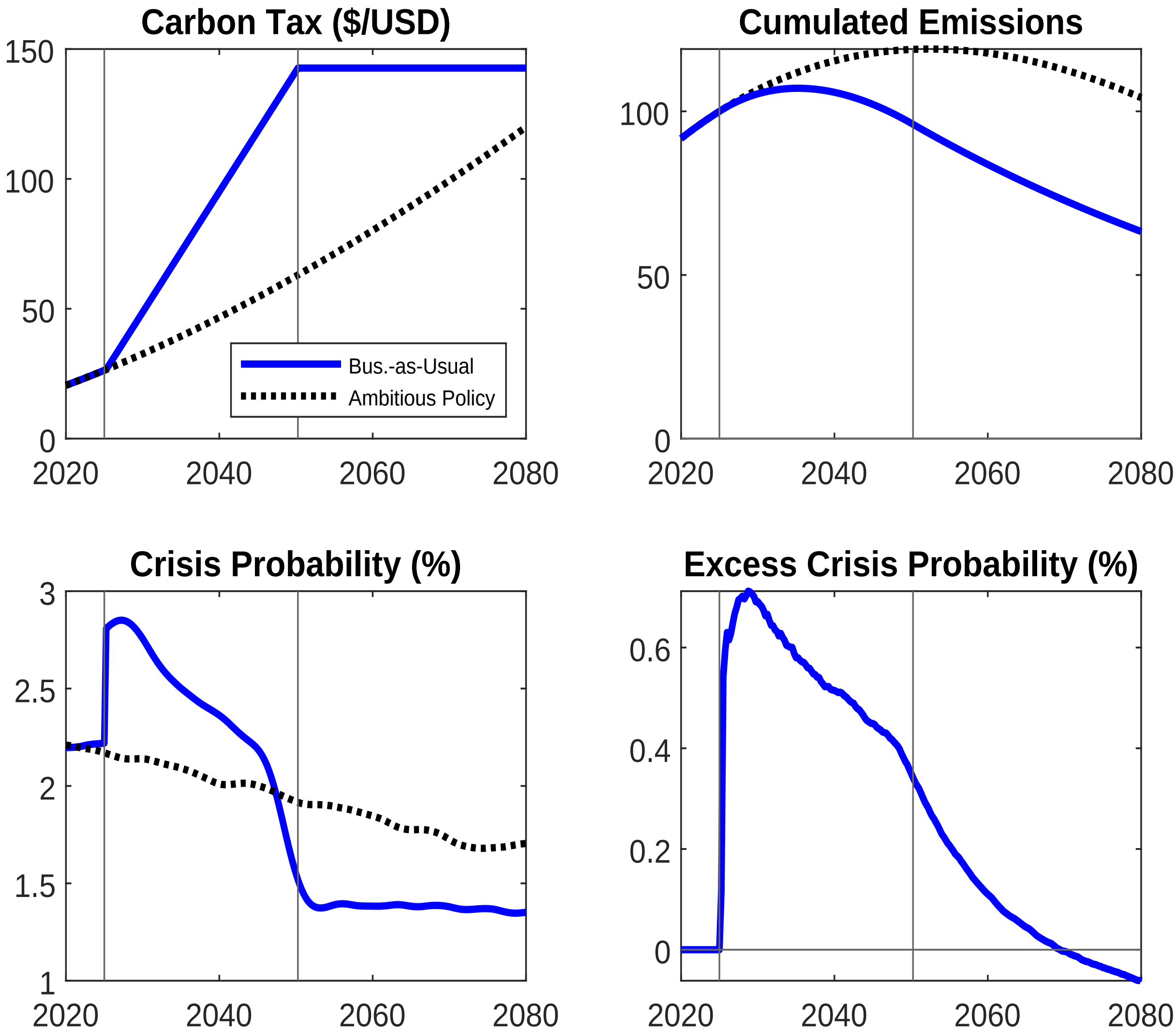
4.2 Financial Stability Along the Transition to Net Zero

We now evaluate the impact of carbon taxes on financial stability during the net zero transition. Specifically, we consider an unanticipated shift from lenient to more stringent climate policies. We first describe the lenient tax path, to which we will refer to as *business-as-usual*, before discussing different *ambitious policy* paths which are in line with climate policy objectives from the Paris Agreement. Our construction of different climate policy scenarios is in the spirit of NGFS (2022), as we also compute carbon tax paths that give rise to specific decarbonization objectives in our model.

The *business-as-usual* path is constructed based on actual emission reductions in the European Union from 1990 to 2023. Emissions declined almost linearly over this period and the average emission reduction relative to 1990 amounts to almost exactly one percentage point. Our *business-as-usual* path simply extrapolates this emission reduction until net zero is reached, which would correspond to 2090. We can compute the carbon tax path that gives rise to such a linear emission reduction from firms' optimal abatement effort (14). The implied carbon tax path is convex by the functional form assumption on the abatement cost function (13) and represented by the dashed black line in the upper left panel of Figure 2.

We then construct an alternative carbon tax path that represents a plausible bench-

Figure 2: **Baseline Transition Path to Net Zero**



Notes: This figure is obtained from simulating the model 100,000 times with a burn-in period of 200 quarters. Cumulated emissions are normalized to 100 in 2025. Crisis probabilities are annualized. We remove the sampling error from the crisis probability using cubic spline smoothing. The beginning and end of the transition period are indicated by vertical lines.

mark scenario of *ambitious climate policy*. In this scenario, the carbon tax path linearly increases until it is large enough to induce net zero emissions ($\eta_t^* = 1$) in period T_{max}. For our benchmark *ambitious policy* path, we set $T_{max} = 2050$. We interpret the year 2025 as the initial period T_0 in which the economy unexpectedly shifts from the *business-as-usual* onto the *ambitious policy* path. This carbon tax path is reflected by the solid blue line in the upper left panel of Figure 2. The tax path exhibits an annual increase in carbon taxes by five percentage points relative to 2025, which is in line with ambitious climate policy paths in multi-sector general equilibrium models (Jorgenson et al., 2018).

First, we discuss the implications of different carbon tax paths for carbon emissions. The upper right panel of Figure 2 demonstrates how carbon taxes affect the stock of atmospheric carbon, which is directly related to climate change damages. The stock of carbon declines if the carbon stock decays faster than current emissions. We normalize emissions to 100 in 2025, i.e. the last period prior to the shift towards ambitious climate policy. Under the *business-as-usual* scenario, there is a net increase of atmospheric carbon until around 2050, while the stock of carbon peaks around 2040 in the *ambitious policy* scenario. Once net zero is reached, the emission stock merely decays over time. Consequently, cumulated emissions are substantially smaller under the *ambitious policy* path than under the *business-as-usual* path at any given period after 2025. In 2070, for example, cumulated emissions would be 12% above their 2025 level if carbon taxes follow the *business-as-usual* path, while they would decline by 27% under *ambitious policy*.

The next step is to evaluate the impact of the transition on financial stability, as measured by the crisis probability. An important element in our analysis is that our framework is stochastic. To account for this, we simulate the economy along a given carbon tax path for 100.000 times, where the risk shock and the sunspot shock are drawn randomly such that the volatility of idiosyncratic productivity shocks follows (6) and the sunspot shock selects the equilibrium if multiplicity is possible. We then average over all economies to calculate the crisis probability.[12] We first focus on a representative average path before highlighting how transition dynamics depend on the financial cycle by considering above- and below-average realizations of the risk shock in the next subsection.

The solid blue line in the upper right panel of Figure 2 shows the crisis probability along the transition. It increases from around 2.2% on the initial path to around 2.7% at the beginning of the transition. At this point in time, the economy experiences an unanticipated shock to the carbon tax path and, thus, a negative permanent shock to the marginal product of capital. This event puts deleveraging pressure on the financial system. Notably, the crisis probability peaks several years into the transition and only slowly converges to its lower long-run level. Since capital and net worth are endogenous state variables, our model features a large degree of endogenous propagation. As the bottom right panel of Figure 2 demonstrates, the crisis probability under the ambitious transition path drops below the level in the *business-as-usual* case in 2045 and stays lower until the *business-as-usual* economy also converges to net zero, approximately in 2100. Clearly, there is a net financial stability gain from a faster convergence to the new stationary long-run equilibrium. Appendix D additionally displays how several key variables evolve during the transition, highlighting the outlined dynamics.

Evaluating the Net Financial Stability Effect To facilitate a comparison of the financial stability implications of different transition paths, it is necessary to define a suitable metric. One candidate is the maximum crisis probability over the transition path, which is typically attained within a dozen quarters after the transition starts.

[12]In order to enhance the readability of our graphs, we apply a cubic spline filter to the crisis probability. All numbers and moments are always computed based on the unfiltered simulation output.

However, this metric does not take into account the number of periods with a high crisis probability. It also does not capture the transition dynamics to the long-run equilibrium that is associated with a smaller crisis probability (see Figure 1).

To take these two features into account, we define the *excess crisis probability (ExCP)*:

$$ExCP(T_{post}, \widetilde{\beta}) = \frac{1}{T_{post} - T_0} \sum_{t=T_0}^{T_{post}} \widetilde{\beta}^t \Big(\pi_t(\text{amb policy}) - \pi_t(\text{business-as-usual}) \Big) \,, \tag{26}$$

where $\pi_t(\textit{amb policy})$ is probability of a financial crisis in period t on the *ambitious policy* path, while $\pi_t(\textit{business-as-usual})$ corresponds to crisis probability in period t on the *business-as-usual* path. We compute the difference from T_0 until the cut-off period T_{post}, allowing for the possibility of discounting future financial stability gains via the parameter $\widetilde{\beta}$. We fix the policymakers' time preference at unity, that is $\widetilde{\beta} = 1$, for the moment and discuss the role of reducing the time preference rate below one at the end of this section.

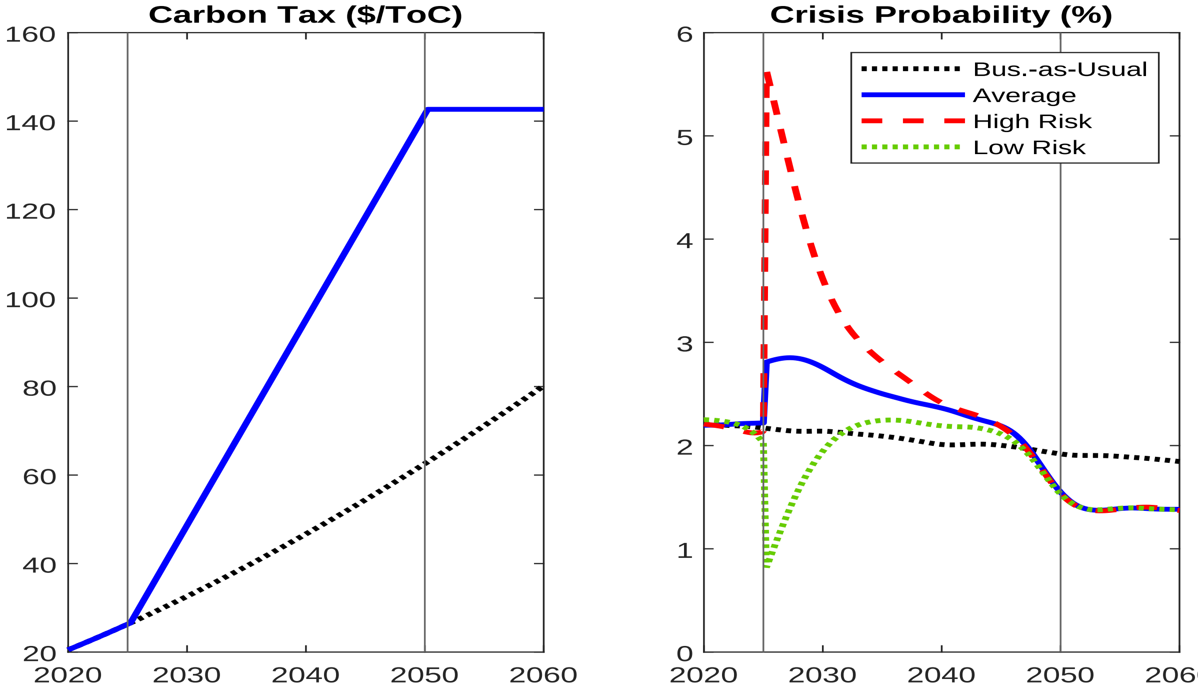
The *ExCP* allows to compare the financial stability impact of different climate policies and is closely connected to the notion of "Climate Minksy Moments". Since financial crises also occur in the absence of climate policy in our model, an appropriate quantification of the threat of "Climate Minksy Moments" requires us to take "Ordinary Minsky Moments" unrelated to ambitious carbon taxes into account. The *ExCP* is conceptually related to the area between the crisis probability under the *ambitious policy* path and the *business-as-usual* path, respectively, and is displayed in the bottom left panel of Figure 2. Due to the non-monotonic transition dynamics, it initially grows as the truncation point T_{post} increases. As soon as the crisis probability under the *ambitious policy* drops below the *business-as-usual* economy, the *ExCP* decreases. For all transition paths that we consider in our policy experiments, this period is reached around 2070.

Furthermore, the *ExCP* turns negative eventually in all ambitious scenarios that we considered, because the lower long-run level of the crisis probability is reached much faster than in the *business-as-usual* economy. The net financial stability effect in the long-run is, therefore, positive and we can compare different carbon tax paths by the inflection period at which the *ExCP* turns negative. In the very long-run, the *ExCP* converges to zero by definition, as all economies eventually converge to the same long-run level.

4.3 The Role of the Financial Cycle

The possibility of a "Climate Minsky Moment" depends jointly on the (exogenous) climate policy stance and the (endogenous) loss-absorbing capacity of the financial sector, i.e. its net worth. We illustrate how the loss-absorbing capacity shapes the financial stability implications of climate policy action. We focus on the same *ambitious policy* path

Figure 3: **Baseline Transition Path to Net Zero: Financial Cycle**



Notes: This figure is obtained from simulating the model 100,000 times with a burn-in period of 200 quarters. The high-risk (low-risk) scenario is obtained by setting the risk shock realization to minus (plus) one standard deviation in the two quarters preceding the shift towards ambitious climate policy. Crisis probabilities are annualized. We remove the sampling error from the crisis probability using cubic spline smoothing. The beginning and end of the transition period are indicated by vertical lines.

as before but condition our simulation on specific realizations of the risk shock, which endogenously affect the financial sectors' loss-absorbing capacity.

First, we evaluate the baseline transition path under the assumption that a sequence of negative (one standard deviation) risk shocks realizes in two quarters prior to the climate policy shift. This period of low volatility induces high leverage and a credit boom, capturing a volatility paradox in the spirit of Brunnermeier and Sannikov (2014). Once the surprise climate policy shift arrives, the financial sector is highly leveraged and lacks loss-absorbing capacity. As a consequence, the annualized crisis probability spikes to slightly more than 5% and stays elevated way into the transition. The dashed red line in the right panel of Figure 3 shows the run probability in the high risk case.

The opposing path, that is a sequence of positive (one standard deviation) risk shock realizations, forces the financial sector to deleverage by tightening credit supply. When the climate policy shift arrives, the financial sector is much better equipped to accommodate the sudden productivity loss without selling securities at a fire sale price. The crisis probability, displayed as the dotted green line in the right panel of Figure 3, declines substantially. The crisis probability remains persistently low, as the capital accumulation channel of climate policy dominates in the medium-run. This analysis outlines that a careful design of the transition to net zero should take vulnerabilities in the financial system into account. The threat of a "Climate Minsky Moment" after the climate policy shift depends to a substantial degree on the vulnerability in the financial sector.

4.4 Speed and Shape of the Transition

In the following, we provide two key comparative static exercises with respect to the shape of *ambitious policy* path.

Transition Speed First, we vary the *speed* of the transition to net zero, as shown in Figure 4. While full abatement is reached after 25 years in the baseline *ambitious policy*, net zero is achieved in the alternative transition scenarios either after 20 years ($T_{max} = 2045$) or after 30 years ($T_{max} = 2055$), respectively. As before, we assume that carbon taxes increase linearly until the terminal period. Consistent with the prediction from similar DSGE models, such as van der Ploeg and Rezai (2020), and recent empirical evidence (Kaenzig, 2023), a faster transition induces a stronger output contraction and larger asset return wedge ξ_t in the short-run (bottom right panel of Figure 4).

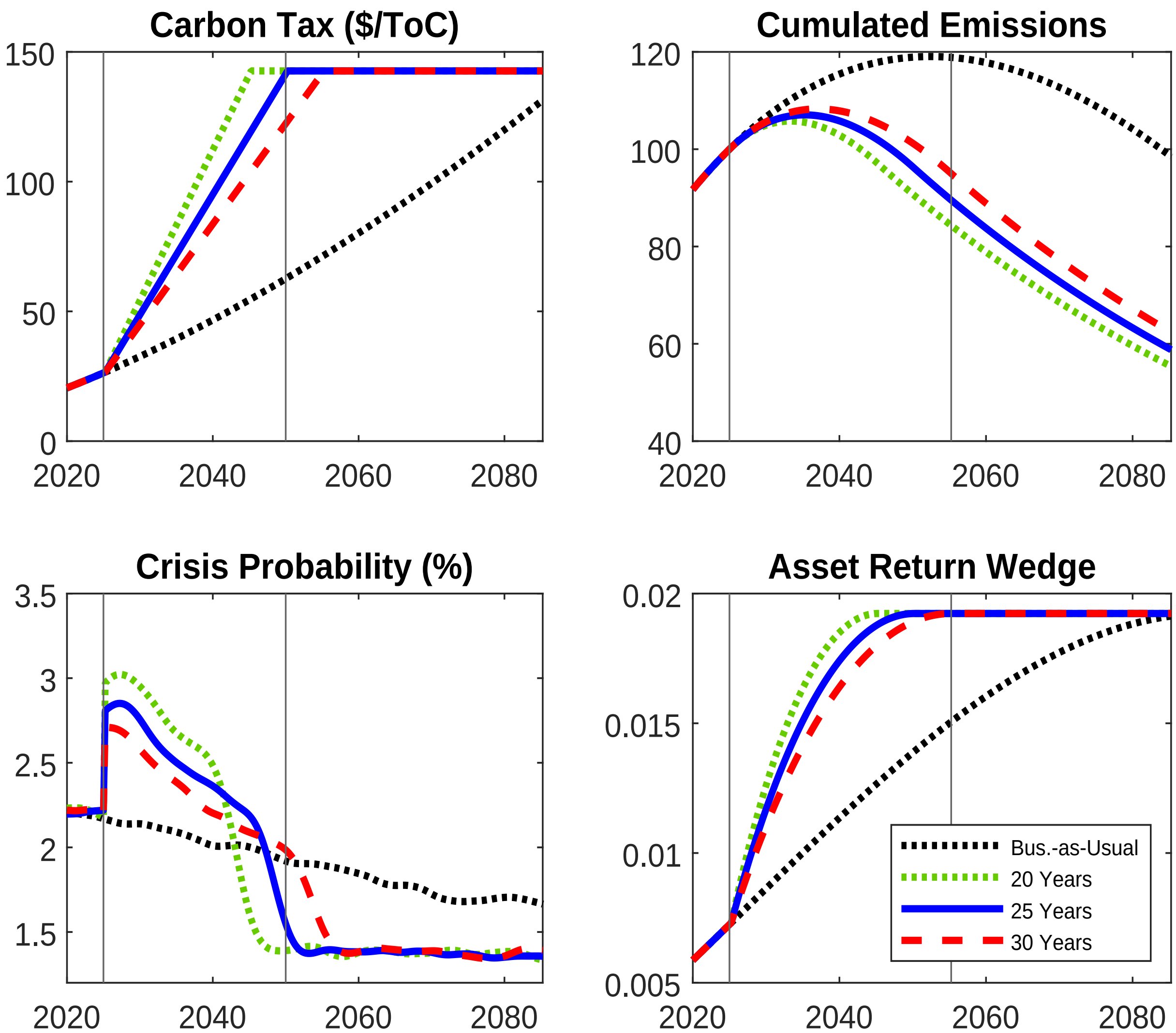
The upper right panel shows how the transition speed affects the crisis probability over time. The more ambitious transition, indicated by the dotted green line, features a larger crisis probability in the first five to ten years, relative to the baseline transition discussed before. After peaking at slightly above 3% p.a., the crisis probability rapidly shrinks towards the new stationary equilibrium. In contrast, the dashed red line represents an economy that reaches net zero after 30 years. In this economy, the crisis probability peaks at around 2.7%, but reaches the stationary long-run equilibrium later, such that the crisis probability is larger in the medium-run. The net financial stability effect of accelerating the transition is ambiguous. At the same time, accelerating the transition has a clearly positive effect on cumulated emissions, as demonstrated by the bottom left panel of Figure 4.

Transition Shape Second, we allow for a front- and a back-loaded transition. Here, we fix the terminal period at $T_{max} = 2050$ and vary the curvature of the tax path. For the back-loaded tax path, we assume that the carbon tax in period $t > T_0$ is a linear combination between the tax in the *business-as-usual* scenario τ_t^{bau} and the tax in the *ambitious policy* scenario τ_t^{amb} that is consistent with net zero in 2050. We define a weight $w_t \equiv \frac{t}{T_{max}-T_0}$ for any $t \in [T_0, T_{max}]$ that gives rise to a back-loading of the tax path:

$$\tau_t^{back} \equiv (1 - w_t)\tau_t^{bau} + w_t\tau_t^{amb} \ .$$

As the dashed red line in Figure 5 reveals, the back-loaded path features a rapid increase in the carbon tax in the last periods before reaching net zero. Such a scenario is sometimes

Figure 4: **Comparative Statics: Transition Speed**



Notes: This figure is obtained from simulating the model 100,000 times with a burn-in period of 200 quarters. Cumulated emissions are normalized to 100 in 2025. Crisis probabilities are annualized. We remove the sampling error from the crisis probability using cubic spline smoothing. The beginning and end of the transition period are indicated by vertical lines.

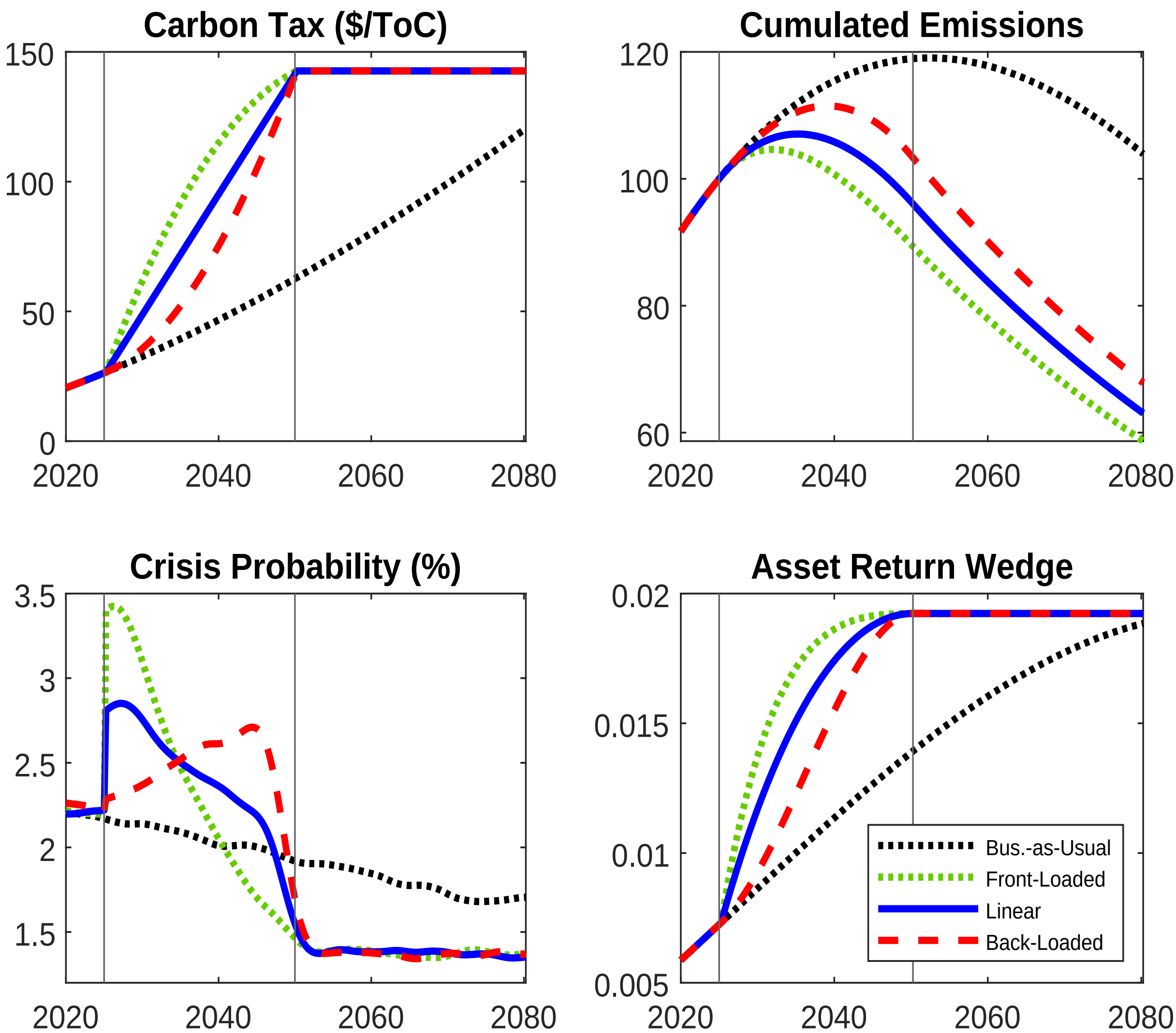
referred to as "disorderly transition".[13] We also define a front-loaded transition path that adds the (time-varying) difference between baseline and back-loaded taxes $(\tau_t^{amb} - \tau_t^{back})$ to the baseline path, resulting in a front-loading:

$$\tau_t^{front} \equiv \tau_t^{amb} + \left(\tau_t^{amb} - \tau_t^{back}\right) .$$

The upper left panel of Figure 5 compares these paths to the linear benchmark transition path, again indicated by the solid blue line. All paths reach net zero in 2050. The shape of the tax path has a substantial impact on financial stability, highlighted by the lower

[13]Note that the steep portion of the back-loaded tax path is anticipated as soon as the economy shifts to the new tax path and that the policymaker is fully committed to this path.

Figure 5: **Comparative Statics: Transition Shape**



Notes: This figure is obtained from simulating the model 100,000 times with a burn-in period of 200 quarters. Cumulated emissions are normalized to 100 in 2025. Crisis probabilities are annualized. We remove the sampling error from the crisis probability using cubic spline smoothing. The beginning and end of the transition period are indicated by vertical lines.

panel of Figure 5. The *front-loaded policy* features substantial additional fragility in the first five years due to the fast tax increase. The crisis probability peaks at almost 3.5%. However, financial fragility already reaches a lower level than the *business-as-usual* in 2040, substantially faster than our baseline. In contrast, the crisis probability peaks close to the end of transition for the *back-loaded policy* tax path. While the initial increase in instability is substantially mitigated, the crisis probability grows over time, peaks close to the end of the transition, and rapidly converges then to the stationary equilibrium. Again, the net financial stability effect is ambiguous.

From varying speed and shape of the transition path we conclude that, relative to the *business-as-usual* scenario, an ambitious transition to net zero is characterized by a temporarily elevated crisis probability and a subsequent convergence to a lower crisis probability in the long-run. More ambitious paths are generally characterized by a lower crisis probability in the medium-run, which comes at the cost of considerable financial fragility during the first years of the transition. Which of these opposing effects dominates is, thus, a quantitative question. In contrast, front-loading climate action has a substantially positive effect on cumulated emissions, while the economy's climate performance is much worse under back-loaded climate action.

Table 2: **Carbon Taxes and Financial Stability: Comparative Statics**

	Speed			Shape		
	20 Years	25 Years	30 Years	Front	Linear	Back
Maximum Crisis Prob (%)	3.22	**3.07**	2.89	3.76	**3.07**	2.93
Excess Crisis Prob (%)	-0.02	**0.00**	0.00	-0.04	**0.00**	0.02
Inflection Period	2067Q4	**2069Q3**	2069Q2	2066Q1	**2069Q3**	2073Q3
Cum. Emissions in 2070 (Rel. to bus.-as-usual, in %)	-37.2	**-33.3**	-29.3	-48.0	**-33.3**	-28.3

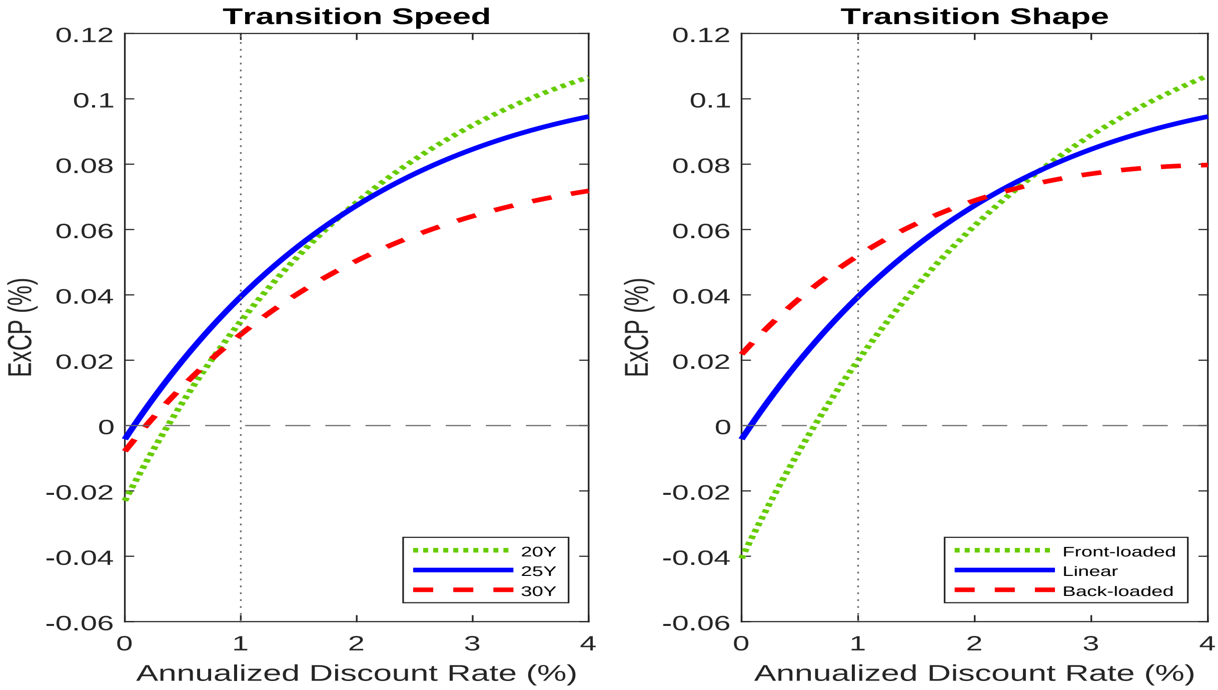
Notes: All moments are based on 100.000 tax paths with 200 burn-in periods per path. The *ExCP* is computed with respect *business-as-usual* transition path. The cut-off period T_{post} for the *ExCP* is set to 2070.

Inspecting the first row of Table 2, we observe that the maximum crisis probability is largest under the most ambitious scenario. In the second row, we are also factoring in the medium-run gains of the transition by comparing the *excess crisis probability* when setting $T_{post} = 2070$. When using this cut-off period, the *ExCP* takes into account that the crisis probability converges to its lower long-run level more quickly if the tax path is steeper. The inflection period in the third row is inversely related to the *ExCP* and is reached earliest (2066) for the front-loaded transition path while it takes until 2073 to reach *ExCP = 0* under a back-loaded transition.

Not surprisingly, the last row of Table 2 reveals that cumulative emissions in 2070, i.e. forty-five years after the shift in climate policies and 20 years after net zero is reached under the *ambitious policy* path, are substantially lower if carbon taxes increase faster or are front-loaded. Taken together, our comparative statics experiments raise doubt on the common narrative of a trade-off between maintaining financial stability and achieving climate policy objectives - provided that policymakers are sufficiently forward-looking to take the positive long-run financial stability gains of the net zero transition into account.

Discounting Long-Run Gains As a last step, we discuss the implications of discounting long-run financial stability gains from the net zero transition. Specifically, we compute the *excess crisis probability* until $T_{post} = 2070$ for different policymaker discount factors $\widetilde{\beta}$, see Equation (26). It should be stressed that $\widetilde{\beta}$ does not affect the equilibrium of our model. The left panel of Figure 6 compares the *discounted ExCP* for the accelerated, baseline, and slow transition path. For low discount rates, the fast transition path has the smallest *discounted ExCP* since the long-run financial stability gains receive a high weight, consistent with the left panel of Table 2. This reverts for discount rates exceeding 0.7% p.a., for which policymakers prefer a slow transition due to the low weight placed on the long-run financial stability gains.

Figure 6: **Net Financial Stability Effect: The Role of Discounting**



Notes: Crisis probabilities are annualized and obtained from simulating the model 100,000 times with a burn-in period of 200 quarters. As a reference point, the vertical dotted line indicates the household discount rate in the model, which is set to 1%.

The right panel of Figure 6 shows the corresponding result for back-loading the transition. While the magnitudes are generally larger in this case, a very similar picture emerges. For annualized discount rates above 2.5%, the *discounted ExCP* of the front-loaded transition exceeds *discounted ExCP* of the back-loaded transition. Put differently, for policymaker discount rates below 2.5%, front-loading climate action simultaneously improves financial stability and the economy's climate performance.

4.5 The Role of Abatement Subsidies

In the last section, we study the financial stability effects of abatement subsidies through the lenses of our model. So far, we assumed that carbon tax revenues are rebated to households in a lump sum fashion. Now, the carbon tax revenue is used as an abatement subsidy for firms.[14] Specifically, firms receive a flat subsidy per abated unit of emissions

[14]While climate policy has usually focused on carbon pricing and R&D subsidies for emission-free technologies, policymakers have recently started to subsidize the adoption of low-emission technologies at a large-scale. Examples include the "Inflation Reduction Act" in the US and the European Unions "Green New Deal".

$\eta_t Y_t$. The subsidy is financed with the carbon tax revenue so that the per-unit subsidy is given by $((1-\eta_t^*)\tau_t^c)/\eta_t^*$. Here, η_t^* is the aggregate level of abatement since firms take the size of the subsidy as exogenously given when choosing their individual abatement effort. The per-unit cost minimization problem becomes:

$$\min_{\eta_t} \quad (1-\eta_t)\tau_t^c + \frac{b_1}{b_2+1}\eta_t^{b_2+1} - \frac{(1-\eta_t^*)\tau_t^c}{\eta_t^*}\eta_t \ .$$

Differentiating with respect to η_t and imposing $\eta_t = \eta_t^*$, we obtain the following optimal abatement effort:

$$\eta_t^* = \min\left\{ \left(\frac{\tau_t^c}{b_1}\right)^{\frac{1}{b_2+1}}, 1 \right\} \ , \tag{27}$$

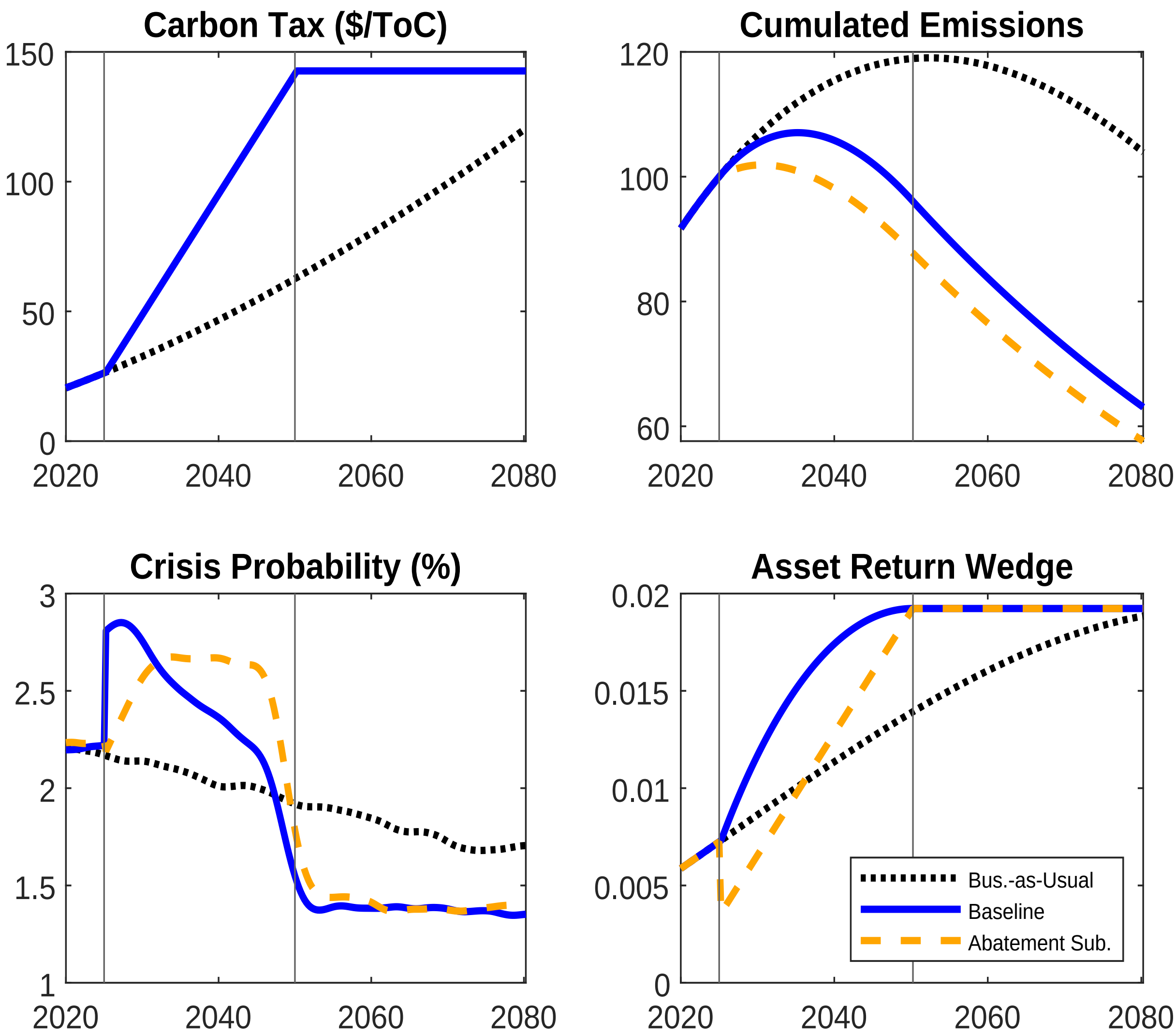
which exceeds the optimal abatement effort without subsidies (14) for any given carbon tax. The associated wedge in the return on capital simplifies to $\xi_{t+1} = \frac{\tau_{t+1}^c}{b_2+1}$. As long as the tax is positive, the wedge is always smaller than under the assumption of tax rebates to households. We compute the transition dynamics in the presence of abatement subsidies for the *ambitious policy* path consistent with net zero in 2050. As before, we compare its financial stability implications to the *business-as-usual* scenario consistent with a linear emission reduction until 2090 but without abatement subsidies.

The dashed orange line in the bottom right panel of Figure 7 shows that the shift towards ambitious climate policy induces a temporary fall in the asset return wedge. This follows from the assumption that there is no abatement subsidy in the *business-as-usual* scenario. After the initial drop, the return wedge linearly increases until 2050, i.e. when net zero is reached. Cumulated emissions since 1990 are 39.0% smaller in 2070 than under business as usual if an abatement subsidy is in place. This is substantially larger than in the case without subsidies (-33.3%) and even exceeds the gains from accelerating the transition and from front-loading climate action (-37.2%, see Table 2).

The top right panel of Figure 7 shows that the crisis probability increases very slowly over the first ten years of the transition without dropping below its initial level. The subsidy cushions intermediary net worth against rapid drops of the return on their assets, which entails a short-run financial stability gain. At the same time, this makes the downward adjustment of capital more sluggish. Therefore, the economy operates a larger capital stock well into the transition, compared to the case without subsidies (solid blue line). Consequently, households incur larger costs from managing capital once intermediaries experience deleveraging pressure, resulting in elevated crisis probabilities.

As we have shown in Figure 1, carbon tax revenues follow a Laffer curve and shrink to zero once full abatement is reached. Consequently, the subsidy becomes small towards the end of the transition, such that intermediaries face pressure to sell capital, which is still costly for households to absorb. The crisis probability, thus, remains above the baseline

Figure 7: **Transition Path to Net Zero: Carbon Tax Rebates**



Notes: This figure is obtained from simulating the model 100,000 times with a burn-in period of 200 quarters. Cumulated emissions are normalized to 100 in 2025. Crisis probabilities are annualized. We remove the sampling error from the crisis probability using cubic spline smoothing. The beginning and end of the transition period are indicated by vertical lines.

path throughout the transition and only drops below the *business-as-usual* scenario in 2048. This results in an *excess crisis probability* of 0.08% over the period 2025 to 2070, which is substantially larger than in the benchmark transition without subsidies. The inflection period at which the *ExCP* turns negative is 2081Q3, compared to 2064Q3 in the benchmark. Our analysis suggest that subsidies - a popular alternative policy instrument to accelerate the net zero transition - conflict to some extent with financial stability objectives.

5 Conclusion

In this paper, we have shown that climate policy has non-trivial effects on financial stability. We propose, solve, and calibrate a DSGE model with carbon taxes and endogenous financial crises and derive three main results. First, climate policy is not detrimental to financial stability in the long-run, since climate policy reduces long-run capital and, thereby, requires households to absorb fewer assets from the financial sector in an economic downturn. This reduces the asset price drop in a downturn and makes systemic financial crises less likely. Second, financial stability decreases in the short-run as the economy moves unexpectedly onto an ambitious carbon tax path. In response to such a shock to the return on their assets, financial intermediaries face deleveraging pressure which induces them to sell assets quickly, potentially at fire sale prices. This makes a systemic financial crisis more likely.

Third, we evaluate transition risk over the entire transition path, measured as *excess crisis probability*, and show that ambitious, front-loaded climate policy has a positive net effect: the *excess crisis probability* declines in climate policy ambition. At the same time, emission reductions are larger. Notably, the crisis probability peaks early and at high values for front-loaded and ambitious transitions. If policymakers are subject to substantial present bias or even myopia, non-trivial trade-offs between financial stability and emission reduction arise. However, for a sufficiently patient policymaker, there is no trade-off between achieving climate policy goals and maintaining financial stability.

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A Financial Intermediaries

In this section, we outline the maximization problem of financial intermediaries, which follows Rottner (2023).[15] The financial intermediary j maximizes its franchise value V_t^j subject to an incentive constraint and a participation constraint. The incentive constraint ensures that the intermediary only invests in the good technology. The participation constraint ensures that the return on deposits is sufficient that households provide deposits to the intermediary. The maximization problem reads as follows:

$$V_t^j(N_t^j) = \max_{K_t^{Bj}, \overline{D}_t} (1-\pi_t^j)\beta E_t^N \Lambda_{t,t+1}\left[\theta V_{t+1}^j\left(N_{t+1}^j\right) + (1-\theta)(R_{t+1}^K Q_t K_t^{Bj} - \overline{D}_t^j \Pi_{t+1}^{-1})\right], \tag{A.1}$$

$$\text{s.t.} \quad (1-\pi_t^j)E_t^N\left[\Lambda_{t,t+1}\theta V_{t+1}\left(N_{t+1}^j\right) + (1-\theta)\Big(1 - \frac{\overline{b}_t^j}{R_{t+1}^K \Pi_{t+1}}\Big)R_{t+1}^K Q_t K_t^{Bj}\right] \geq \tag{A.2}$$

$$\beta\Lambda_{t,t+1}E_t\left[\Lambda_{t,t+1}\int_{\frac{\overline{b}_t^j}{R_{t+1}^K \Pi_{t+1}}}^{\infty} \theta V_{t+1}\left(N_{t+1}^j\right) + (1-\theta)\Big(\omega - \frac{\overline{b}_t^j}{R_{t+1}^K \Pi_{t+1}}\Big)R_{t+1}^K Q_t K_t^{Bj} d\tilde{F}_{t+1}(\omega)\right],$$

$$(1-\pi_t^j)\beta E_t^N[\Lambda_{t,t+1}Q_t K_t^{Bj}\overline{b}_t^j \Pi_{t+1}^{-1}] + \pi_t^j \beta \mathbb{E}_t^R[R_{t+1}^K Q_t K_t^{Bj}] \geq D_t^j. \tag{A.3}$$

We define $\overline{D}_t^j = \overline{R}_t D_t^j$ and $\overline{b}_t^j = \left(\overline{R}_t D_t^j\right)/(Q_t K_t)$. As shown step-by-step in Rottner (2023), Appendix B, we can use a guess and verify approach to derive the incentive and participation constraint:

$$(1-\pi_t)\mathbb{E}_t^N\left[\Lambda_{t,t+1}R_{t+1}^K(\theta\lambda_{t+1} + (1-\theta))\big(1 - e^{\frac{-\psi}{2}} - \Omega_{t+1}\big)\right] = \pi_t \mathbb{E}_t^R\left[\Lambda_{t,t+1}R_{t+1}^K\big(e^{-\frac{\psi}{2}} - \overline{\omega}_{t+1} + \Omega_{t+1}\big)\right], \tag{A.4}$$

$$(1-\pi_t)\mathbb{E}_t^N\left[\beta\Lambda_{t,t+1}\overline{R}_t^D D_t] + \pi_t \mathbb{E}_t^R[\beta\Lambda_{t,t+1}R_{t+1}^K Q_t K_t^B\right] = D_t\,. \tag{A.5}$$

Note that the incentive constraint and the participation constraint do not depend on intermediary j specific values. The multiplier for the incentive constraint (κ_t) and participation constraint (λ_t) are given as:

$$\kappa_t = \frac{\beta(1-\pi_t)\mathbb{E}_t^N \Lambda_{t,t+1}\left[\lambda_t - (\theta\lambda_{t+1} + 1 - \theta)\right]}{(1-\pi_t)\mathbb{E}_t^N\Lambda_{t,t+1}\left[(\theta\lambda_{t+1} + 1 - \theta)\widetilde{F}_{t+1}(\overline{\omega}_{t+1})\right] + \pi_t\mathbb{E}_t^R\Lambda_{t,t+1}\left[(\theta\lambda_{t+1} + 1 - \theta)\left(1 - \widetilde{F}_{t+1}(\overline{\omega}_{t+1})\right)\right]}, \tag{A.6}$$

$$\lambda_t = \frac{(1-\pi_t)\mathbb{E}_t^N\Lambda_{t,t+1}R_{t+1}^K[\theta\lambda_{t+1} + (1-\theta)](1-\overline{\omega}_{t+1})}{1 - (1-\pi_t)\mathbb{E}_t^N[\Lambda_{t,t+1}R_{t+1}^K\overline{\omega}_{t+1}] - \pi_t\mathbb{E}_t^R[\Lambda_{t,t+1}R_{t+1}^K]}. \tag{A.7}$$

B Global Solution Method

We solve the model with global methods to account for the runs on the financial sector and the stochastic transition path to a net zero economy. We extend the global solution

[15] We also refer to Adrian and Shin, 2014 and Nuño and Thomas, 2017.

method of Rottner (2023), which can solve the type of run models studied here, to feature stochastic transition paths. Incorporating this feature is key to evaluating the financial stability impact of climate policies during the transition and in the long-run.

The state variables are previous period capital, current period net worth, the risk shock and the sunspot shock, that is $X_t = \left\{K_{t-1}, N_t, \epsilon_t^{\xi}, \epsilon_t^{\pi}\right\}$. We also condition the solution on the carbon tax path $\{\tau_l^c\}_{l=t}^{\infty}$ to allow for changing carbon taxes. In particular, we consider two distinct cases for the tax path in the model.

1. Long-run equilibrium: The tax path is constant. This case is relevant once the transition is completed or before agents anticipate future carbon taxation. The tax sequence is then constant for all periods, that is $\tau_t^c = \tau^c, \forall t$.

2. Transition dynamics: The tax path follows a commonly known path with time-varying taxes. Specifically, the tax path consists of two parts: First, the tax rate changes over time until its terminal level is reached in period T_{max}, that is $\{\tau_l^c\}_{l=t}^{T_{max}}$. This part reflects the transition. Once the maximum tax rate is reached, the tax remains constant, that is $\tau_t^c = \tau^c, \forall t > T_{max}$. At this level, we are back in the first case denoted as long-run equilibrium.

While the tax path is constant and known by the agents, the economy is subject to shocks. Therefore, we are analyzing stochastic transition dynamics, in which the agents expect the materialization of shocks.[16] The remaining parameters of the model are summarized as θ^P.

To find the model solution, we solve the policy functions for the asset price, consumption, the multiplier on the participation constraint, a measure of the promised repayments, and inflation. The policy function in period t depends on the state variables, the parameters, and the sequence of carbon shocks from period t onwards:

$$Q_t(X_t; \{\tau_l^c\}_{l=t}^{\infty}, \Theta^P), C_t(X_t; \{\tau_l^c\}_{l=t}^{\infty}, \Theta^P), \bar{b}_t(X_t; \{\tau_l^c\}_{l=t}^{\infty}, \Theta^P),$$
$$\Pi_t(X_t; \{\tau_l^c\}_{l=t}^{\infty}, \Theta^P), \quad \text{and} \quad \lambda_t(X_t; \{\tau_l^c\}_{l=t}^{\infty}, \Theta^P).$$

We also solve for the law of motion of net worth and the probability of observing a run next period:

$$N_t'(X_t, \epsilon_{t+1}^{\xi}; \{\tau_l^c\}_{l=t}^{\infty}, \Theta^P), \quad \text{and} \quad \pi_t(X_t; \{\tau_l^c\}_{l=t}^{\infty}, \Theta^P),$$

where ϵ_{t+1}^{ξ} are the risk shock realizations next period. Once we have solved for these objects, we can back out all other variables.

The solution algorithm uses time iteration with linear interpolation (see e.g. Richter et al., 2014). We also use an additional piecewise approximation of the policy functions

[16]The framework can be easily extended by tax paths that are subject to shocks themselves. In such a case, the shock component of the tax rate enters as a state variable.

by deriving separate policy functions to approximate the run and normal equilibrium as discussed in detail Rottner (2023). The expectations are approximated with Gauss-Hermite quadrature.

Our global solution algorithm is summarized below:

1. We first define a grid for the state variables (without the sunspot shock): $\boldsymbol{X} \in [\underline{K}_{t-1}, \overline{K}_{t-1}] \times [\underline{N}_t, \overline{N}_t] \times [\underline{\sigma}_t, \overline{\sigma}_t] \times [\underline{A}_t, \overline{A}_t]$. Using Gauss-Hermite quadrature, we set up integration nodes for the expectations with respect to the risk shock $\boldsymbol{\epsilon} \in [\underline{\epsilon^{\xi}}_{t+1}, \overline{\epsilon^{\xi}}_{t+1}]$. We denote the considered tax path by $\{\tau_l^c\}_{l=t}^{\infty}$.

2. We guess the piecewise linear policy functions to initialize the algorithm. This includes a separate guess for the policy function for each different carbon tax level. As an example, we have the following set of policy functions for the asset price:

$$\{Q_t(X_k; \{\tau_l^c\}_{l=t}^{\infty}, \Theta^P)\}_{t=t_0}^{\infty}$$

   While this would result in an infinite set of policy functions, we can exploit that policy functions are time-invariant once the terminal tax rate is reached. Therefore, we can simplify the set of policy functions that we need to solve for the two different cases that we consider:

   (a) Long-run equilibrium: The tax path is time-invariant. As a consequence, the policy function is not path-dependent. We then have:

$$Q_t(X_t; \{\tau_l^c\}_{l=t}^{\infty}, \Theta^P) = Q(X_t; \{\tau_l^c\}_{l=t}^{\infty}, \Theta^P) = Q(X_t; \tau^c, \Theta^P), \forall t$$

   (b) Transition dynamics: At the beginning, the tax path changes over time, while it then converges to the terminal rate. Therefore, we have two different problems at different stages in time:

$$\forall t \leq T_{max} : \{Q_t(X_t; \{\tau_l^c\}_{l=k}^{\infty}, \Theta^P)\}_{t=t_0}^{T_{max}} = \{Q_t(X_t; \{\tau_l^c\}_{l=k}^{T_{max}}, \Theta^P)\}_{t=t_0}^{T_{max}},$$
$$\forall t > T_{max} : Q_t(X_t; \{\tau_l^c\}_{l=t}^{\infty}, \Theta^P) = Q(X_t; \{\tau_l^c\}_{l=t}^{\infty}, \Theta^P) = Q(X_t; \tau_{T_{max}}^c, \Theta^P).$$

   This notation highlights that we can use a time iteration algorithm to solve for the policy functions. If we are in an infinite time horizon, that is either the long-run equilibrium or at the terminal tax rate, we solve the problem using policy function iteration. We can divide the transition dynamics in a finite horizon problem during the transition and an infinite horizon problem with the terminal tax rate after $t > T_{max}$. We first solve the infinite horizon problem using policy function iteration as before. We can then use this to conduct backward induction to solve the finite horizon problem of the transition.

While we discussed this for the specific asset price policy function, this generalizes to all policy functions that we need to solve. In particular, we need a guess for all policy functions, the probability that a run occurs next period, and the law of motion of net worth. The latter $N_t'(X_t, \epsilon_{t+1}^{\xi}; \Theta^P)$ provides a mapping from state variables today into net worth next period at each integration point coming from Gauss-Hermite quadrature.

3. We solve for all time t variables for a given state vector and tax path ahead focusing on the no run equilibrium. We use the law of motion for net worth and the run probability from the previous iteration j as given. We also need to calculate our next period values using policy functions. In the infinite horizon problem, we use the guess of the policy function iteration from iteration $j-1$. In the finite horizon problem, we use the policy function from period $t+1$, i.e. $Q_{t+1}(\cdot)$. Expected values are computed using Gauss-Hermite quadrature. We then use a numerical root finder to minimize the error of these equations. The inputs are the time-invariant policy functions in the infinite horizon problem and the period t policy functions for the finite horizon problem:

$$
\begin{aligned}
\text{err}_1 &= \left(\frac{\Pi_t}{\Pi} - 1\right)\frac{\Pi_t}{\Pi} - \left(\frac{\epsilon}{\rho^r}\left(MC_t - \frac{\epsilon-1}{\epsilon}\right) + \Lambda_{t,t+1}\left(\frac{\Pi_{t+1}}{\Pi} - 1\right)\frac{\Pi_{t+1}}{\Pi}\frac{Y_{t+1}}{Y_t}\right),\\
\text{err}_2 &= 1 - \beta\mathbb{E}_t\Lambda_{t,t+1}\frac{R_t^I}{\Pi_{t+1}},\\
\text{err}_3 &= (1-\pi_t)\mathbb{E}_t^N\left[\beta\Lambda_{t,t+1}\overline{R}_t D_t\right] + \pi_t\mathbb{E}_t^R\left[\beta\Lambda_{t,t+1}R_{t+1}^K Q_t K_t^B\right] - D_t,\\
\text{err}_4 &= (1-\pi_t)\mathbb{E}_t^N\left[\Lambda_{t,t+1}R_{t+1}^K(\theta\lambda_{t+1} + (1-\theta))(1 - e^{\frac{-\psi}{2}} - \Omega_{t+1})\right]\\
&\quad - \pi_t\mathbb{E}_t^R\left[\Lambda_{t,t+1}R_{t+1}^K(e^{-\frac{\psi}{2}} - \overline{\omega}_{t+1} + \Omega_{t+1})\right],\\
\text{err}_5 &= \lambda_t - \frac{(1-\pi_t)\mathbb{E}_t^N\Lambda_{t,t+1}R_{t+1}^K[\theta\lambda_{t+1} + (1-\theta)](1-\overline{\omega}_{t+1})}{1 - (1-\pi_t)\mathbb{E}_t^N[\Lambda_{t,t+1}R_{t+1}^K\overline{\omega}_{t+1}] - \pi_t\mathbb{E}_t^R[\Lambda_{t,t+1}R_{t+1}^K]}.
\end{aligned}
$$

4. We now take our policy functions as well as the law of motion for net worth and the run probability from iteration $j-1$ as given. Using these objects, we calculate the variables for the period t and $(t+1)$ variables. We use these points to calculate N_{t+1} across the integration nodes and update the law of motion for net worth:

$$N_{t+1} = \max\left[R_{t+1}^K Q_t K_t^B - \overline{R}_t D_t, 0\right] + (1-\theta)\zeta K_t. \tag{B.1}$$

To determine whether the run equilibrium is supported on a specific node, we compute

$$R_{t+1}^K Q_t K_t^B - \overline{R}_t D_t \leq 0. \tag{B.2}$$

which evaluates to one if a run is possible.[17] This can be now used to evaluate the probability of a run next period based on Gauss-Hermite quadrature.

5. We repeat the steps 3 and 4 focusing also on the run equilibrium in the current period.

6. We update the policy functions, the law of motion for net worth, and the run probability using a weighted combination of our results from iteration j and the previous guess.

7. We repeat the steps 3 - 6 until the errors of all functions (policy functions, law of motion of net worth, and the probability of a run) are sufficiently small at each point of the discretized state space.

8. The infinite horizon problem is solved at this stage.

   For the finite horizon problem, we redo the steps 3 - 7 for all periods backwards, i.e. in the order of $T_{max}-1, T_{max}-2, ..., t_0+1$, and finally t_0. Furthermore, we also need to calculate one additional object. The law of motion that gives the mapping from the period t_0-1 without the tax path and the period in which the transition arrives unanticipated: $N'_{t_0-1}(X_{t_0-1}, \epsilon^{\xi}_{t_0}; \{\tau^c_l\}^{\infty}_{l=t_0-1}, \Theta^P)$. For this, we use step 4 using the old policy functions for the period t_0-1 (e.g. the previous long-run equilibrium) and the newly obtained policy functions for period t_0-1.

We can now use the obtained functions to simulate our model and calculate our transition dynamics.

C Robustness

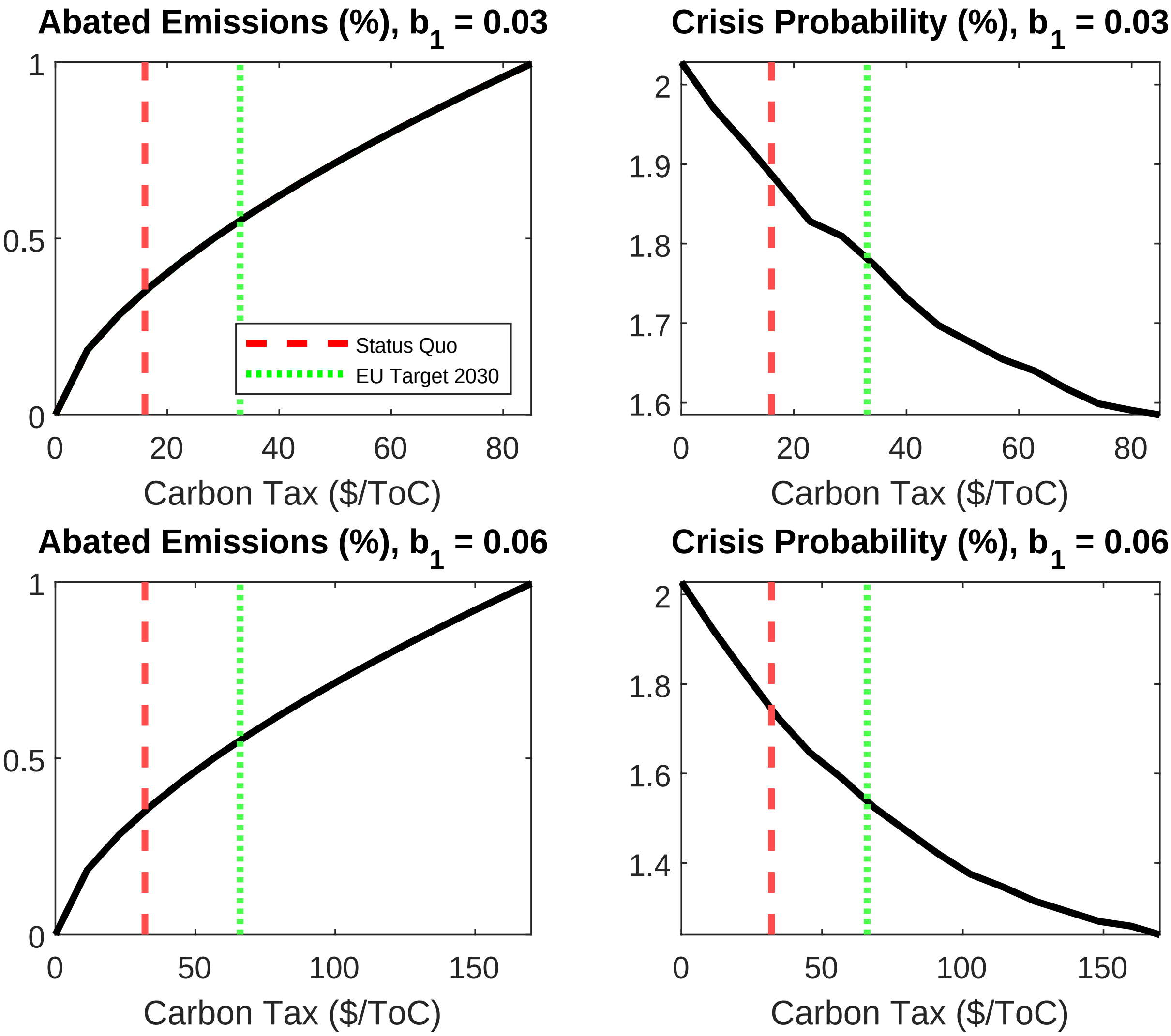
In this section, we demonstrate that our key results are robust to empirically plausible variations in the abatement cost parameters, which are subject to considerable parameter uncertainty.

Robustness with respect to $\mathbf{b_1}$ Figure C.1 shows the long-run financial stability effects of changing carbon taxes for different values of the slope parameter b_1 in the abatement cost function. In the upper panel, we set $b_1 = 0.03$, which implies that net zero is already reached at a carbon tax of 86\$/ToC. Similarly, a tax of 33\$/ToC suffices to

[17] The equation implies a zero and one indicator, which is a very unsmooth object. As a consequence, we use the following functional forms based on the exponential function to determine the run probability in this state of the world: $\frac{\exp(\zeta_1(1-D_{t+1}))}{1+\exp(\zeta_1*(1-D_{t+1}))}$ where $D_{t+1} = \frac{R^k_{t+1}}{R^D_t}\frac{\phi}{\phi-1}$ at each calculated N_{t+1}. We set ζ_1 to 500 which ensures sufficient steepness. While this approximation induces smoothness, it is still very close to an indicator function with 0 and 1 values.

reach the EU's 55% emission reduction target in 2030, which is indicated by the vertical red line.

Figure C.1: **Carbon Taxes and Long-Run Financial Stability for Different** b_1



Notes: The crisis probability is computed based on a simulation with 100.000 periods with 10.000 burn-in periods.

The lower panel presents the results from setting $b_1 = 0.06$. Under this parameter, a carbon tax of 171\$/ToC implements net zero while a 66\$/ToC is necessary to induce an emission reduction of 55% relative to 1990. The carbon tax necessary to achieve a given emission reduction increases in the slope parameter since exercising abatement effort is more costly if b_1 is high. This is also reflected in the different ranges on the x-axis in the upper and lower panel of Figure C.1, respectively. The results are qualitatively and quantitatively very similar to our baseline calibration of $b_1 = 0.05$.

When constructing transition paths under different parameterizations of the abatement cost function, we still maintain the assumption that the *business-as-usual* path is characterized by a linear emission reduction over 100 years and we adjust the tax path

Table C.1: **Financial Stability along the Transition for Different b_1**

$b_1 = 0.03$	Speed			Shape		
	20 Years	25 Years	30 Years	Front	Linear	Back
Maximum Crisis Prob (%)	3.00	**2.70**	2.69	3.16	**2.70**	2.70
Excess Crisis Prob (%)	-0.04	**-0.03**	-0.03	-0.06	**-0.03**	-0.02
Inflection Period	2064Q3	**2065Q1**	2065Q4	2061Q3	**2065Q1**	2066Q4
Cum. Emissions in 2070 (Rel. to bus.-as-usual, in %)	-37.1	**-33.2**	-29.1	-37.9	**-33.2**	-28.2
$b_1 = 0.06$	Speed			Shape		
	20 Years	25 Years	30 Years	Front	Linear	Back
Maximum Crisis Prob (%)	3.36	**3.14**	2.98	3.94	**3.14**	2.90
Excess Crisis Prob (%)	-0.02	**-0.01**	-0.01	-0.04	**-0.01**	0.04
Inflection Period	2068Q2	**2068Q2**	2069Q3	2066Q2	**2068Q2**	2075Q1
Cum. Emissions in 2070 (Rel. to bus.-as-usual, in %)	-37.3	**-33.4**	-29.3	-38.0	**-33.4**	-28.3

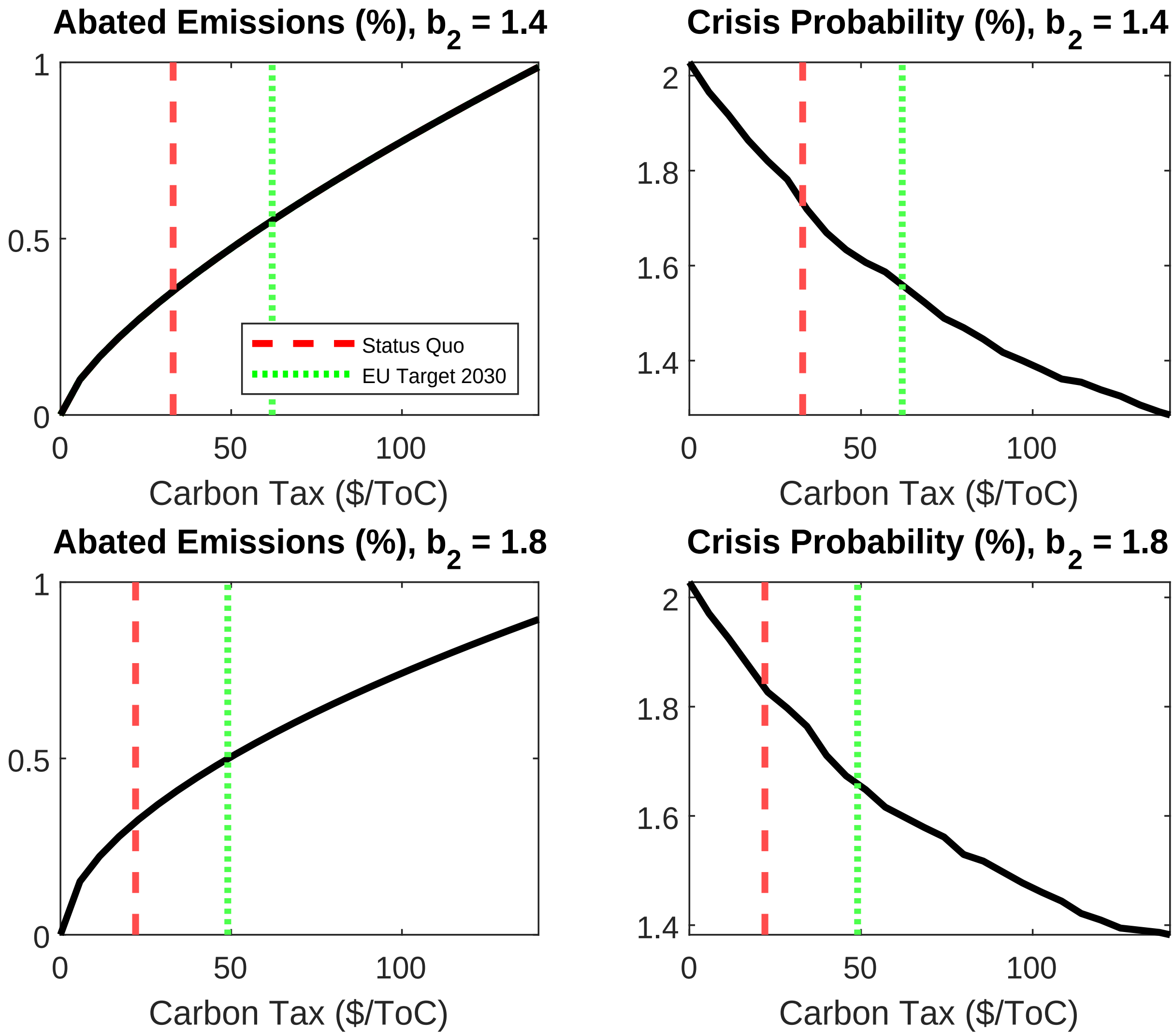
Notes: All moments are based on 100.000 tax paths with 200 burn-in periods per path. The terminal carbon tax corresponds to 143\$/ToC. The baseline transition path reaches net zero within 25 years, in 2050. The *ExCP* is computed with respect business-as-usual transition path which reaches net zero in 2090. The cut-off period T_{post} for the *ExCP* is set to 2070.

accordingly. For the *ambitious policy* path, we choose the terminal carbon tax level such that it implies net zero after the specified terminal period T_{max}, respectively. The model-implied carbon tax consistent with a 35% emission reduction in 2025 is given by $\tau^c = 0.00559$ (16\$/ToC) for $b_1 = 0.03$ and by $\tau^c = 0.0112$ (32 \$/ToC) for $b_1 = 0.06$, respectively, which is indicated by the vertical blue lines in the left panel of Figure C.1.

In Table C.1, we report the financial stability implications of the net zero transition for $b_1 = 0.03$ and $b_1 = 0.06$, respectively. Consistent with the baseline results, the *ExCP* computed from 2025 to 2070 and the inflection period are approximately independent of transition speed. However, front-loading climate action has a slightly positive effect on financial stability. The effects of changing transition speed and shape are also quantitatively similar to the baseline calibration.

Robustness with respect to $\mathbf{b_2}$ We also perform a robustness check for the curvature of the abatement cost function. The model-implied carbon tax consistent with a 35% emission reduction from 1990 to 2025 is given by $\tau^c = 0.0115$ (33 \$/ToC) for $b_2 = 1.4$ and by $\tau^c = 0.007756$ (22 \$/ToC) for $b_2 = 1.8$, respectively. An abatement share of 55% is induced by $\tau^c = 0.0115$ (33 \$/ToC) for $b_2 = 1.4$ and by $\tau^c = 0.007756$ (22 \$/ToC) for $b_2 = 1.8$, respectively. Notably, the curvature parameter does not change the carbon tax consistent with full abatement. However, even a small tax provides substantial abatement incentives if b_2 is large, as the left panel of Figure C.2 shows. Conversely, a higher curvature b_2 implies that the wedge in the return on capital is quite small for

Figure C.2: **Carbon Taxes and Long-Run Financial Stability for different b_2**



Notes: The crisis probability is computed based on a simulation with 100.000 periods with 10.000 burn-in periods.

low carbon tax levels, since abatement is not very costly initially, but increases rapidly towards the end of the transition.

In Table C.2, we show how changing the speed of the transition and front-loading climate action affect financial stability for different values of b_2. Again, changing structural parameters also affect the *business-as-usual* tax path that gives rise to a linear emission reduction, such that the financial stability effects of climate policy for the cases of $b_2 = 1.4$ (upper panel) and $b_2 = 1.8$ (lower panel) can not be directly compared with each other and to the baseline calibration. However, within each parameterization, there are modest financial stability gains from accelerating the transition and substantial gains from front-loading climate action. Specifically, the inflection period in which the *ExCP* turns negative is around three years earlier under front-loading while it is more than five years later under back-loading. These results are even stronger than under the baseline calibration.

Table C.2: **Financial Stability along the Transition for Different b_2**

$b_2 = 1.4$	Speed			Shape		
	20 Years	25 Years	30 Years	Front	Linear	Back
Maximum Crisis Prob (%)	3.15	**2.93**	2.78	3.55	**2.93**	2.72
Excess Crisis Prob (%)	-0.02	**-0.02**	-0.02	-0.04	**-0.02**	0.03
Inflection Period	2067Q2	**2067Q2**	2068Q1	2065Q2	**2067Q2**	2074Q3
Cum. Emissions in 2070	-36.8	**-32.7**	-28.5	-37.3	**-32.7**	-27.9
(Rel. to bus.-as-usual, in %)						
$b_2 = 1.8$	Speed			Shape		
	20 Years	25 Years	30 Years	Front	Linear	Back
Maximum Crisis Prob (%)	3.41	**3.18**	2.95	3.81	**3.18**	2.98
Excess Crisis Prob (%)	-0.04	**-0.02**	-0.02	-0.06	**-0.02**	0.02
Inflection Period	2066Q4	**2067Q4**	2067Q4	2064Q1	**2067Q4**	2073Q1
Cum. Emissions in 2070	-37.8	**-34.1**	-30.2	-38.8	**-34.1**	-28.7
(Rel. to bus.-as-usual, in %)						

Notes: All moments are based on 100.000 tax paths with 200 burn-in periods per path. The terminal carbon tax corresponds to 143\$/ToC. The baseline transition path reaches net zero within 25 years, in 2050. The *ExCP* is computed with respect business-as-usual transition path which reaches net zero in 2090. The cut-off period T_{post} for the *ExCP* is set to 2070.

Robustness with respect to T_{post} In Table C.3, we complement our main numerical results on the net financial stability of the net zero transition (Table 2) by considering different cut-off periods T_{post} for the *ExCP* and the cumulated emission reduction. Notably, the maximum crisis probability and the inflection period are not affected by the choice of T_{post}. Consistent with the results from setting $T_{post} = 2070$, we observe that the *ExCP* is largely independent of the transition speed, while emission reductions are much stronger in the economy with an accelerated transition path. Furthermore, front-loading climate action does not pose a trade-off between financial stability and climate performance, irrespective of T_{post}.

Table C.3: **Financial Stability along the Transition for Different T_{post}**

$T_{post} = 2050$	Speed			Shape		
	20 Years	25 Years	30 Years	Front	Linear	Back
Excess Crisis Prob (%)	0.31	**0.34**	0.26	0.29	**0.34**	0.40
Cum. Emissions in 2050	-16.9	**-11.8**	-7.2	-17.9	**-11.8**	-5.1
(Rel. to bus.-as-usual, in %)						
$T_{post} = 2060$	Speed			Shape		
	20 Years	25 Years	30 Years	Front	Linear	Back
Excess Crisis Prob (%)	0.08	**0.10**	0.10	0.07	**0.10**	0.14
Cum. Emissions in 2060	-27.8	**-23.3**	-18.6	-28.6	**-23.3**	-17.5
(Rel. to bus.-as-usual, in %)						
$T_{post} = 2080$	Speed			Shape		
	20 Years	25 Years	30 Years	Front	Linear	Back
Excess Crisis Prob (%)	-0.07	**-0.06**	-0.07	-0.09	**-0.06**	-0.04
Cum. Emissions in 2080	-45.4	**-42.1**	-38.5	-46.1	**-42.1**	-37.7
(Rel. to bus.-as-usual, in %)						

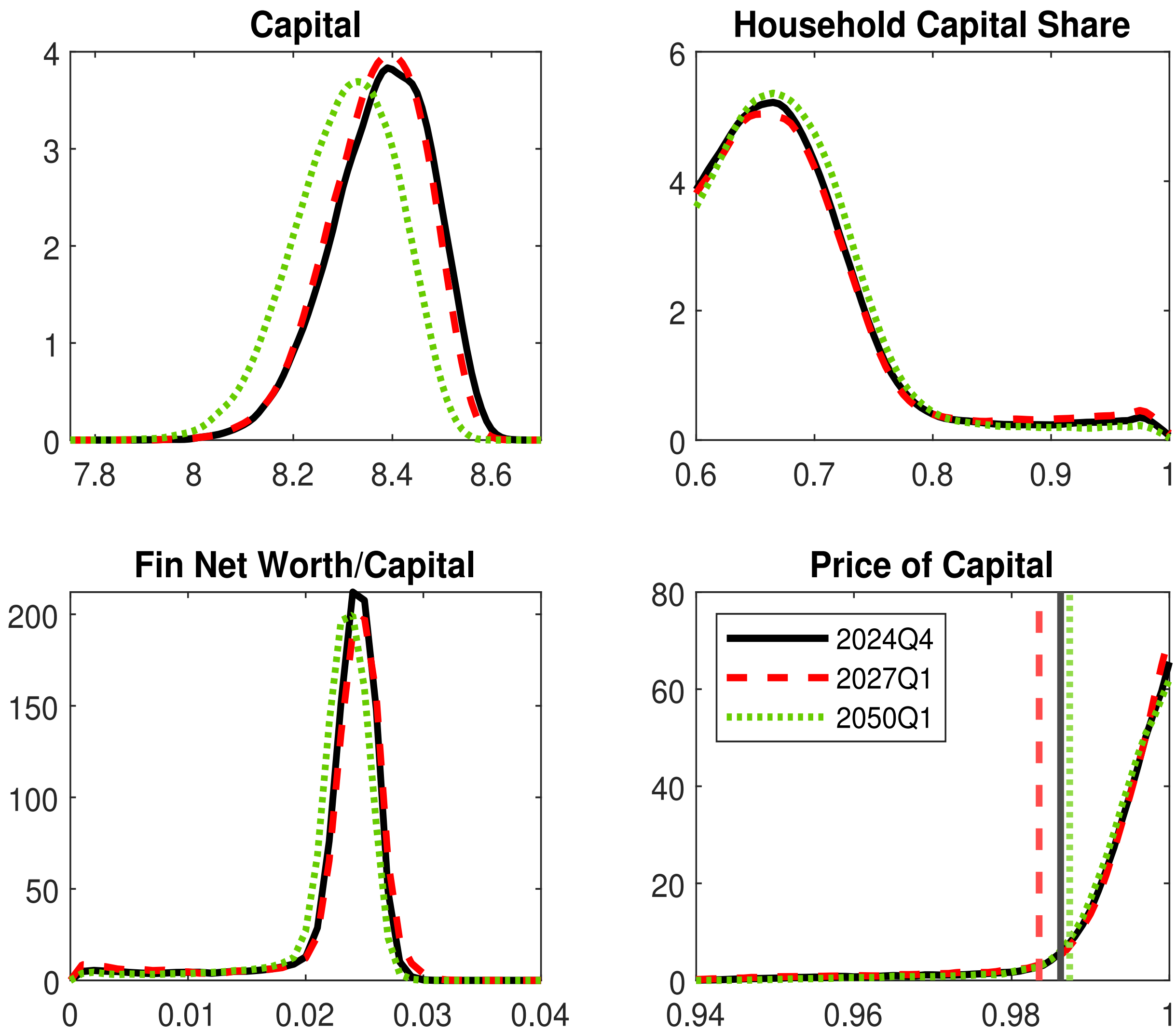
Notes: All moments are based on 100.000 tax paths with 200 burn-in periods per path. The terminal carbon tax corresponds to 143$/ToC. The baseline transition path reaches net zero within 25 years, in 2050. Excess crisis probabilities are computed with respect business-as-usual transition path which reaches net zero in 2090.

D Illustrating the Non-Linear Effect of Carbon Taxes

To illustrate the workings of our non-linear model, we first discuss how a sudden shift from one monotonically increasing tax path to a steeper, but still monotonic, tax path can have non-monotonic effects on the crisis probability. In Figure D.1, we show the distribution of several key endogenous variables at different points of the baseline transition path. The last quarter prior to the shift onto the *ambitious policy* path, i.e. the last period on the *business-as-usual* path, is indicated by solid black lines. Dotted red lines represent the distribution 10 quarters into the transition, while the dotted green lines correspond to the first quarter at which taxes reach their terminal level.

The top left panel shows total capital, which declines from its initial distribution in a quite monotonic fashion towards the long-run equilibrium. In the top right panel, we show the household capital share. Note that its mean of 66% is a calibration target for the initial steady state. We focus on the right tail since financial crises are associated with households holding almost the entire capital stock. As the dashed red line shows, there are more states in the beginning of the transition (2027Q1) in which the household capital share is close to one due to relatively high crisis probability. As the dotted green line shows, the household asset share is slightly larger towards the long-run equilibrium since households face a smaller capital management cost. In contrast, we observe a smaller mass in the right tail towards the end of the transition (2050Q1, dotted green line).

Figure D.1: **Baseline Transition Path to Net Zero: Non-Linearities**



Notes: The distribution of endogenous model objects at different stages of the transition are obtained from simulating the model 100,000 times with a burn-in period of 200 quarters. Capital holdings are expressed relative to quarterly GDP. The 5%-quantiles are indicated by vertical lines for the asset price.

As the bottom left panel reveals, the financial sectors' net worth is lower, relative to total capital, towards the new stochastic steady state. This is consistent with the larger household asset share and reflects the smaller social value of having a financial system in a less productive economy. As the left tail shows, there is a sizable mass in the very low net worth region, which corresponds to the run states. Finally, the non-linear implications of the transition are perhaps best represented by the price of capital. While the distribution exhibits the most mass around one, the tail is representative for financial crisis states. Therefore, we indicate the 5% quantiles by vertical lines. While the left tail is more pronounced ten quarters into the transition (characterized by an elevated crisis probability, dotted green line), the tail features less mass in the new long-run equilibrium (characterized by a lower crisis probability, dashed red line).