Climate Minsky Moments and Endogenous Financial Crisis*

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Abstract

Does a shift to ambitious climate policy increase financial fragility? By reducing the return on assets, carbon taxes can force the financial sector to de-leverage and sell assets at fire sale prices, which triggers a self-fulfilling run on the financial system. To characterize the probability of such a "Climate Minsky Moment" along the transition to net zero emissions, we propose a quantitative non-linear DSGE model with endogenous financial crises and obtain three results. First, carbon taxes are not detrimental to long run financial stability since a permanently lower asset return prevents the excessive buildup of financial sector leverage. Second, the net zero transition is initially characterized by a substantially elevated crisis probability since the financial sector might not be able to de-leverage fast enough. Third, neither accelerating or front-loading climate action reduces financial stability, but drastically reduces emissions in the medium run. Our analysis raises doubt on the notion of a trade-off between front-loading climate action and financial stability.

Keywords: Climate Policy, Financial Stability, Leverage Cycles, Transition Risk

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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 fossil fuel technologies. It has been argued that increases in carbon taxes negatively affect financial market outcomes through asset stranding, i.e. a sharp and permanent drop in the valuation of assets relying on the availability of (cheap) fossil energy sources. By inducing stranded assets at a macroeconomically relevant scale, ambitious climate policy can give rise to "Climate Minsky Moments". A sudden reduction of asset prices raises the concern that financial intermediaries are unable to repay depositors. These concerns can become self-fulfilling, resulting then in a systematic financial crisis.[1]

In this paper, we characterize the probability of "Climate Minsky Moments" in a quantitative macroeconomic model with endogenous financial crises, emissions in the manufacturing sector, and carbon taxes. To allow for the possibility of financial crisis, our model adds run-prone financial intermediaries to a New Keynesian dynamic stochastic general equilibrium (DSGE) model.[2] Financial intermediaries are protected by limited liability and are more efficient at managing capital holdings than households (Brunnermeier and Sannikov, 2014), but have risk-shifting incentives (Adrian and Shin, 2014). An incentive compatibility constraint ensures that intermediaries do not engage in risk-shifting in equilibrium, which endogenously constrains their leverage choice. In spirit of Christiano et al. (2014), we assume that the (bank-specific) return volatility of risky investment opportunities is stochastic. An increase in the riskiness tightens the leverage constraint and forces intermediaries to sell assets to households since intermediary net worth is slow-moving. Crucially, the model is capable of generating pro-cyclical leverage and investment (Nuño and Thomas, 2017). Furthermore, the model is able to reconcile the volatility paradox (Brunnermeier and Sannikov, 2014) and "credit booms gone bust" dynamics (Schularick and Taylor, 2012).

Households willingness to rollover intermediaries' liabilities gives rise to multiple equilibria (Diamond and Dybvig, 1983). In response to tightening leverage constraints intermediaries sell a large share of their capital to households. The asset price drops because households are only able to manage capital at a cost. If the asset price drop is sufficiently large, intermediaries are unable to service all depositors, should they have to sell their assets at a fire-sale price, justifying households' initial desire to withdraw deposits. The possibility of such a systemic run depends on fundamentals of the financial sector and the price of capital. If there is a positive likelihood of switching to the run equilibrium, we use sunspot shocks (Cole and Kehoe, 2000) as equilibrium selection device.

Climate policy enters the model through the production sector. Perfectly competitive firms use capital and labor to produce a homogeneous intermediate good and emit greenhouse gases during the production process. Unabated emissions are taxed by the fiscal authority, but we allow for costly abatement (Nordhaus, 2008), such that the tax bill is given by the amount of

[1] For a summary of scenario-based assessments of financial stability impacts of climate policy, we refer to this VoxEU column. The term "Climate Minsky Moments" was coined by Mark Carney in 2016 (see this link).

[2] See also Moreira and Savov (2017), Boissay et al. (2016), Gertler et al. (2020) and Rottner (2023).

unabated emissions times the carbon tax. We refer to abatement costs and the carbon tax bill jointly as the climate policy compliance costs, which monotonically increase in the tax rate and reduce the marginal product of capital (Heutel, 2012).

Climate policy affects financial stability through two opposing channels. By reducing its marginal product, higher carbon taxes reduce the incentives to accumulate capital. 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. On the other hand, a lower marginal product of capital reduces the market value of assets held by the financial sector, which endogenously tightens the financial sectors' leverage constraint. 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 that supports runs. It turns out that both channels matter, but at different time horizons.

As a first result, we show that permanently higher carbon taxes *increase* financial stability in the long run. The reason behind this perhaps surprising result is that the capital/GDP ratio is smaller in the stochastic steady state 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 levered: intermediaries can de-leverage 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 stochastic steady state without climate policy to 1.5% in the stochastic steady state with full abatement.

These long run gains, however, come at the cost of an elevated crisis probability along 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 Unions emission reduction path from 1990 to 2023. Emissions 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. The model-implied carbon tax path that gives rise to a linear emission reduction is convex. This is consistent with the notion of some technologies being much harder to decarbonize than others. Full abatement is reached for a carbon tax level of 143$/ToC in our calibration.

As a baseline ambitious climate policy scenario, we assume that, in 2025, the economy suddenly shifts to an ambitious climate policy path under which carbon taxes increase linearly to the full abatement level in 2050. This transition speed ensures that climate policy 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.[3] 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

[3]The EU transition plans represent a reasonable upper bound for the speed of the net zero transition, such that the implied adverse financial stability effects can be interpreted as conservative predictions.

the new stochastic steady state with a smaller crisis probability 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.[4]

To jointly measure the financial stability net effect of ambitious climate policy, we introduce a metric of financial stability along transition paths. The *excess crisis probability* is defined as the average difference between crisis probability under an ambitious transition and the *business-as-usual* economy.[5] Our model predicts an excess crisis probability of around -0.02% in the period 2025 to 2060 for the stringent climate policy that implies net zero by 2050. Since the economy with an ambitious transition path is characterized by a lower crisis probability in the long run, the excess crisis probability turns negative eventually. The inflection period at which this happens is an alternative measure of financial stability along different transition paths that is inversely related to the excess crisis probability.

We then perform a comparative static experiments regarding the *speed* and *shape* of the net zero transition. First, we change the time until net zero is reached, i.e. we vary *speed* of the transition. This improves short-run financial stability by allowing intermediaries to deleverage over a longer time period. At the same time, the stochastic steady state with a lower 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 2060 is effectively independent from variations in the transition speed. The implications for climate policy sharply contrast this approximate irrelevance since slow transition paths are characterized by substantially elevated levels of atmospheric carbon in 2075, 50 years after the shift towards ambitious climate policy in our model, which are ultimately relevant for the adverse effects of climate change.

While our baseline transition path imposes a linear increase of carbon taxes, we also allow for the possibility of front- or back-loading climate action. In the case of front-loading, the crisis probability spikes early but at a higher level. In contrast, if ambitious climate policy is deferred to the future, but still committed to reach net zero by 2050, the crisis probability peaks later, but remains elevated essentially for the entire transition path.[6] Notably, the excess crisis probability is even smaller for the front-loaded transition than in the baseline transition. In contrast, the inflection period at which the excess crisis probability turns negative increases to 2057Q3, from 2054Q2.

Our quantitative results mitigate concerns about a trade-off between financial stability and ambitious climate policy - provided that policymakers are sufficiently forward-looking. Since crisis probabilities peak early and at comparatively high levels if climate policy is ambitious and front-loaded, a present bias by the regulator might imply that delayed action is preferred. The

[4]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.

[5]The *excess crisis probability* is not restricted to climate policy applications. It can be used to measure the net financial stability effect of secular shifts more generally.

[6]Note that it might not be optimal ex-post for the policymaker to adhere to the committed back-loaded tax path. For a discussion of financial frictions in the context of optimal climate policy, we refer to Döttling and Rola-Janicka (2022). Studying the interactions between climate policy and financial stability under discretion is beyond the scope of this paper.

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 general. [7]

Lastly, we also allow for the possibility of abatement subsidies. We assume that the subsidy has to be financed entirely by carbon tax revenues, such that the terminal stochastic steady state 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. While the subsidy initially cushions the financial sector from losses and at the same time sustains a large incentive to accumulate physical capital, it merely shifts the de-leveraging pressure into future periods. Once tight climate policy is in place and carbon tax revenues start to fall, the subsidy declines quickly which forces banks to sell assets quickly, while households still incur a large cost from managing them. The excess crisis probability is 0.11% p.a. and the inflection point increases to 2060Q1. Again, taking a general equilibrium perspective allows to cleanly assess the implications of different policy options. While subsidies appear to address adverse side effects of climate policy on the financial sector by stabilizing asset returns, they do not fundamentally solve the problem that the cost of the net zero transition have to be borne eventually.

Related Literature. We relate to the fast growing literature on the interactions between financial markets and climate policy. Jondeau et al. (2021) propose an analytically tractable model of liquidity backstops to address the risk of fire sales of emission-intensive assets. Using an asset pricing approach, Barnett (2023) studies such a sudden sectoral reallocation in a general equilibrium setting which abstracts from financial stability considerations. Alessi et al. (2022) take a stress-testing approach and conclude that a modest increase in bank capital requirements renders the banking sector resilient to transition risk in the short run. By construction, such an approach delivers a quite accurate quantification of transition risk in the banking sector but abstracts from behavioral responses in the financial and non-financial sectors as well as from general equilibrium effects.

There are a few fully-fledged DSGE models with climate policy and frictions in the financial sector that can deliver quantitative predictions, such as Giovanardi et al. (2023) or Giovanardi and Kaldorf (2023), which explicitly model endogenous default and risk-taking in the firm and banking sector, but do not allow for the possibility of financial crises. Carattini et al. (2023) study (sector-specific) macroprudential policies in the context of socially inefficient asset stranding. Comerford and Spiganti (2023) show how financial frictions can give rise to fire-sales of carbon-intensive assets if climate policy is tied to carbon budgets. Diluiso et al. (2021) demonstrate that transition risk acts as an amplification mechanism of shocks at business cycle frequencies using a multi-sector DSGE model. Airaudo et al. (2024) study the transition to higher carbon tax in a small open economy DSGE model with an energy sector.

[7] The horizon of policymakers in the context of climate policy has been subject to discussion at least since Mark Carney's speech in 2015, see This Link.

2 Model

Time is discrete and denoted by $t = 1, 2, ...$ The model features a representative household and a representative financial intermediary that is funded by runnable deposits. Households and intermediaries can invest into claims on the manufacturing sector who emits greenhouse gases in the production process and is subject to carbon taxes. 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: Preliminaries The representative household consists of workers and bankers that have perfect insurance for their consumption C_t. Workers supply labor L_t and earn the wage W_t. Intermediaries return their net worth to the household with probability of $1-\theta$, which excludes the possibility of self-financing. 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:

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

where x_t^* is the recovery rate on bank deposits which we derive below. Additionally, households and intermediaries can invest into the production sector by purchasing securities S_t^H and S_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 $S_t = S_t^H + S_t^B$. Households maximize utility subject to the following period budget constraint:

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

Household: Preferences We assume that households are less efficient in managing securities (Brunnermeier and Sannikov, 2014). As in Gertler et al. (2020), households incur a utility cost from managing capital. The period utility function is given by

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

Inspecting the capital management cost function, i.e. the last part of (3), we observe that

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

Holding aggregate capital S_t constant, management costs increase in S_t^H for any household capital holdings beyond the target share $S_t^H > \gamma^F S_t$, and up to a certain cost level $\frac{\omega_F}{2}(1-\gamma^F)^2 S_t$ at which households manage the entire capital stock. Furthermore, for any $\frac{S_t^H}{S_t} > \gamma^F$, management costs decrease in aggregate capital S_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.

The capital management cost function can also be expressed in terms of the total capital stock S_t and the household capital share $\frac{S_t^H}{S_t}$. It is helpful to discuss its properties in order to provide intuition on the financial stability effects of climate policy. The first partial derivatives of the capital management cost function with respect to total capital S_t and with respect to the share managed by households $\frac{S_t^H}{S_t}$ are trivially positive whenever households manage more assets than the target share γ^F. The cross derivative is given by

$$\frac{\partial^2 cost_t}{\partial \frac{S_t^H}{S_t} \partial S_t} = \omega^F \left(\frac{S_t^H}{S_t^2} - \gamma^F \right) > 0 \, . \tag{4}$$

This implies that both, the capital management cost increase and the associated capital price drop, are larger if the economy has accumulated a large amount of capital.

Financial Intermediaries and Risk-Shifting Incentives Financial intermediaries convert each security into ω_{t+1} efficiency units, either using a *safe* or a *risky* technology. While the safe technology converts each security into one efficiency unit ($\omega_t = 1$), the risky technology is subject to (bank-specific) idiosyncratic productivity shocks $\widetilde{\omega}$. The shock is i.i.d. over time and intermediaries. We assume that shock is log-normally distributed:

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

where $\psi < 1$. The volatility of bank-specific productivity shocks ξ_t is an exogenous driver of financial cycles, specified below. The good security is superior as it has a higher mean and a lower variance due to $\psi < 1$ (see also Rottner, 2023). The risky security is characterized by higher upside risk due to the possibility of a large idiosyncratic shock realization $\widetilde{\omega}$. In the spirit of Christiano et al. (2014), the idiosyncratic shock variance ξ_t is exogenous and follows an AR(1) process:

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

Risk shocks ϵ_t^ξ are an important trigger of financial crises in this model. The intermediary earns the return $R_t^{K,j}$ on its securities that 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 security, which is given by $\widetilde{\omega}_t^j R_t^K$. 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

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

Limited liability protecting the intermediary in case of default distorts the intermediaries' security 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 the promised deposit value. The gain from limited liability 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 securities' higher mean return versus the gains from limited liability for the risky security. The incentive constraint ensuring that intermediaries only invest in the good security enters as an additional equilibrium condition:

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

The LHS shows the trade-off between the higher mean return $(1 - e^{\frac{-\psi}{2}})$ and the upside risk Ω_{t+1}^j. This is the relevant consideration if there is no run next period. The RHS displays an additional gain of investing in the risky security in case of a run. The risky security offers the possibility to have 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 provide deposits to the intermediaries. While the households earn the predetermined interest rate $\overline{R}_t^D$ in normal times, the households recovers the gross return of the securities if a run takes place. As the return in a run is lower, an increase in the run probability π_t increases intermediaries' funding cost. The participation constraint can be written as:

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

Runs and Equilibrium Selection In our model, a systemic financial crisis corresponds to a state in which households are not willing to roll over bank deposits. Runs are self-fulfilling in the sense that households' expectations about a low liquidation value of financial intermediaries' assets induces them to withdraw deposits, which forces banks 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 banks and households are the only agents left to acquire assets, which induces the price of capital to fall dramatically. We denote the firesale price of capital by Q_t^* in order to determine whether a self-fulfilling run is supported. Define the recovery ratio

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

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, 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. Denoting the abatement share by η_t, total emissions are therefore given by $(1-\eta_t)Y_t$ while the total carbon tax payed 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 lump sum fashion. In Section 4.4, we also consider a policy in which carbon tax revenues are used to subsidize firms' abatement cost. 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

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

It follows immediately from Equation (14) that the abatement effort is increasing in the current carbon tax, but independent of future carbon taxes, such that no additional state variables enter the model. Furthermore, we cap η_t^* by one, i.e. we do not allow for the possibility of net negative emissions. In our model, emission reduction comes at a macroeconomic cost since emission-reduction activities are costly (see Nordhaus, 2008). We sketch the macroeconomic relevance of abatement in Figure 1.[8]

[8] 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

Since climate policy directly affects the accumulation and pricing of capital in our model economy, it is helpful to define the policy-induced wedge into the return on capital. To do so, note that the carbon tax *compliance cost* per unit are obtained from plugging-in the optimal abatement effort η_t^* and summarizes all expenses induced by 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 $\overline{p}_t$ as given, the first-order condition for capital and labor

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

$$W_t = (p_t - \xi_t)(1-\alpha)\frac{Y_t}{L_t} \ , \tag{17}$$

contain the wedge ξ_t induced by carbon taxes. Since emissions and abatement cost are proportional to total output, the carbon tax does not affect the capital share but rather resembles a negative TFP shock.

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

$$Y_t = \left[\int_0^1 (Y_t^j)^{\frac{\epsilon-1}{\epsilon}} dj \right]^{\frac{\epsilon}{\epsilon-1}} \ . \tag{18}$$

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

$$Y_t^j = \left(P_t^j / P_t \right)^{-\epsilon} Y_t \ . \tag{19}$$

The price index thus follows as:

$$P_t = \left[\int_0^1 (P_t^j)^{1-\epsilon} dj \right]^{\frac{1}{1-\epsilon}} \ . \tag{20}$$

that some technologies, such as aviation, cement or steel production are very costly to substitute. This notion is reflected in the convex functional form assumption on abatement costs. While such a sectoral re-allocation has potentially important macroeconomic (Campiglio et al., 2023) and macro-financial (Giovanardi and Kaldorf, 2023) implications, it is only relevant for financial stability in this model as far as aggregate outcomes are concerned. There is only one representative intermediary that is perfectly diversified across all assets in the economy, such that the financial stability effects of climate policy merely depend on the effect of climate policy on the aggregate return on assets.

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

$$\mathbb{E}_t \sum_{s=0}^{\infty} \Lambda_{t,t+s} \left[\left(\frac{P_{t+s}^j}{P_{t+s}} - \overline{p}_{t+s} \right) Y_{t+s}^j - \frac{\rho^r}{2} Y_{t+s}^j \left(\frac{P_{t+s}^j}{\Pi P_{t+s-1}^j} - 1 \right)^2 \right] , \tag{21}$$

where Π is the inflation target. 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

$$\left(\frac{\Pi_t}{\Pi} - 1 \right) \frac{\Pi_t}{\Pi} = \frac{\epsilon}{\rho^r} \left(MC_t - \frac{\epsilon - 1}{\epsilon} \right) + \Lambda_{t,t+1} \left(\frac{\Pi_{t+1}}{\Pi} - 1 \right) \frac{\Pi_{t+1}}{\Pi} \frac{Y_{t+1}}{Y_t} . \tag{22}$$

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

$$\max_{I_t} \; Q_t \left(a_1 (I_t / S_{t-1})^{1-a_2} + a_0 \right) S_{t-1} - I_t, \tag{23}$$

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

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:

$$R_t^I = \max \left\{ R^I \left(\frac{\Pi_t}{\Pi} \right)^{\kappa_\Pi} \left(\frac{\varphi_t^{mc}}{\varphi^{mc}} \right)^{\kappa_y} , 1 \right\} , \tag{24}$$

where deviations of marginal costs from its deterministic steady state φ^{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:

$$\mathbb{E}_t \left[\Lambda_{t,t+1} R_t^I / \Pi_{t+1} \right] = 1 . \tag{25}$$

The resource constraint includes investment adjustment and abatement cost:

$$Y_t = C_t + I_t + G + \frac{\rho^r}{2} \left(\Pi_t / \Pi - 1 \right)^2 Y_t + \frac{b_1}{b_2 + 1} \left(\frac{\tau_t^c}{b_1} \right)^{\frac{b_2+1}{b_2}} Y_t , \tag{26}$$

where G is government spending. From (26), 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 carbon according to

$$E_t = \delta_E E_{t-1} + (1 - \eta_t) Y_t \tag{27}$$

Since damages from climate change are directly linked to the stock of atmospheric carbon, this variable is a key policy objective and 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, also drawing on Rottner, 2023. This results in a general calibration strategy that can easily adapted to potential country use cases. When we target specific 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 low 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 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. While the functional forms are largely following the DICE model of Nordhaus (2008), we consider different values for slope and curvature parameter of the abatement cost function (13). 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). 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 steady state* (i.e. without abatement) to current world GDP ($y^{world} = 105$ trillion USD in 2022, at PPP, see IMF, 2022) and current global carbon emissions ($e^{world} = 33$ gigatonnes in 2022), respectively. Since output and emissions are normalized to one in the model, the carbon price in \$/ToC associated with a given tax τ^c_t is then given by $p^C_t = \frac{y^{\text{world}}}{e^{\text{world}}}\tau^c_t$. Under our baseline value for θ_1, we obtain a full abatement tax of $\tau^c_t = 0.05$ 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 households 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 parameters govern the mean risk of security 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 models 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 banks 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). Regarding the sunspot shock, we normalize it to a value of 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 states, total capital S_t and financial sector net worth N_t, and one exogenous state, the exogenous risk affecting the payoff profile from the risky security ξ_t.

Transition paths are solved by backward induction starting from the terminal stochastic steady state 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.

4 Quantitative Analysis

In this section, we use our calibrated model to study the financial stability implications of climate policy. We proceed in two steps. First, we demonstrate how carbon taxes affect financial stability in the stochastic steady state. Second, we study the transition dynamics from a slow transition path ("business-as-usual") to an ambitious climate policy which is consistent with the climate goals set in the Paris agreement.

4.1 Carbon Taxes: Long Run Effects

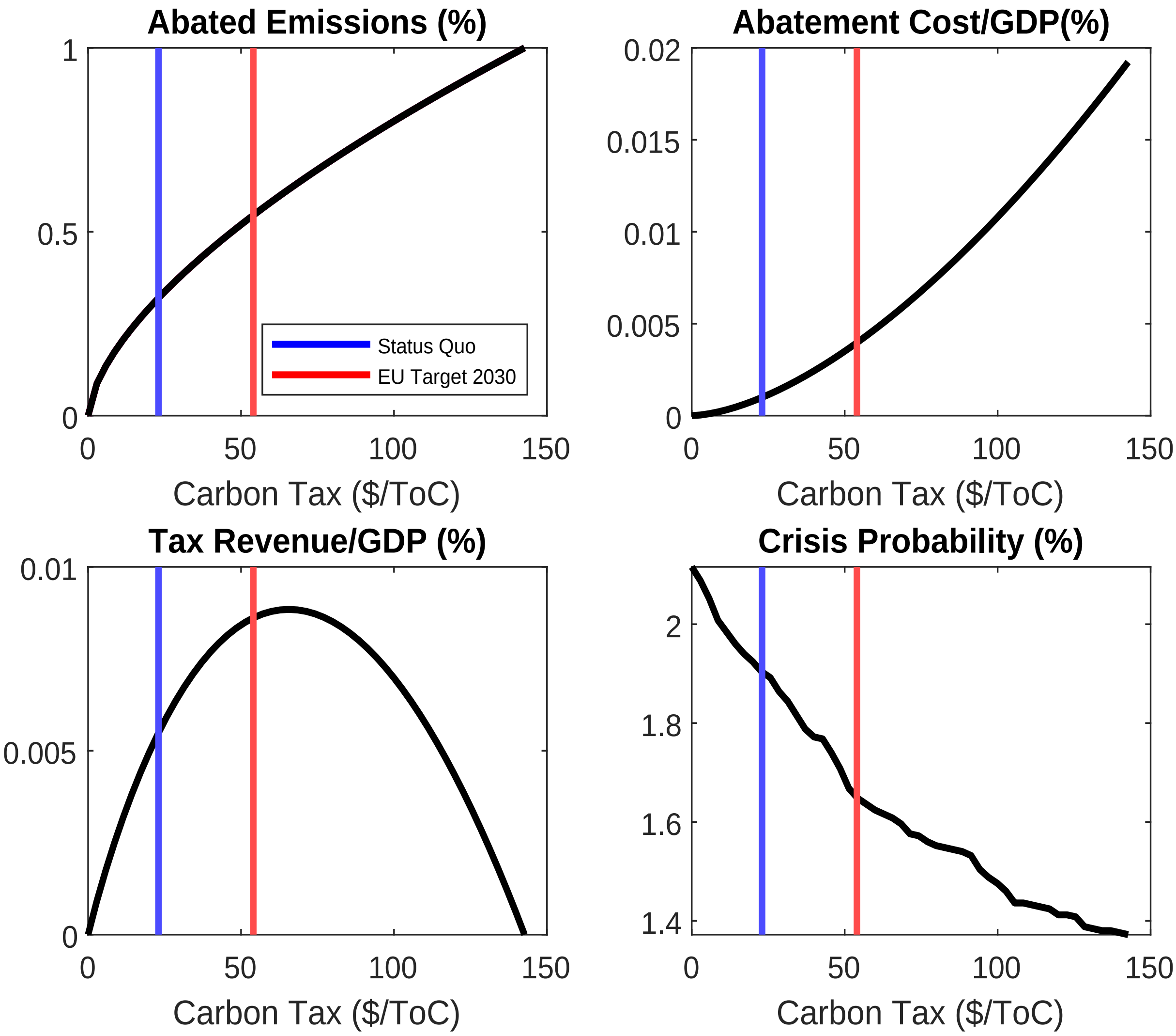
Figure 1 demonstrates how carbon taxes affect the macroeconomy and financial stability in the stochastic steady state. We consider carbon taxes between zero and 143$/ToC, which

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 security	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	Υ	0.50	Normalization

implies full abatement in our baseline calibration. The vertical blue line indicates a value of 27$/ToC. This tax implies an abatement share of 33%, consistent with the empirically observed emission reduction from 1990 to 2023. The red line refers to a value of 54$/ToC, which implies an abatement share of 55%, see the upper left panel. This level of η_t^* is consistent with the European Union's emission reduction target in 2030.[9]

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.

The upper right panel shows that abatement cost increase in a concave fashion towards full abatement. In the bottom right panel, we demonstrate how the carbon tax bill per unit of output is affected. Consistent with standard public finance models, tax revenues exhibit a concave shape. They vanish once full abatement is reached since the tax base is zero in this case. Note that abatement costs are larger than the carbon tax burden. This will imply that

[9] 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.

the wedge ξ_{t+1} in the return on capital is an increasing function of climate policy stringency.

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 the average productivity of the economy, aggregate capital is smaller in the stochastic steady state. 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 banking system affects the crisis probability: 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 fire-sale higher price for holding capital. Thus, banks are more likely to service depositors at the fire-sale price. This reduces the size of the run region in the state space and, thereby, reduces the run frequency in the stochastic steady state.

4.2 Financial Stability and the Clean Transition

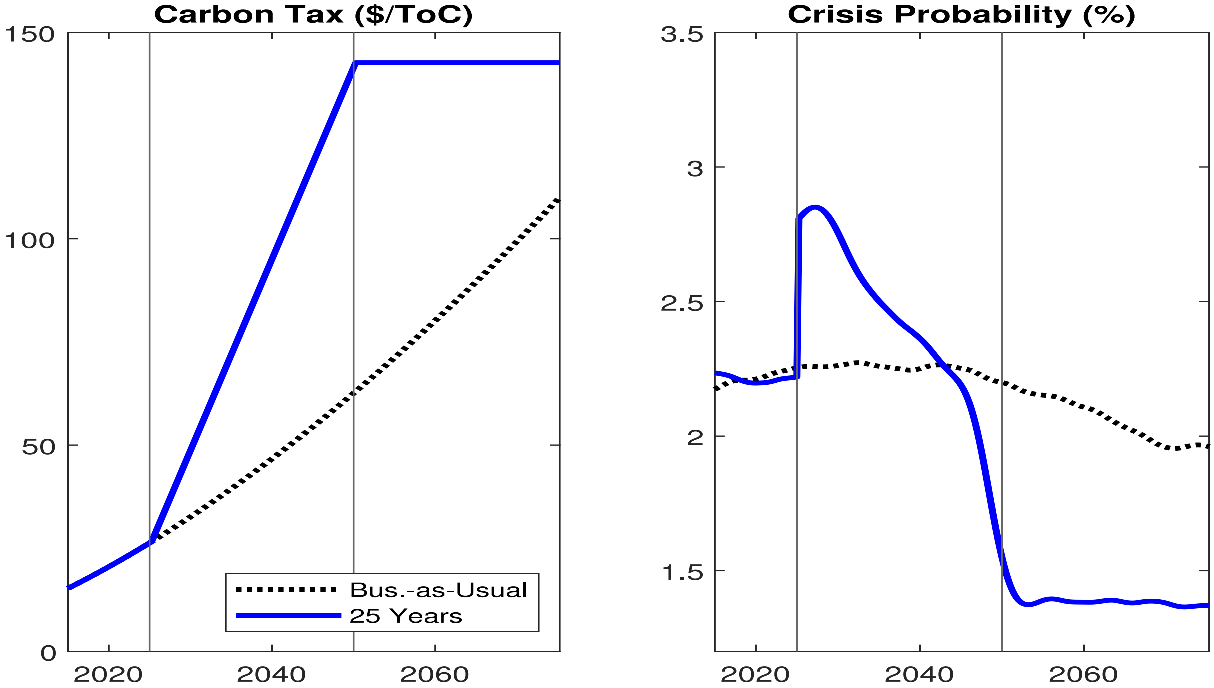
Having discussed the long run implications of carbon taxes for financial stability, we now move to the transition from lenient to more stringent climate policies. We first describe the lenient tax path, to which we will refer to as *business-as-usual*, before discussing different ambitious tax paths which are in line with current policy packages by the European Union. While our analysis is not supposed to evaluate specific policies, we argue that the European Union's climate policy packages are among the most stringent policies proposed such that our results represent an upper bound on the financial stability implications of the net zero transition.

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 left panel of Figure 2.

We then solve the model with a carbon tax path that linearly increases to a level consistent with net zero. The period at which net zero is reached will be denoted by T_{max}. We interpret the year 2025 as the initial period T_0 at which the economy unexpectedly leaves the business-as-usual path. This is reflected by the solid blue line in the right panel of Figure 2.

As the blue solid line in the right panel of Figure 2 shows, the crisis probability increases from around 2.3% on the initial path to around 2.7% at the beginning of the transition. Here, the economy experiences an unanticipated shock to carbon taxes and, thus, a negative productivity shock that puts de-leveraging pressure on the financial system. Notably, the crisis probability

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



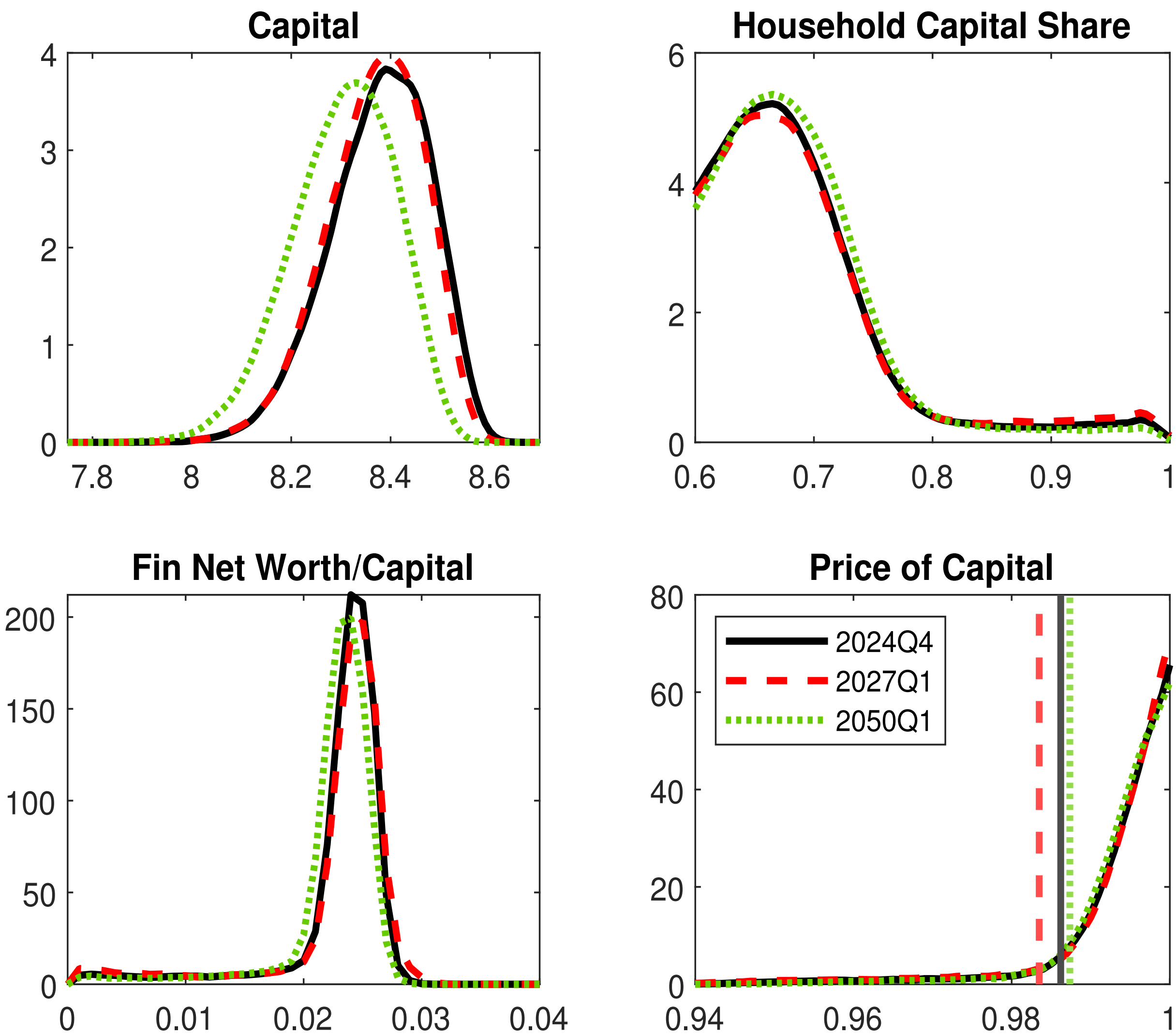
Notes: Run probabilities are annualized and obtained from simulating the model 100,000 times with a burn-in period of 200 quarters. We remove the sampling error using cubic spline smoothing. Beginning and end of the transition period are indicated by vertical lines.

peaks several years into the transition and only slowly converges to the terminal stochastic steady state. Since capital and net worth are endogenous state variables, our model features a large degree of endogenous propagation. 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 converging to the new stochastic steady state faster.

Non-Linear Effects of Climate Policy Before turning to our main comparative statics experiments, we 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 3, we show the distribution of several key endogenous variables at different points of the baseline transition path. The last quarter prior to the shift towards a more ambitious climate policy, i.e. the last period on the business-as-usual transition 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 new stochastic steady state. 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

Figure 3: **Baseline Transition Path to Net Zero: Non-Linearities**

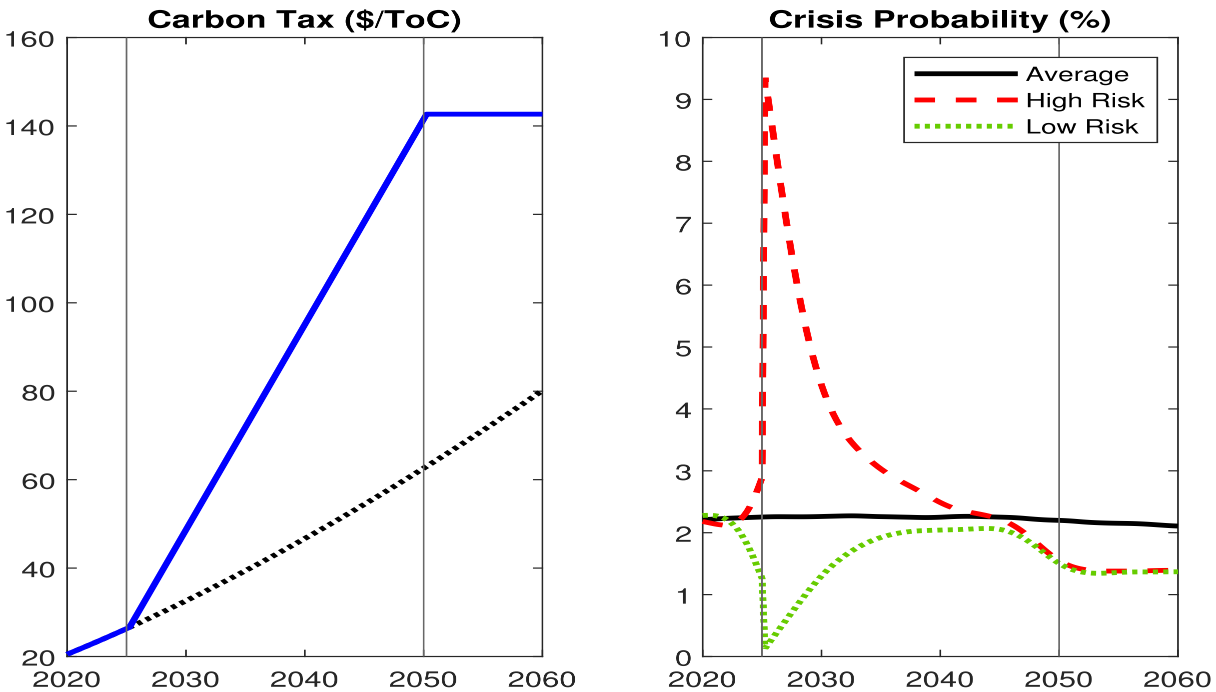


Notes: The distribution of endogenous model objects at different stages of the transition are obtained from simulating the model 100,000 times with a burn-in period of 200 quarters. Capital holdings are expressed relative to quarterly GDP. The 5%-quantiles are indicated by vertical lines for the asset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

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 new stochastic steady state 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).

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 banking system in the 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 most mass around one, the tail is indicative of the 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, green line), the tail features less mass in the new stochastic steady state (characterized by a lower crisis probability, red line).

Figure 4: **Baseline Transition Path to Net Zero: Financial Cycle**



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

The Role of the Financial Cycle The possibility of a *Climate Minsky Moments* depends jointly on the (exogenous) climate policy stance and the (endogenous) loss-absorbing capacity by the financial sector, i.e. its net worth. We illustrate how the loss-absorbing capacity shapes the financial stability implications of a shift to ambitious climate policies by simulating the baseline transition path once under the assumption that the risk shock realizes at plus one standard deviation in the last year prior to the climate policy shift. This is represented by the green line in the left panel of Figure 4. In this situation, the financial sector was forced to de-leverage already prior to the climate policy shift and is, therefore, able to accommodate the sudden productivity loss without having to sell capital to an extent that the run equilibrium is supported. To the contrary, the run probability declines substantially and persistently since the capital accumulation channel of climate policy dominates.

The dashed red line in the left panel of Figure 4 corresponds to a risk shock realization of minus one standard deviation. This implies a temporary low gain from limited liability and allows intermediaries to increase their leverage by the incentive constraint. Consequently, the loss-absorbing capacity is low and the financial sector faces enormous de-leveraging pressure once climate policy shifts. The crisis probability spikes to almost 10% p.a. and stays elevated way into the transition. This implies that a careful design of transition paths to net zero should take vulnerabilities in the financial system into account.

4.3 Speed and Shape of the Transition: Comparative Statics

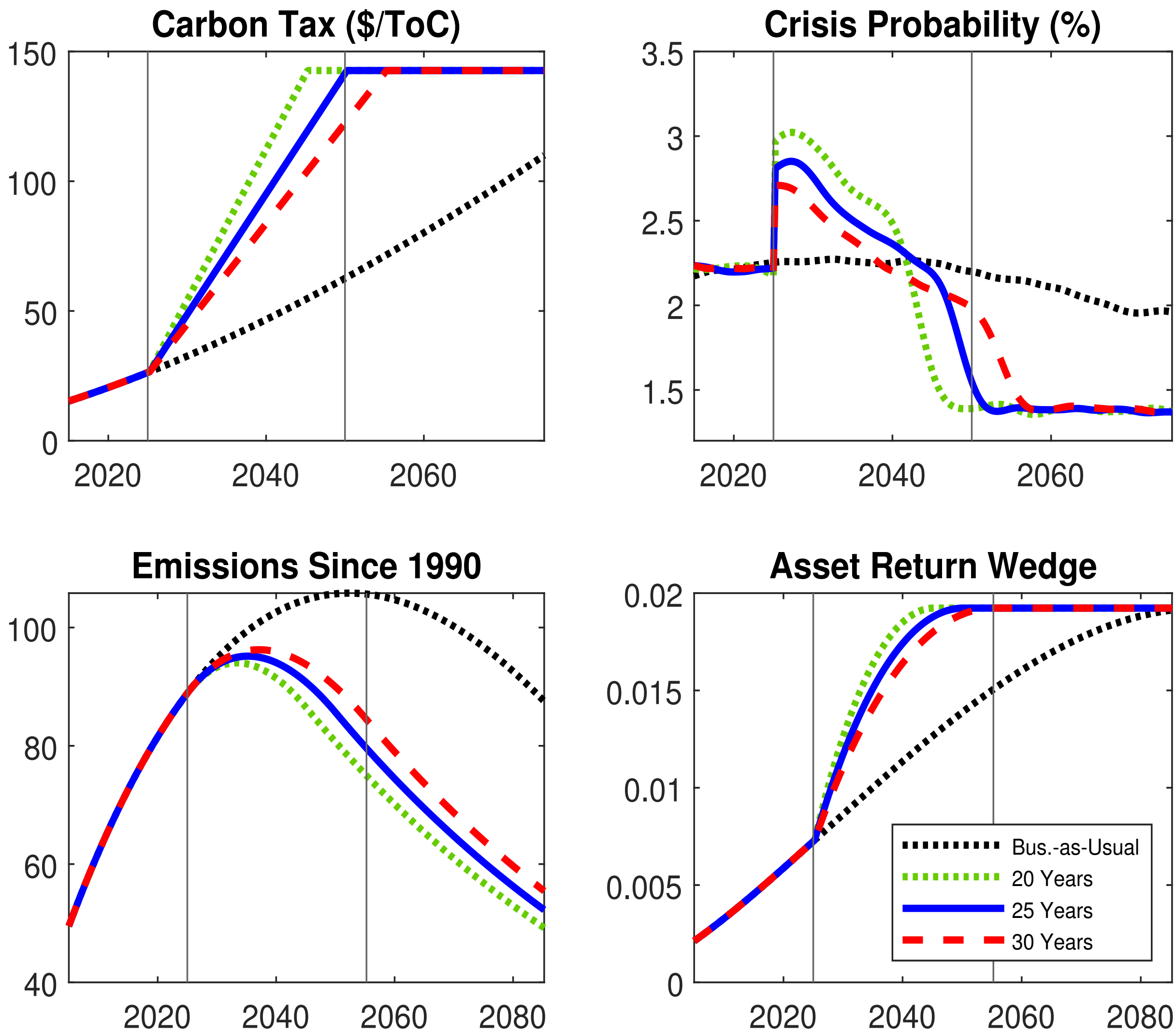
In the following, we provide several comparative static exercises with respect to the shape of the carbon tax path. First, we vary the *speed* by considering a value of 20 years and 30 years until the full abatement tax is reached. As in the baseline transition, we assume that carbon taxes increase linearly until the terminal period. Consistent with the prediction from similar DSGE models, such as Airaudo et al. (2024), a faster transition induces a stronger output contraction and larger asset return wedge ξ_t in the short run (bottom right panel of Figure 5). The upper right panel shows how the speed at which net zero is reached affects the crisis probability over time. A more ambitious transition that reaches net zero by 2045, 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 stochastic steady state. In contrast, the dashed red line represents the an economy that does not reach net zero before 2055, i.e. within 30 years. In this economy, the crisis probability peaks at around 2.7% but naturally takes more time to reach the new stochastic steady state.

Second, we allow for a front- and a back-loaded transition. Here, we fix the terminal period at 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 business-as-usual scenario and the ambitious transition path consistent with net zero in 2050. Let $w_t \equiv \frac{t}{T_{max}-T_0}$ for any $t \in [T_0, T_{max}]$ be a time-varying weight on the ambitious transition. Then, the back-loaded path is given by

$$\tau_t^{back} \equiv (1 - w_t)\tau_t^{b.a.u.} + w_t\tau_t^{trans} \ .$$

As the dashed red line in Figure 6 reveals, the back-loaded path features a rapid increase in the

Figure 5: **Comparative Statics: Transition Speed**



Notes: Run probabilities are annualized and obtained from simulating the model 100,000 times with a burn-in period of 500 quarters. 90% confidence intervals are indicated by dashed lines. We remove the sampling error from all variables using cubic spline smoothing. Beginning and end of the transition period are indicated by vertical lines.

carbon tax in the last periods prior to reaching net zero. Such a scenario is sometimes referred to as "disorderly transition".[10] We also define a front-loaded transition path that adds the (time-varying) difference between baseline and back-loaded taxes ($\tau_t^{trans} - \tau_t^{back}$) to the baseline path:

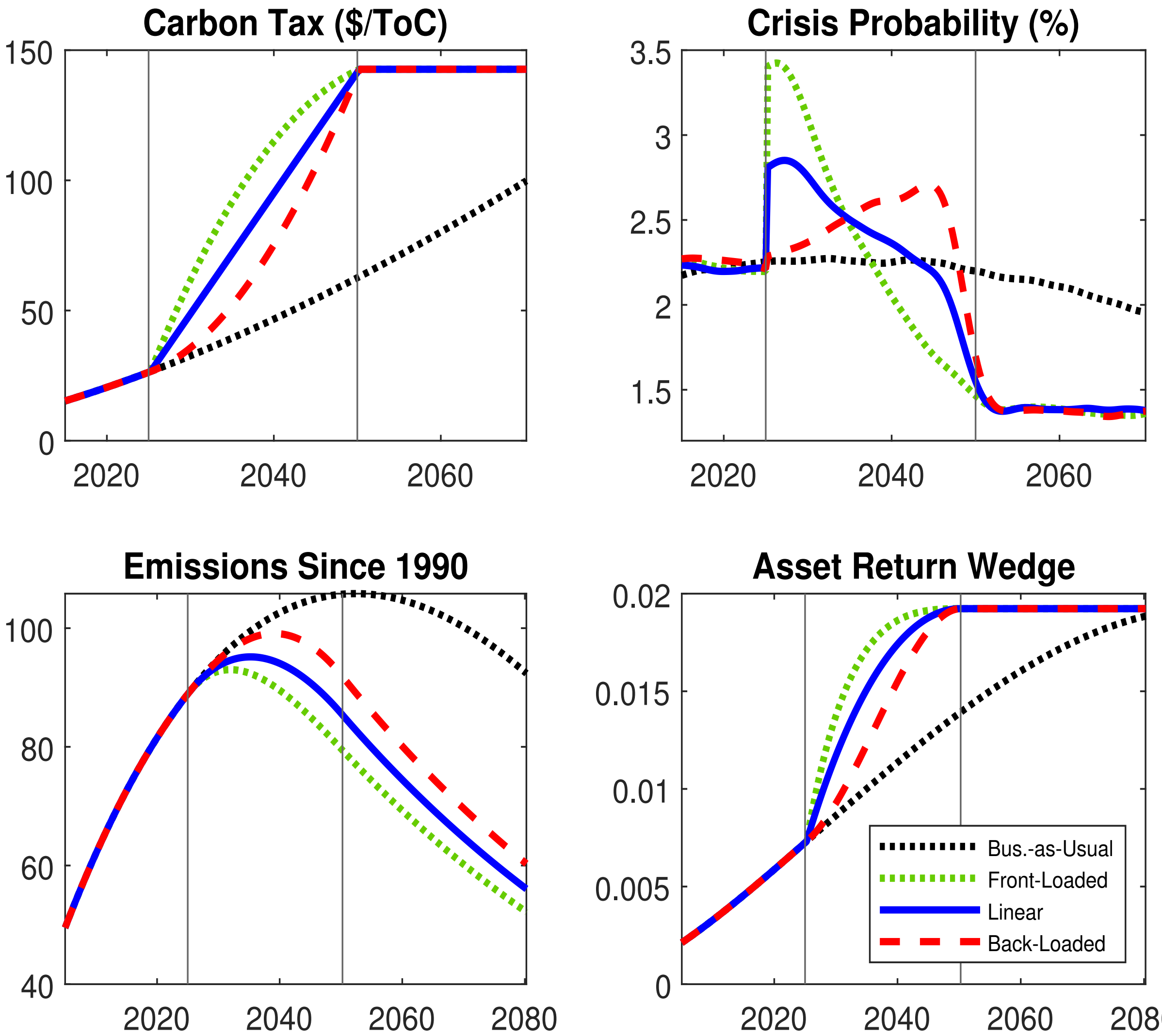
$$\tau_t^{front} \equiv \tau_t^{trans} + \left(\tau_t^{trans} - \tau_t^{back}\right) .$$

This is represented by the dashed green line in the left panel of Figure 6. In the right panel

[10]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 full committed to this path. An analysis regarding the optimality of such a delayed action under discretion is beyond the scope of this paper.

of Figure 6, we show how delaying the transition affects financial stability. The front-loaded transition features substantial fragility in the first five years, with a crisis probability peaking at almost 3.5%. However, it already reaches a lower level than the business-as-usual in 2040. In contrast, the crisis probability peaks close to the end of the transition after being elevated above the business-as-usual case for the entire transition path. Note that all paths reach the new stochastic steady state at almost the same point in time since we have fixed $T_{max} = 2050$.

Figure 6: **Comparative Statics: Transition Shape**



Notes: Run probabilities are annualized and obtained from simulating the model 100,000 times with a burn-in period of 200 quarters. We remove the sampling error from all variables using cubic spline smoothing. Beginning and end of the transition period are indicated by vertical lines.

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 new stochastic steady state. 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.

To facilitate a comparison of the financial stability implications of different transition paths, it is necessary to define a suitable metric. The most obvious one is the maximum crisis probability over the transition path, which is typically attained within a dozen quarters after the transition starts. Note that this metric does not take into account the number of periods with an high crisis probability. It also does not capture the transition dynamics to the new stochastic steady state that is associated with a smaller crisis probability (see **??**). To take these two features into account, we define the *excess crisis probability*:

$$ExCP(transition) = \frac{1}{T_{post} - T_0} \sum_{t=T_0}^{T_{post}} \beta^t \Big(p_t(\text{transition}) - p_t(\text{business-as-usual}) \Big) \ , \tag{28}$$

which depends on the slope and shape of the carbon tax path as well as the truncation point T_{post}. Note that this metric imposes that a financial crisis is equally harmful from a social point of view in 2026 and in 2050. This is justified by the observation that, in the model, the welfare loss of a systemic financial crisis does not depend on climate policy. In this sense, it is possible to aggregate crisis probabilities over time. We allow for the possibility of discounting future financial stability gains. For the moment, we fix β at unity and discuss the role of setting the time-preference rate to some $\beta < 1$ later.

The *excess crisis probability* can be interpreted graphically as the area between the crisis probability under the ambitious transition path and the business-as-usual path. Due to the non-monotonic effect of the transition it initially grows as the truncation point T_{post} increases. As soon as the crisis probability under the ambitious transition drops below the business-as-usual economy, the excess crisis probability decreases. For all transition paths we considered in our policy experiments, this period is reached between 2040 and 2050. Furthermore, the excess crisis probability turns negative eventually in all ambitious scenarios that we considered, since the new stochastic steady state is reached much faster than in the business-as-usual economy. The net effect on financial stability is, therefore, positive and we can compare different carbon tax paths by the inflection period at which the excess crisis probability turns negative. In the very long run, the excess crisis probability converges to zero by definition, because all economies eventually converge to the new stochastic steady state with full abatement.

From the first row of Table 2 we observe that the maximum crisis probability is largest under the most ambitious scenarios. In the second row, we are also factoring in the medium run gains of the transition by comparing the excess crisis probability when setting $T_{post} = 2060$. Under 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 reached earliest for the front-loaded transition path consistent with net zero in 2050.

Not surprisingly, the last row of Table 2 reveals that cumulative emissions in 2075, i.e. 50 years after the shift in climate policies are substantially lower if carbon taxes increase faster

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

	Speed			Shape		
	20 Years	25 Years	30 Years	Front	Linear	Back
Maximum Crisis Prob (%)	3.31	**2.94**	2.91	3.78	**2.94**	2.96
Excess Crisis Prob (%)	-0.02	**-0.02**	0.00	-0.05	**-0.02**	0.06
Inflection Period	2054Q3	**2054Q3**	2055Q1	2053Q2	**2054Q3**	2057Q3
Cum. Emissions in 2075 (Rel. to bus.-as-usual, in %)	-41.3	**-37.6**	-33.8	-42.0	**-37.6**	-32.9

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. The cut-off period T_{max} for the excess crisis probability is set to 2060.

and earlier. Taken together, our comparative statics experiments raise doubt on the common narrative of a trade-off between financial stability and ambitious climate policy - provided that policymakers are sufficiently forward-looking to take the medium run financial stability effects of the net zero transition into account.

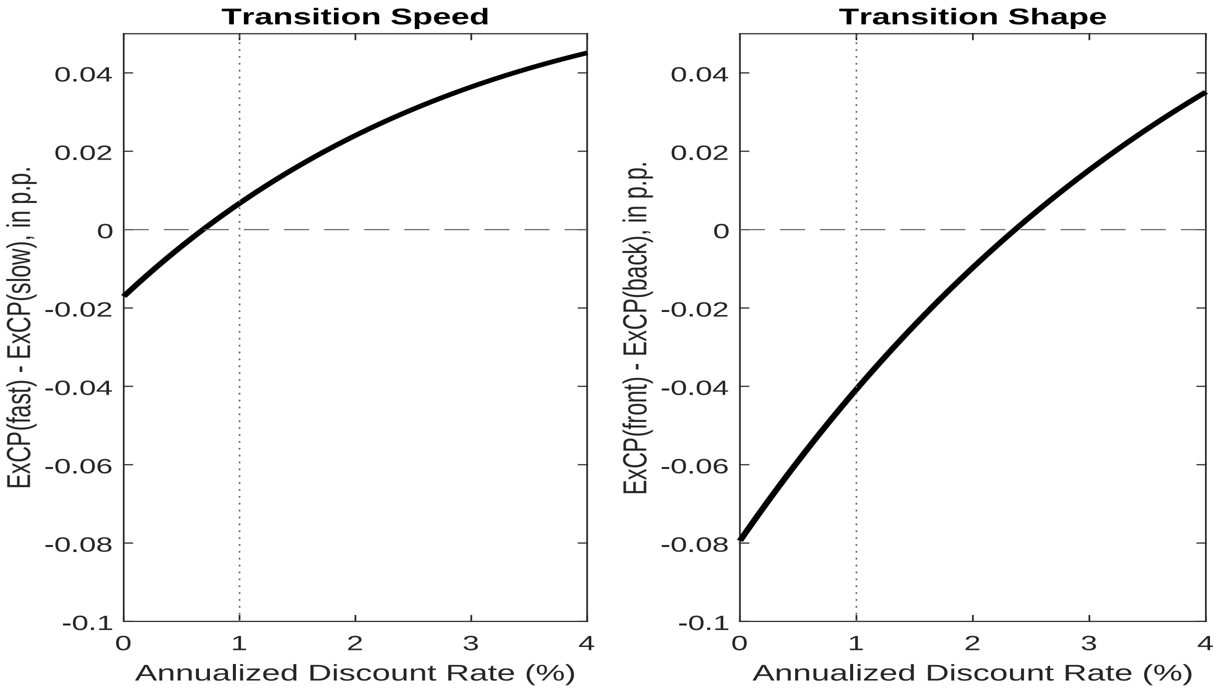
To the net financial stability effect into a quantifiable relationship with policymaker discount factors, we compare the net financial stability effect of different ambitious climate policies rather than using the *business-as-usual* scenario as a benchmark. The left panel of Figure 7 compares the accelerated (20 years) to the slow (30 years) transition path. We compute the difference in crisis probabilities for each quarter from 2025 to 2060 but weight their difference using different discount factors in the *ExCP*, see Equation (28). For low discount rates, the fast transition path has a lower discounted excess crisis probability since the medium run financial stability gains are hardly discounted. This reverts for discount rates exceeding 0.7% p.a. The right panel shows the corresponding result for back-loading the transition. Here, the annualized discount rate has to be around 2.5% in order to render the net financial stability effect of a front-loaded transition negative.

4.4 The Role of Abatement Subsidies

In all policy experiments discussed in Section 4.3, we maintained the assumption that carbon tax revenues are rebated to households in a lump sum fashion. In this section, we instead assume that all carbon tax revenues are rebated to firms as an abatement subsidy. Specifically, firms receive a flat subsidy per abated unit of emissions $\eta_t Y_t$. Carbon tax revenues exactly cover total public spending on the subsidy, i.e. $(1-\eta_t^*)\tau_t^c Y_t = \eta_t^* Y_t$, which enters the model as an additional equilibrium condition. Consequently, the per-unit subsidy is given by $\frac{(1-\eta_t^*)\tau_t^c}{\eta_t^*}$, which firms take as exogenously given when choosing their individual abatement effort. The per-unit cost minimization problem becomes

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

Figure 7: **Net Financial Stability Effect of the Transition: The Role of Discounting**



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

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

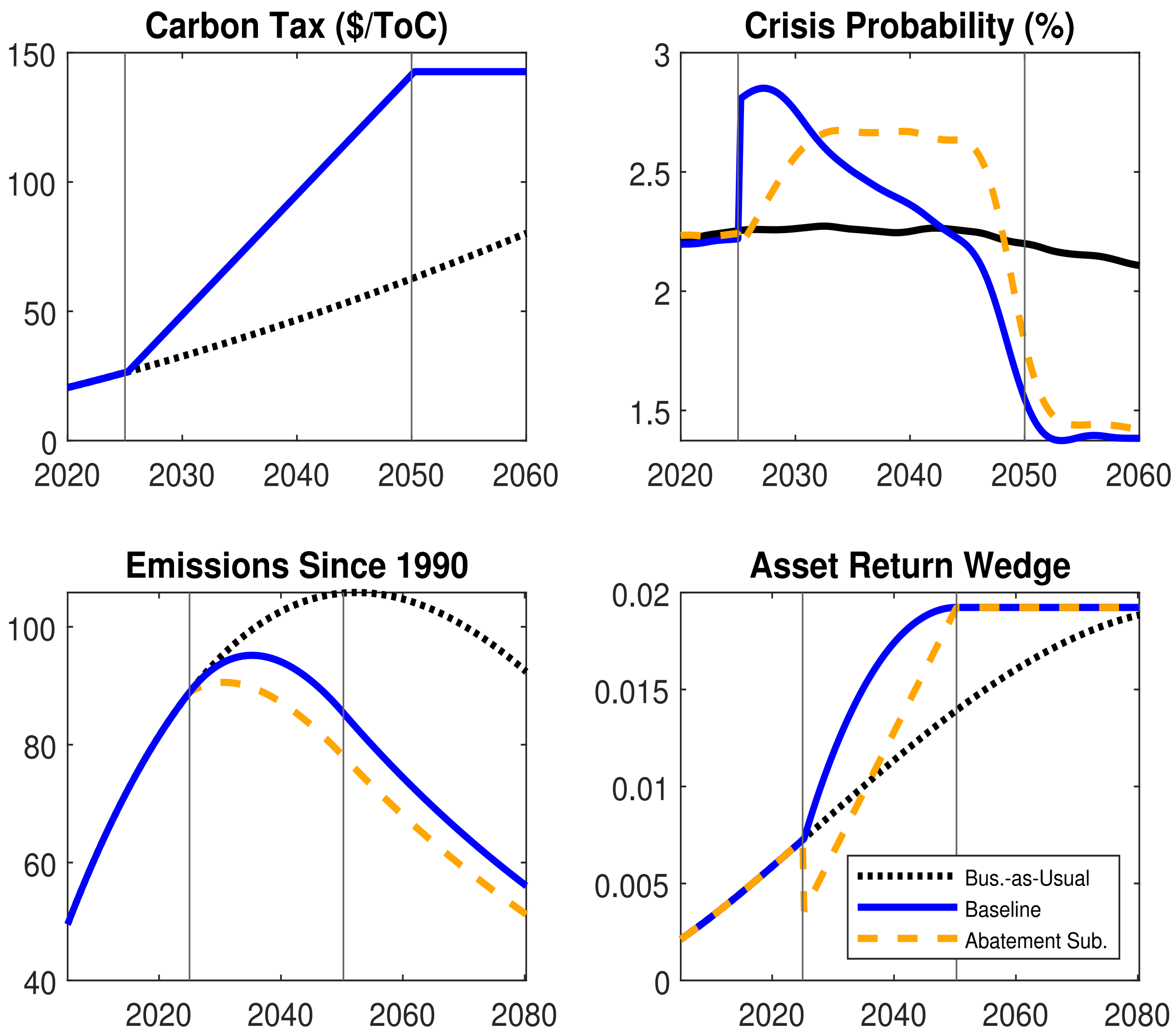
$$\eta_t^* = \min\left\{\left(\frac{\tau_t^c}{b_1}\right)^{\frac{1}{b_2+1}}, 1\right\}, \tag{29}$$

which exceeds the optimal abatement effort without subsidies (14). The associated wedge in the return on capital simplifies to $\xi_{t+1} = \frac{\tau_{t+1}^c}{b_2+1}$, which is always smaller than under the assumption of tax rebates to households. We compute the financial stability implications of abatement subsidies for the baseline transition 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 8 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 when net zero is reached. Cumulated emissions since 1990 are 43.0% smaller in 2070 than under business as usual if an abatement subsidy is in place. This exceeds the gains from accelerating the transition and from front-loading climate action (see Table 2).

The top right panel of Figure 8 shows that the crisis probability increases very slowly over

Figure 8: **Transition Path to Net Zero: Carbon Tax Rebates**



Notes: Run probabilities are annualized and obtained from simulating the model 100,000 times with a burn-in period of 200 quarters. We remove the sampling error using cubic spline smoothing. Beginning and end of the transition period are indicated by vertical lines.

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).[11]

As we have shown in Figure 1, carbon taxes follow a Laffer curve and vanish 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 path throughout the transition and only drops below the *business-as-usual* scenario in 2048. This results in an excess crisis probability of 0.11%, which is substantially larger than in the baseline. The inflection period at which the *ExCP* turns negative is 2060Q1, compared to 2054Q3 in the baseline.

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 such a shock to the return on their assets, financial intermediaries face de-leveraging 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.

[11]In a small open economy model with an energy sector, Airaudo et al. (2024) consider the role of green investment subsidies and find that it incentivizes capital accumulation, similar to our model. At the same time, such a subsidy provides less incentives to increase energy efficiency than in the carbon tax in their model. In contrast, abatement subsidies have an unambiguously positive climate impact in our model with endogenous abatement effort but without an energy sector.

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