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Energy Shocks and the Climate Transition

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Abstract

We present a two-sector growth model in which a representative agent invests in fossil fuel-based energy and renewable energy. These differ in capital intensity and project duration: fossil fuel investments require lower upfront investment and have shorter duration, whereas renewables are more capital-intensive with longer-lived assets. We show that a negative economic shock (such as an energy supply shock or recession) leads to both cuts in total investment and to a shift in the composition of the remaining investment toward fossil fuel projects. This delays the clean energy transition, even if renewable energy is cost-effective on a levelised cost basis, implying a role for policies to sustain clean investment during recessions. We discuss how this mechanism can be amplified by higher interest rates, pro-cyclical climate policies, perceived risk, and financial frictions, and we relate our findings to recent empirical episodes (e.g. the 2022-23 energy crisis and post-2008 recession).

Keywords: Energy transition; consumption-smoothing; capital intensity; energy shocks; financial frictions; recessions.

JEL Codes: Q43, E22.

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1 Introduction

The recent surge in energy prices has highlighted the value of prior investment in renewable energy, as economies with more renewables or energy efficient infrastructure would have been more resilient. However, trying to undertake these costly projects during a crisis is challenging. Whereas high energy prices incentivise new energy supply and conservation investments via relative-price effects, the contemporaneous adverse shock to income or output can induce agents to reduce overall investment to smooth consumption. In this paper, we show how the composition of investment in the energy sector may also shift in downturns: specifically, we highlight that recessions may tilt investment away from capital-intensive projects. When faced with a negative shock, agents become unwilling to commit to projects (e.g. wind farms or solar arrays) with large upfront costs and long payback periods, even if those projects offer lower long-run costs per unit of energy. Instead, there is a bias toward projects with lower initial investment requirements and quicker, albeit less sustainable, returns (e.g. expanding fossil fuel extraction or reactivating coal-fired capacity).

To highlight this mechanism, we propose a two-sector neoclassical growth model where a final good is produced combining energy from fossil fuel and renewable sources. A risk-averse representative agent chooses the stream of consumption and investments in energy capitals to maximize lifetime utility. Importantly, we modify the capital accumulation equations of fossil fuel and renewable capital to capture that fossil fuel technology usually has a lower upfront capital requirement but greater ongoing costs, whereas renewable technology requires a larger upfront investment but lower ongoing costs.

In line with the standard consumption-smoothing behaviour, a negative shock to household's income or wealth raises the marginal utility of current consumption, causing them to partially reduce investment. In our model, there is also an effect on the composition of investments. To smooth consumption, our agent allocates relatively more of the diminished investment budget to the technology that yields energy more immediately and with less upfront expense. Thus, recessions induce a temporary reversion to fossil fuel investment, which delays renewable capital accumulation and the transition to a clean energy infrastructure, even if in normal times agents would have preferred the renewable project on cost grounds.

Our model contributes to understanding why progress on decarbonisation often stalls during economic downturns. For example, global clean energy investment fell sharply during the 2008–09 crisis, with a 53% slump in new renewable investment in the first quarter of 2009 (UNEP, 2009). Without sustained investment, emission reductions during recessions are fleeting: for example, the dip in global CO_2 emissions in 2009 was followed by a rapid rebound to record highs in 2010 (Global Carbon Atlas, 2025). Similarly, in the 2022 energy crisis triggered by Russia's invasion of Ukraine, many countries responded by scrambling to secure short-run fossil fuel supplies (e.g. coal and liquefied natural gas) even as they reaffirmed long-run green targets.

We relate to the literature showing that business cycles interact with optimal emissions policy. This usually argues that policy should be made less stringent during recessions (see the review by Annicchiarico et al., 2022). Whereas such easing might be warranted in models without different capital intensities, it could inadvertently compound the delay in the transition if fossil investments have lower upfront capital requirements.

Section 2 lays out the model and examines the impact of a negative shock. Sections 3 and 4 discuss extensions and real-world implications, respectively. Section 5 concludes.

2 Model

We consider an infinite-horizon economy in discrete time. Output Y_t is produced competitively by a representative firm through

$$Y_t = E_t^{\alpha} L_t^{1-\alpha}, \tag{1}$$

where $\alpha \in (0,1)$, L_t is labour, and E_t is a composite of "dirty" energy E_{dt} and "clean" energy E_{ct},

$$E_t = \left(E_{dt}^{(\epsilon-1)/\epsilon} + E_{ct}^{(\epsilon-1)/\epsilon} \right)^{\epsilon/(\epsilon-1)}, \tag{2}$$

with $\epsilon > 1$ the elasticity of substitution.[1] The first-order conditions (FOCs) of the final good producer imply that the relative demands for energy inputs are inversely related to their prices p_{it}.

In each energy sector $i = \{d, c\}$, a representative firm generates E_{it} via $E_{it} = K_{it}$, where K_{dt} and K_{ct} are dirty and clean capitals, respectively. Given the linear production, energy firms make zero profits, and the rental rate of capital equals its marginal product in energy terms,

$$p_{it} = \frac{\partial Y_t}{\partial E_t} \frac{\partial E_t}{\partial E_{it}}. \tag{3}$$

Importantly, dirty and clean capitals differ in their dynamics. Dirty capital is shorter-lived and subject to resource depletion, while clean capital is longer-lived and benefits from technological improvements. We capture these differences through the accumulation equations,

$$K_{ct+1} = I_{ct} + (1-\delta_c) K_{ct} \tag{4a}$$

$$K_{dt+1} = D_t I_{dt} + (1-\delta_d) K_{dt}, \tag{4b}$$

[1] Elasticities used in macroeconomic models vary: Acemoglu et al. (2012) use 3 and 10, Golosov et al. (2014) use 1, Hart (2019) uses 4, van der Ploeg and Rezai (2021) use 0.945, and Campiglio et al. (2024) use 3. Empirical estimates range between 0.5 and 3 (Stern, 2012, Papageorgiou et al., 2017).

where I_{it} is investment in capital of type $i \in \{d, c\}$, $\delta_i \in (0,1)$ is the depreciation rate, and D_t represents the efficiency of new dirty investment over those in clean energy capacity (i.e. technological progress is embodied as in Greenwood et al., 1997, Krusell, 1998).

We assume D_t starts high but exogenously declines at rate $\Delta > 0$, reflecting fossil resource depletion and improving competitiveness of renewables. We also assume $\delta_d > \delta_c$. As a consequence, clean investments have initially a shorter effective project duration (the weighted average time until cash flows are received). In other words, dirty projects require lower effective cost per unit of capacity initially, but dirty capital also has higher ongoing cost in the form of faster depreciation (reflecting the need for fuel inputs, which we abstract from).

The representative household inelastically supplies one unit of labour, owns all capital, and chooses $\{C_t, I_{dt}, I_{ct}\}_{t=0}^{\infty}$ to maximise lifetime utility,

$$\sum_{t=0}^{\infty} \beta^t \frac{C_t^{1-\theta} - 1}{1-\theta}, \tag{5}$$

where $\beta \in (0,1)$ is the discount factor and $\theta > 0$ is the coefficient of relative risk aversion, subject to the accumulation equations in (4), a transversality condition, the flow budget constraint $C_t + I_{dt} + I_{ct} = w_t + p_{dt}K_{dt} + p_{ct}K_{ct}$, and given initial capital stocks.

The FOCs include an Euler equation for intertemporal allocation and a condition for the choice between investments. These can be summarised as

$$\left(\frac{C_t}{C_{t+1}}\right)^{-\theta} = \beta \max\left\{r_{dt+1};\, r_{ct+1}\right\} = \beta \max\left\{D_t p_{dt+1} + \frac{1-\delta_d}{1-\Delta};\, p_{ct+1} + (1-\delta_c)\right\}. \tag{6}$$

In deciding where to invest, the agent compares the two returns r_{it+1}, including the efficiency of investment times the rental rate of capital plus any change in the asset's value net of depreciation. They take into account that, since clean capital is more durable, its payoff is relatively more back-loaded.

The economy exhibits a unique equilibrium path, illustrated in Figure 1.[2] Initially, dirty investment dominates due to high D_t. Agents optimally invest until returns are equalised, $r_{dt+1} = r_{ct+1}$, which implies $\partial E_{t+1}/\partial E_{dt+1} < \partial E_{t+1}/\partial E_{ct+1}$: the economy initially embarks onto a "fossil investment" regime, where agents invest more in dirty capital. Over time, declining D_t and dirty capital accumulation reduce the marginal return to dirty investment; to equalise returns, agents invest increasingly more in clean capital and the economy embarks onto a "green investment" regime. Eventually, the decline in D_t is so severe that clean returns overtake dirty ones, and agents switch to investing only in clean capital, initiating an endogenous transition to a clean steady state.

[2] The decentralised equilibrium is Pareto optimal. In Appendix A, we add climate damages.

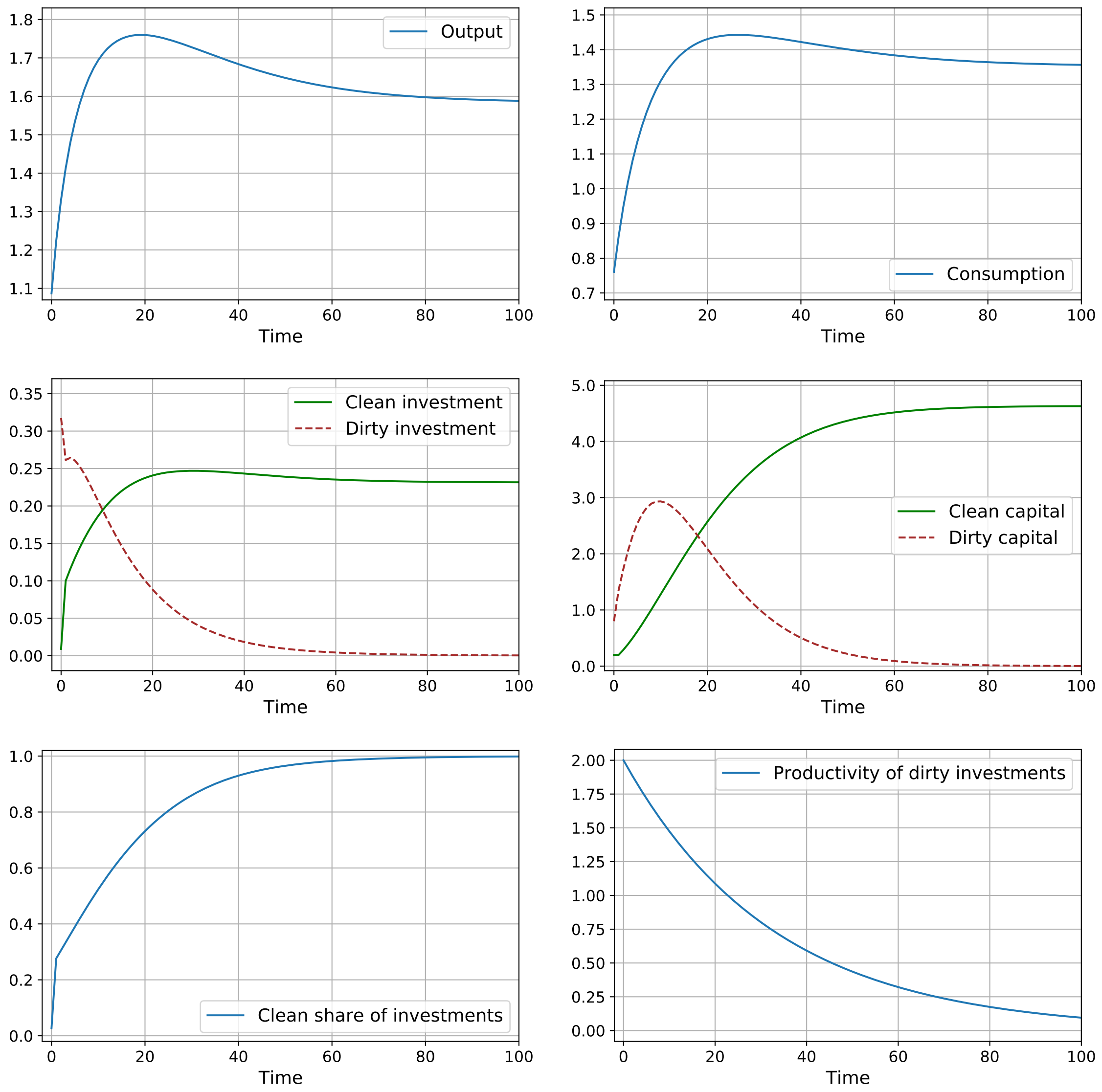

Figure 1: The Equilibrium Path

Notes. Long-run equilibrium of the the model under the following parametrization: $\theta = 2$, $\alpha = 0.3$, $\beta = 0.95$, $\delta_c = 0.05$, $\delta_d = 0.10$, $\Delta = 0.03$, $\epsilon = 3$, $K_{c0} = 0.2$, $K_{d0} = 0.8$, and $D_0 = 2$.

2.1 Implications

We focus on short-run dynamics following an unexpected shock to capital. Specifically, we consider a drop in $K_{d0} + K_{c0}$, which could proxy an energy supply disruption, destruction of capital infrastructure, or sudden obsolescence, and examine the impacts on C_t, I_{dt}, and I_{ct}. Figure 2 proposes comparative dynamics following a shock to both capitals, but those following a shock to one type are similar (see Appendix B.1).

2.1.1 Aggregate Investment

The immediate effect of the unexpected negative shock is a reduction in available energy E_0 and hence a drop in output Y_0 (first panel of Figure 2). This makes the

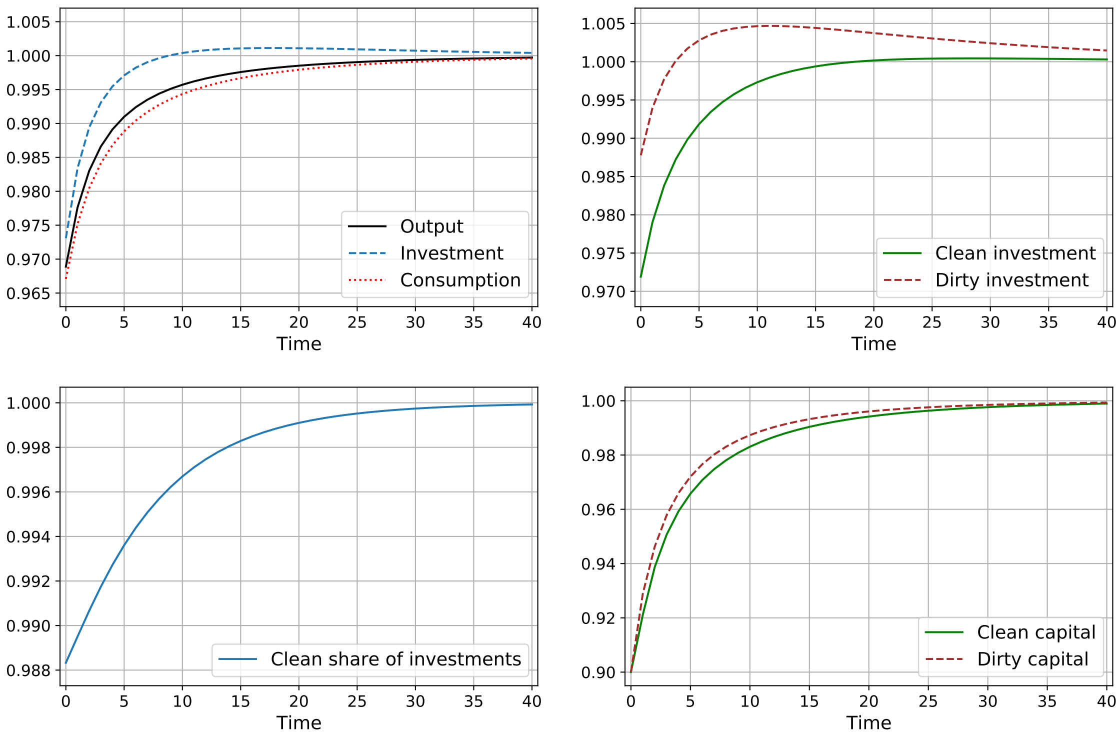

Figure 2: Impact of a Negative Shock

Notes. Changes in the named variable following an unexpected 10% loss in both types of capital, relative to the same variable in the no-shock scenario.

representative agent poorer in terms of resources.

Since output can be only used for consumption and investments, $Y_0 = C_0 + I_{d0} + I_{c0}$. Following the shock, consumption does not fall for the full amount of the output loss. Indeed, as consumption decreases, the marginal utility $u'_0 \equiv C_0^{-\theta}$ on the left-hand side of the Euler equation (6) rises, making the households willing to forgo future consumption (via reduced investment) to sustain current consumption, which is the standard consumption-smoothing response. Similarly, aggregate investment does not fall to the full output loss: this is a particularly good period to invest, as the loss of capital triggers an increase in the interest rate through diminishing marginal returns. This boosts the right-hand side of (6), moderating the investment drop.[3]

2.1.2 Investment Composition

More interestingly, our model predicts a shift in the composition of investments. Indeed, the shock raises the marginal utility of current relative to future consumption, which decreases the actual discount factor $\beta u'_{t+1}/u'_t$, making the agent effectively more impatient than it would have been without the shock, even if the subjective discount factor β is unchanged. Since the economy was investing in both types of capital pre-shock, the present

[3]If θ is sufficiently high, the consumption rate increases after the shock; see Appendix B.2.

values of future returns were equalised through the choice of a given split between investments. However, the shock has changed household's valuation of those future returns, as when current consumption is suddenly scarce, it behaves as if effectively applying a temporarily higher effective discount rate to long-horizon projects. Thus, a split relatively more in favour of dirty investments that may have been suboptimal in normal times (due to lower overall return or higher levelised cost) becomes optimal in a recession (second and third panels of Figure 2).

This compositional shift is a temporary equilibrium response. As the economy recovers and consumption-smoothing considerations ease, the preference for quick-payoff projects diminishes; moreover, the decline in D_t pushes the economy back toward the clean path. Nonetheless, this slows down the transition and has persistent effects, as fewer renewables installed during the downturn lowers their capital base, prolonging the reliance on dirty energy (last panel of Figure 2).

3 Additional Mechanisms

Our aim is to highlight the importance of consumption-smoothing, combined with the relative capital intensity of renewables, for the composition of investments following a negative shock and its repercussions for the decarbonisation path. Here, we show that this mechanism can be strengthened by several other characteristics of renewables investment; see Appendix A for an extended model embedding some of these factors.

First, financial frictions can play a critical role, as renewable investments involve large upfront financing needs (Ghisetti et al., 2017), have long amortisation periods (Couture and Gagnon, 2010), and highly rely on debt provision (Haas and Kempa, 2023). Since borrowing constraints tighten in recessions, investors will find those projects harder to fund than fossil fuel investments, with their smaller scale and quicker payback. In Appendix A, we embed Matsuyama's (2007) trade-off between long-term productivity and short-term pledgeability to our model: a negative shock lowers borrower net worth and causes a shift towards more pledgeable dirty investments, thus reinforcing the consumption-smoothing mechanism. This channel has been noted as a concern in policy discussions (e.g. IEA, 2009).

Second, investment adjustment costs will tend to dampen volatile swings in investment allocation at the short horizon, as investment cannot jump costlessly. In Appendix A, we add capital-producing firms subject to investment adjustment costs, similarly to Diluiso et al. (2021). Immediately following a shock, we might see both a less extreme drop in clean investment, and dirty investment tempered by the rising marginal cost of installation, compared to the baseline model. However, the economy will adjust more gradually: the Tobin's Q of dirty capital will remain relatively high for several periods, attracting investment until enough new capital has been built, whereas clean capital's

Q might remain relative low, signifying a continued lull in clean investment. Moreover, these Qs imply asset value impacts which interact with financial frictions to multiply that effect.

Third, most macro-environmental models suggest that the Ramsey-optimal emissions tax should be eased during recessions (e.g. Heutel, 2012, Annicchiarico et al., 2021, 2022). We showed that, even without policy changes, the private sector will invest less in clean energy during recessions: in Appendix A, we argue that a climate policy relaxation would compound this effect, and thus may be suboptimal once we account for our mechanism. Thus there may be merit in policies that actively encourage or maintain investment in renewables during downturns (e.g. green investment guarantees, public infrastructure programmes, or green banks) to counteract the private tendency to delay the transition (see Comerford and Spiganti, 2023).

Finally, we highlight two mechanisms not explicitly modelled in Appendix A. First, fossil fuel projects, backed by existing infrastructure and known technologies, may be viewed as having more certain short-term returns, whereas novel renewable projects may be perceived as riskier, especially if relying on policy support. If a shock increases uncertainty about future policy or demand, investors may exhibit heightened risk aversion, leading to a stronger tendency to smooth consumption and further disadvantaging capital-intensive renewable investments. Second, if central banks respond to the inflationary costs imposed by climate policy by raising interest rates (as in Sahuc et al., 2024), any given imposition of this policy would lead to weaker emissions reduction, because the central bank's interest rate rises would discourage renewables investment. Our model thus highlights that the relative capital intensity of renewables adds nuance to the optimal central bank response to greenflation.

4 Empirical Examples

The broad patterns above find support in recent history. During the financial crisis of 2008-09, many countries saw declines in overall investment and steep drops in renewable energy investment. After years of growth, global new renewables investment fell in 2009 (REN21, 2014), partly due to the credit crunch and lower appetite for capital-intensive projects (IEA, 2009). Even though stimulus packages (e.g. the 2009 American Recovery and Reinvestment Act) tried to promote green projects, the uncertainty and financial stress meant that fossil fuel interests did not lose ground (IEA, 2014). Indeed, as economies recovered, emissions and fossil fuel use bounced back quickly (Global Carbon Atlas, 2025). Similarly, in the aftermath of the COVID-19 shock there was a brief drop in emissions, but by 2021 global CO_2 emissions had reached new highs, in part because the recovery efforts did not decisively shift the energy mix towards renewables (Jackson et al., 2022).

The 2022-23 energy price shock offers a more nuanced case. On the one hand, the spike in natural gas and oil prices made renewable energy and efficiency investments extremely attractive in terms of energy security (Kim et al., 2025) and cost savings (IRENA, 2024). On the other hand, the shock occurred as inflation surged and interest rates rose, and in the midst of broader economic uncertainty. In Europe, even as governments announced ambitious long-term targets for wind and solar, immediate responses included securing additional fossil fuel supplies (new liquefied natural gas terminals, short-term contracts for gas, and temporary coal power restarts). The high cost of energy left consumers with less disposable income to invest in home retrofits or electric vehicles; and has led to political opposition to climate action. Investment data for 2022 show a mixed picture: global clean energy investment rose to record levels, helped by policy support (e.g. the US Inflation Reduction Act and EU REPowerEU plan), but there was also a boost in fossil fuel revenues and reinvestment. Fossil fuel companies enjoyed unprecedented cash flows in 2022, yet less than half of that windfall was reinvested into new supply, and only a small fraction into clean energy (IEA, 2023). This suggests that while high prices incentivised some investment, the uncertainty and focus on quick returns meant much of the windfall was not used for any investment (instead going to dividends or debt reduction).

These examples underscore our central point: economic disruptions tend to retard the shift in investment needed for the transition, both by shrinking total investment and by reallocating investment towards projects with shorter-term payoffs. Even when clean technologies have become cheaper than fossil alternatives on a per-unit basis, the timing of costs and benefits matters greatly. Agents with limited resources in a downturn will defer large upfront expenditures, preferring options that keep near-term consumption higher. This myopic reaction, while individually rational, poses a collective challenge for decarbonisation.

5 Conclusions

We developed a two-sector growth model illustrating how negative economic shocks can delay the transition. The mechanism hinges on differences in capital intensity and effective project duration between fossil fuel and renewable energy investments. Following a negative shock, the desire to smooth consumption leads to a cutback in overall investment and a bias in remaining investment toward lower-duration, lower-upfront-cost fossil fuel projects. We discussed how this effect could be amplified by rising interest rates, heightened risk aversion, pro-cyclical carbon policies, and credit market frictions during downturns.

This helps explain why carbon emissions often decline only transiently during recessions and why surges in energy prices accompanied by economic stress do not automatically produce a green investment boom. This carries a policy implication: to maintain momentum in the transition, it may be necessary to counteract the private-sector tendency to underinvest in capital-intensive clean energy during recessions. Importantly, traditional advice that calls for relaxing environmental policies in recessions should recognise the long-run cost of delayed investment in clean capital.

However stylised, our model highlights that business cycles and climate transition dynamics are interlinked, and managing this interaction is key to achieving climate targets on schedule. Future research could incorporate uncertainty, policy optimisation, and empirical estimation of the described mechanism. In the meantime, recent crises suggest that ensuring the resiliency of the climate transition against economic shocks remains a pressing challenge.

References

Acemoglu, D., Aghion, P., Bursztyn, L., and Hémous, D. (2012). The environment and directed technical change. *American Economic Review*, 102(1):131 – 166.

Annicchiarico, B., Carattini, S., Fischer, C., and Heutel, G. (2022). Business cycles and environmental policy: A primer. *Environmental and Energy Policy and the Economy*, 3:221–253.

Annicchiarico, B., Dio, F., and Molina, E. (2021). Climate policy and the business cycle: On the optimality of adjusting climate policy to the business cycle. *Environmental and Resource Economics*, 79(4):751–782.

Campiglio, E., Spiganti, A., and Wiskich, A. (2024). Clean innovation, heterogeneous financing costs, and the optimal climate policy mix. *Journal of Environmental Economics and Management*, 128:103071.

Carattini, S., Heutel, G., and Melkadze, G. (2023). Climate policy, financial frictions, and transition risk. *Review of Economic Dynamics*, 51:778–794.

Comerford, D. and Spiganti, A. (2023). The Carbon Bubble: Climate policy in a fire-sale model of deleveraging. *Scandinavian Journal of Economics*, 125(3):655–687.

Couture, T. and Gagnon, Y. (2010). An analysis of feed-in tariff remuneration models: Implications for renewable energy investment. *Energy Policy*, 38(2):955–965.

Diluiso, F., Annicchiarico, B., Kalkuhl, M., and Minx, J. C. (2021). Climate actions and stranded assets: The role of financial regulation and monetary policy. *Journal of Environmental Economics and Management*, 110:102548.

Gertler, M. and Karadi, P. (2011). A model of unconventional monetary policy. *Journal of Monetary Economics*, 58(1):17–34.

Ghisetti, C., Mancinelli, S., Mazzanti, M., and Zoli, M. (2017). Financial barriers and environmental innovations: Evidence from EU manufacturing firms. *Climate Policy*, 17(sup1):S131–S147.

Global Carbon Atlas (2025). `http://www.globalcarbonatlas.org`.

Golosov, M., Hassler, J., Krusell, P., and Tsyvinski, A. (2014). Optimal taxes on fossil fuel in general equilibrium. *Econometrica*, 82(1):41–88.

Greenwood, J., Hercowitz, Z., and Krusell, P. (1997). Long-run implications of investment-specific technological change. *American Economic Review*, 87(3):342–362.

Haas, C. and Kempa, K. (2023). Low-carbon investment and credit rationing. *Environmental and Resource Economics*, 86:109–145.

Hart, R. (2019). To everything there is a season: Carbon pricing, research subsidies, and the transition to fossil-free energy. *Journal of the Association of Environmental and Resource Economists*, 6(2):349–389.

Heutel, G. (2012). How should environmental policy respond to business cycles? Optimal policy under persistent productivity shocks. *Review of Economic Dynamics*, 15(2):244–264.

IEA (2009). The impact of the financial and economic crisis on global energy investment. Technical report, Organization for Economic Co-operation and Development and International Energy Agency.

IEA (2014). World energy investment output. Technical report, International Energy Agency.

IEA (2023). World energy investment 2023. Technical report, International Energy Agency.

IRENA (2024). Renewable power generation costs in 2023. Technical report, International Renewable Energy Agency.

Jackson, R. B., Friedlingstein, P., Le Quéré, C. ., Abernethy, S., Andrew, R. M., Canadell, J. G., Ciais, P., Davis, S. J., Deng, Z., Liu, Z., Korsbakken, J. I., and Peters, G. P. (2022). Global fossil carbon emissions rebound near pre-COVID-19 levels. *Environmental Research Letters*, 17(3):031001.

Kim, J., Jaumotte, F., Panton, A. J., and Schwerhoff, G. (2025). Energy security and the green transition. *Energy Policy*, 198:114409.

Krusell, P. (1998). Investment-specific R&D and the decline in the relative price of capital. *Journal of Economic Growth*, 3(2):131–141.

Matsuyama, K. (2007). Credit traps and credit cycles. *American Economic Review*, 97(1):503 – 516.

Nordhaus, W. D. (2018). Projections and uncertainties about climate change in an era of minimal climate policies. *American Economic Journal: Economic Policy*, 10(3):333–360.

Papageorgiou, C., Saam, M., and Schulte, P. (2017). Substitution between clean and dirty energy inputs: A macroeconomic perspective. *Review of Economics and Statistics*, 99(2):281–290.

Queirós, F. (2025). The savings rate in a discrete-time Ramsey economy with CRRA preferences and full depreciation. *Economics Letters*, 253:112384.

REN21 (2014). Ten years of renewable energy progress. Technical report, Renewable Energy Policy Network for the 21st Century.

Sahuc, J., Smets, F., and Vermandel, G. (2024). The New Keynesian climate model. CEPR Discussion Paper No. 19745.

Stern, D. I. (2012). Interfuel substitution: A meta-analysis. *Journal of Economic Surveys*, 26(2):307–331.

UNEP (2009). Global trends in sustainable energy investment 2009. Technical report, United Nations Environment Programme.

van der Ploeg, F. and Rezai, A. (2021). Optimal carbon pricing in general equilibrium: Temperature caps and stranded assets in an extended annual DSGE model. *Journal of Environmental Economics and Management*, 110:102522.

A Appendix: Extended Model

In this Appendix, we extend the baseline model of Section 2 to include financial frictions, investment adjustment costs, and productivity damages.

Final Sector. Output Y_t is produced competitively by a representative firm according to the following constant returns to scale technology,

$$Y_t = \Gamma(S_t)\, E_t^{\alpha} L_t^{1-\alpha}, \tag{A.1}$$

where $\alpha \in (0,1)$, L_t is labour, $\Gamma_t(S_t)$ is a net-of-damage function (linking cumulative emissions S_t to percentage decreases in productivity, in the spirit of Golosov et al., 2014, Nordhaus, 2018), and E_t is a composite of energy generated from fossil fuel sources E_{dt} and renewable sources E_{ct}. These are combined according to the following constant elasticity of substitution technology,

$$E_t = \left(E_{dt}^{(\epsilon-1)/\epsilon} + E_{ct}^{(\epsilon-1)/\epsilon}\right)^{\epsilon/(\epsilon-1)}, \tag{A.2}$$

where ϵ is the elasticity of substitution between the two intermediate inputs. We focus on the more empirically relevant case in which the two energy inputs are substitutes, $\epsilon > 1$. The price of the final good is normalised to one at each date. The first-order conditions of the final good producer imply that the relative demands for the energy inputs are inversely related to their prices, $\frac{E_{ct}}{E_{dt}} = \left(\frac{p_{dt}}{p_{ct}}\right)^{\epsilon}$.

Energy Sectors. In each energy sector $i = \{d, c\}$, a representative energy firm generates E_{it} via a linear technology $E_{it} = K_{it}$, where K_{dt} and K_{ct} are fossil fuel capital and green (renewable) capital, respectively. In other words, K_{it} represents the effective energy capacity of i-type capital. Whereas green energy does not create carbon emissions, fossil energy production emits κ units of carbon per unit of energy, i.e. cumulative emissions at time t are $S_t = \sum_{\tau=-\infty}^{t} \kappa E_{d\tau}$; therefore, the representative fossil firm may be subject to a carbon tax τ_t imposed by the government.

At the end of period t, firms buy capital K_{it+1} to be used in production at time $t+1$ from capital-producing firms at market price Q_{it}; this capital acquisition is financed by borrowing an amount $Q_{it}K_{it+1}$ from banks. After production takes place in $t+1$, firms repay banks at rate R_{it+1}, resell undepreciated capital $(1-\delta_i)\, K_{it+1}$ at price Q_{it+1} to capital-producing firms, and purchase capital that will be employed in the subsequent period.

As a consequence, realized profits in t are

$$(p_{it} - \tau_{it})\, E_{it} - R_{it}Q_{it-1}K_{it} + (1-\delta_i)Q_{it}K_{it}. \tag{A.3}$$

Energy firms are subject to a borrowing constraint, as only a fraction ν_i of the project revenue can be pledged for repayment; knowing this, lenders would lend only up to $\nu_i p_{it} E_{it}/R_{it}$. Therefore, the representative energy firm can borrow only if the following borrowing constraint is satisfied,

$$\nu_i p_{it} E_{it} \geq R_{it} Q_{it-1} K_{it}. \tag{A.4}$$

Capital-Producing Sectors. The capital-producing sectors follow closely the specification in Gertler and Karadi (2011). Capital is sector-specific and immobile across sectors, and two representative capital-producing firms build competitively fossil and renewable capital goods. After production takes place in any period t, the i-type capital-producing firm buys back undepreciated capital $(1-\delta_i)\,K_{it}$ from current period producers in sector i at price Q_{it}, and refurbish it at no cost. They then decide how much new sector-specific capital to produce I_{it}, and sell the aggregate level of new and refurbished capital K_{it+1} to be used in production in $t+1$ at the same price Q_{it}, commonly known as Tobin's Q.

The novelty with respects to previous literature is that fossil and renewable capital differs in their dynamics. Fossil capital is shorter-lived and subject to resource depletion, while renewable capital is longer-lived and benefits from ongoing technological improvements. We parsimoniously capture these differences through the following accumulation equations,

$$K_{ct+1} = I_{ct} + (1-\delta_c)K_{ct} \tag{A.5a}$$

$$K_{dt+1} = D_t I_{dt} + (1-\delta_d)K_{dt}, \tag{A.5b}$$

where I_{it} is gross investment in period t in capital of type $i \in \{d, c\}$, $\delta_i \in (0,1)$ is the capital-specific depreciation rate, and D_t represents the relative efficiency of new fossil fuel investment at time t over the equivalent investment in green energy capacity. We normalise the efficiency of new renewable investment to one. We assume D_t starts high but declines at rate $\Delta > 0$, reflecting fossil resource depletion and improving competitiveness of renewables. We also assume $\delta_d > \delta_c$, so that fossil capital depreciates faster. As a consequence of these assumptions, green investments have initially a shorter effective project duration (i.e. the weighted average of times until the cash flows are received). In other words, fossil projects require lower effective cost per unit of capacity initially (when $D_t > 1$), but fossil capital also has higher ongoing cost in the form of faster depreciation (reflecting the need for fuel inputs, which we abstract from here). These assumptions capture that fossil fuel technology has a lower upfront capital requirement but greater ongoing costs, whereas renewable technology requires a larger upfront investment but lower ongoing costs.

As in Gertler and Karadi (2011), Diluiso et al. (2021), and Carattini et al. (2023), capital producers face investment adjustment costs associated with new capital production. The competitive representative capital good producers then choose the stream of I_{it} to maximize

$$\sum_{t=0}^{\infty} \beta^t \left[Q_{it} D_{it} I_{it} - I_{it} - \frac{\gamma_i}{2}\left(\frac{I_{it}}{I_{it-1}} - 1\right)^2 I_{it} \right], \tag{A.6}$$

where $\gamma_i \geq 0$ controls the size of the adjustment cost, $D_{dt} = D_t$, and $D_{ct} = 1$. The FOC is

$$Q_{it} = \frac{1}{D_{it}} \left[1 + \frac{\gamma_i}{2}\left(\frac{I_{it}}{I_{it-1}} - 1\right)^2 + \gamma_i \left(\frac{I_{it}}{I_{it-1}} - 1\right)\frac{I_{it}}{I_{it-1}} - \beta\gamma_i \left(\frac{I_{it+1}}{I_{it}}\right)^2 \left(\frac{I_{it+1}}{I_{it}} - 1\right) \right].$$

Banks. There is a competitive financial sector. In every t, the representative bank raises deposits B_t from households at the risk-free rate R_{t+1} and provide funds $Q_{it}K_{it+1}$ to energy firms at loan rates R_{it+1}.

Households. The representative household inelastically supplies one unit of labour and chooses the stream of consumption C_t and deposits B_t to maximise the net present value of its lifetime utility,

$$\sum_{t=0}^{\infty} \beta^t \frac{C_t^{1-\theta} - 1}{1-\theta}, \tag{A.7}$$

where $\beta \in (0,1)$ is the discount factor and $\theta > 0$ is the coefficient of relative risk aversion. The optimization is subject to a transversality condition and the flow budget constraint $C_t + B_t = w_t + R_t B_{t-1} + T_t$, where T_t is a lump-sum tax or transfer. This leads to the usual Euler equation,

$$\left(\frac{C_t}{C_{t+1}}\right)^{-\theta} = \beta R_{t+1}. \tag{A.8}$$

Equilibrium. The first-order condition of the energy firms implies

$$R_{it} = \frac{p_{it} - \tau_{it}}{Q_{it-1}} + (1-\delta_i)\frac{Q_{it}}{Q_{it-1}}, \tag{A.9}$$

where $p_{it} = \frac{\partial Y_t}{\partial E_t}\frac{\partial E_t}{\partial E_{it}}$ from the FOC of the final firm. At the same time, borrowing is incentive compatible if and only if

$$\frac{\nu_i p_{it} E_{it}}{Q_{it-1} K_{it}} \geq R_{it}. \tag{A.10}$$

Thus, the equilibrium loan rates for energy firms in sector i must satisfy

$$R_{it} \leq \min\left\{\frac{\nu_i p_{it} E_{it}}{Q_{it-1} K_{it}}, \frac{p_{it} - \tau_{it}}{Q_{it-1}} + (1-\delta_i)\frac{Q_{it}}{Q_{it-1}}\right\} \equiv r_{it}. \tag{A.11}$$

Combining this with the Euler equation in (A.8) and the free-entry condition in the banking sector, consumption evolves according to

$$\left(\frac{C_t}{C_{t+1}}\right)^{-\theta} = \beta \max\left\{r_{dt+1}; \quad r_{ct+1}\right\}. \tag{A.12}$$

Note that, if $\gamma_i = 0$, there are no adjustment costs (so that $Q_{it} = 1/D_t$); if ν_i is high, borrowing constraints never bind; finally, if $\kappa = 0$, fossil energy production does not create carbon emissions and $\tau_{it} = 0$. Under these conditions, the model simplifies to the one in the main text.

First, consider a carbon tax, i.e. $\tau_{dt} > 0$ and $\tau_{ct} = 0$. Compared to a laissez-faire scenario without policy, a carbon tax lowers the attractiveness of fossil investments by depressing r_{dt}, and thus changes the relative composition of investments towards renewables. However, it is then easy to see from (A.11) how a pro-cyclical carbon taxation would compound the effect we highlight in the main text.

Second, consider financial frictions. To capture the fact that renewables investment may be harder to finance than fossil fuel ones, a reasonable parametrisation implies $\nu_c < \nu_d$. As in Matsuyama (2007), this creates a trade-off between long-term profitability and pledgeability. Compared to the baseline model, these financial frictions redirects relatively more investments towards more pledgeable fossil investments both in normal times and especially when the income of the agents is relatively low as after a negative shock.

Finally, the effect of investment adjustment costs work through the Tobin's Q, which is above one for both types of capital if the size of adjustment costs γ_i are positive. Since resources are wasted in adjustment costs, aggregate investments and households' actual discount factor are lower than in the baseline model, thus strengthening the consumption-smoothing mechanism we highlight but also stretching out responses to shocks over more periods. Moreover, Diluiso et al. (2021) estimate slightly higher adjustment costs for green than for fossil capital: on the one hand, this would tend to limit the magnitude of the drop in green investments right after the shock; on the other, it would increase the persistence of the shock in terms of delay of the green transition.

B Appendix: Robustness

B.1 Other Shocks to Capital

Figures B.1 and B.2 provides the equivalent of Figure 2, but following a shock of 10% to green capital only or fossil capital only, respectively. The rest of the parametrization is the same as in the main text. These show that results are qualitatively the same as under a shock that impacts both types of capital simultaneously.

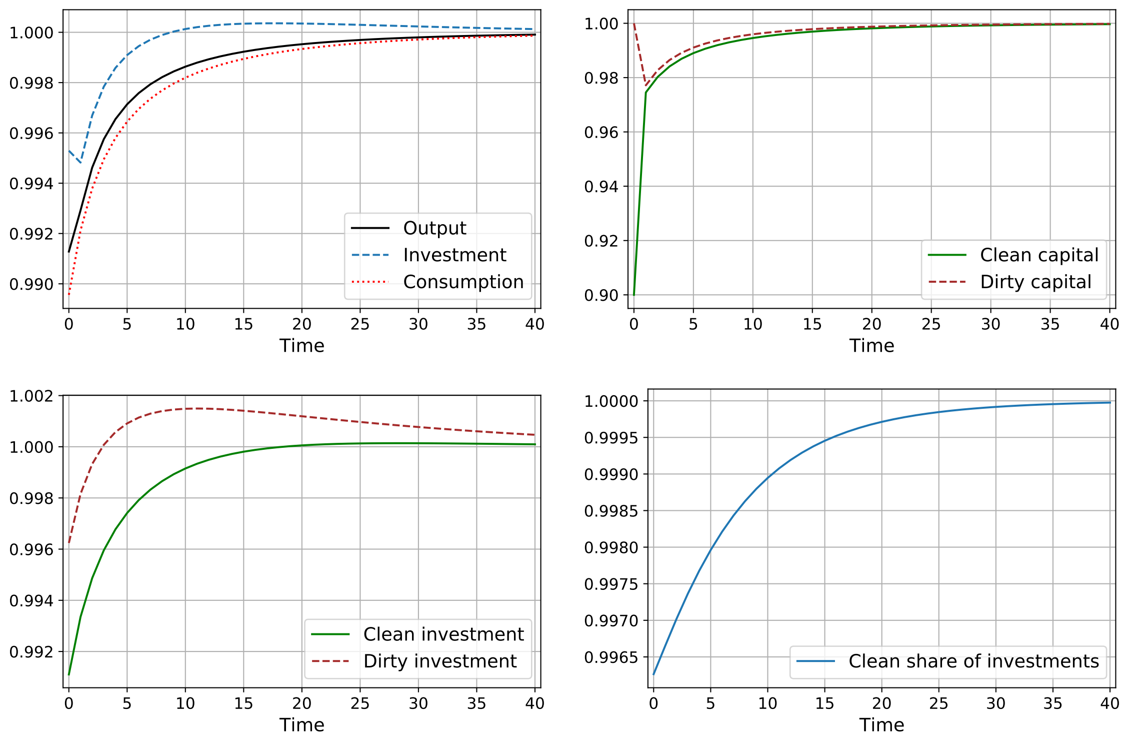

Figure B.1: A Shock to K_{c0}

Notes. Changes in the named variable following an unexpected 10% loss in renewable capital, relative to the same variable in the no-shock scenario.

B.2 Different IES

Figures B.3 and B.4 provides the equivalent of Figure 2 but with different values of the CRRA parameter θ, everything else equal. In particular, Figure B.3 analyses the case with a smaller IES (a higher $\theta = 3$, as compared to 2 in the main text), while in Figure B.4 the IES is higher (a smaller $\theta = 1.5$).

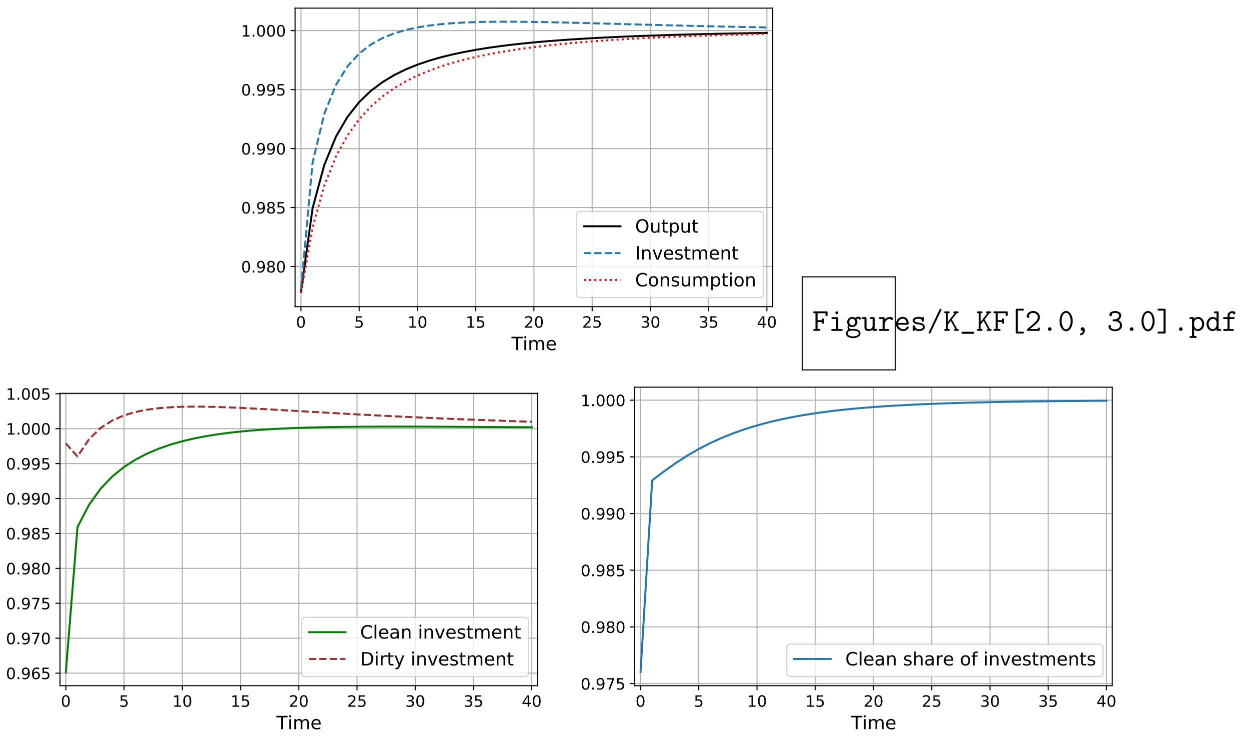

Figure B.2: A Shock to K_{d0}

Notes. Changes in the named variable following an unexpected 10% loss in fossil capital, relative to the same variable in the no-shock scenario.

A smaller IES translates in a greater household's desire to smooth consumption, who is thus more willing to sacrifice future consumption (through reduced investment) to preserve current consumption following the negative shock to capital. As a consequence, the smaller is the IES, the stronger is the consumption-smoothing mechanism we highlight.[4]

[4]In the discrete Ramsey model with CRRA preferences, Cobb–Douglas production, and full depreciation, the savings rate increases in the capital stock when the intertemporal elasticity of substitution (IES) is lower than one (Queirós, 2025): there, consumption relative to output would be higher at the time of the shock than it would be without it. This happens in our more complicated model if the IES is sufficiently lower than one.

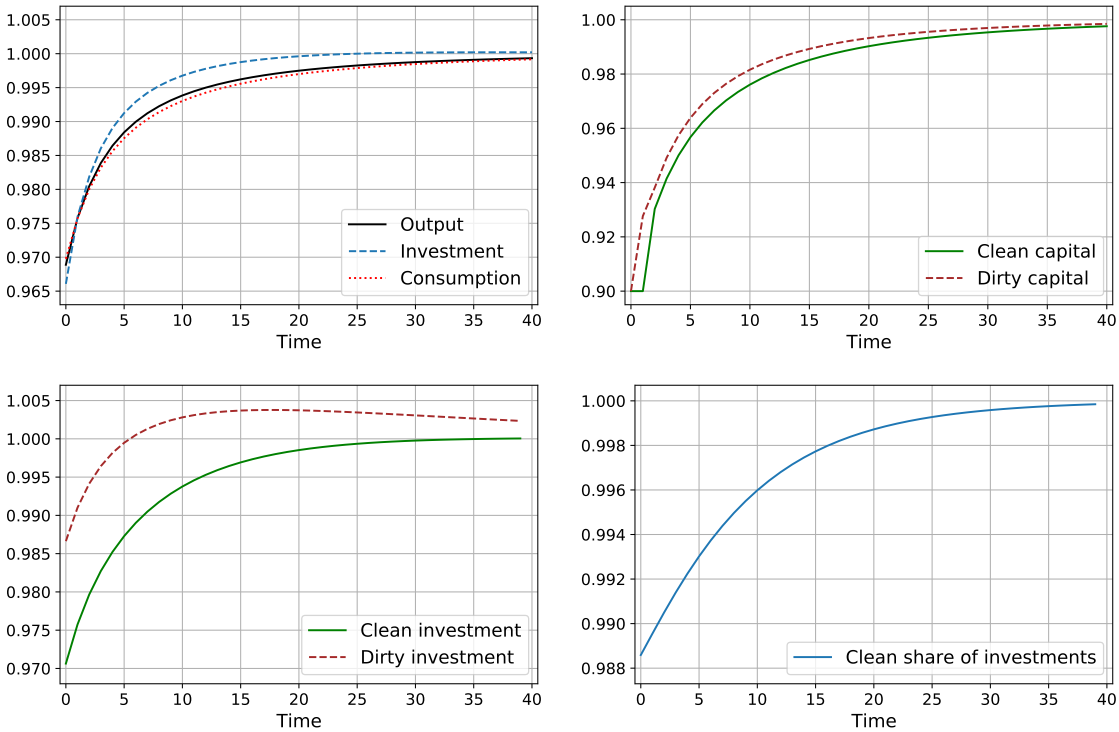

Figure B.3: $\theta = 3.0$

Notes. Relative changes in the named variable following an unexpected 10% loss in both types capital. The only difference with the simulation in the main text is the value of θ, here set to 3.

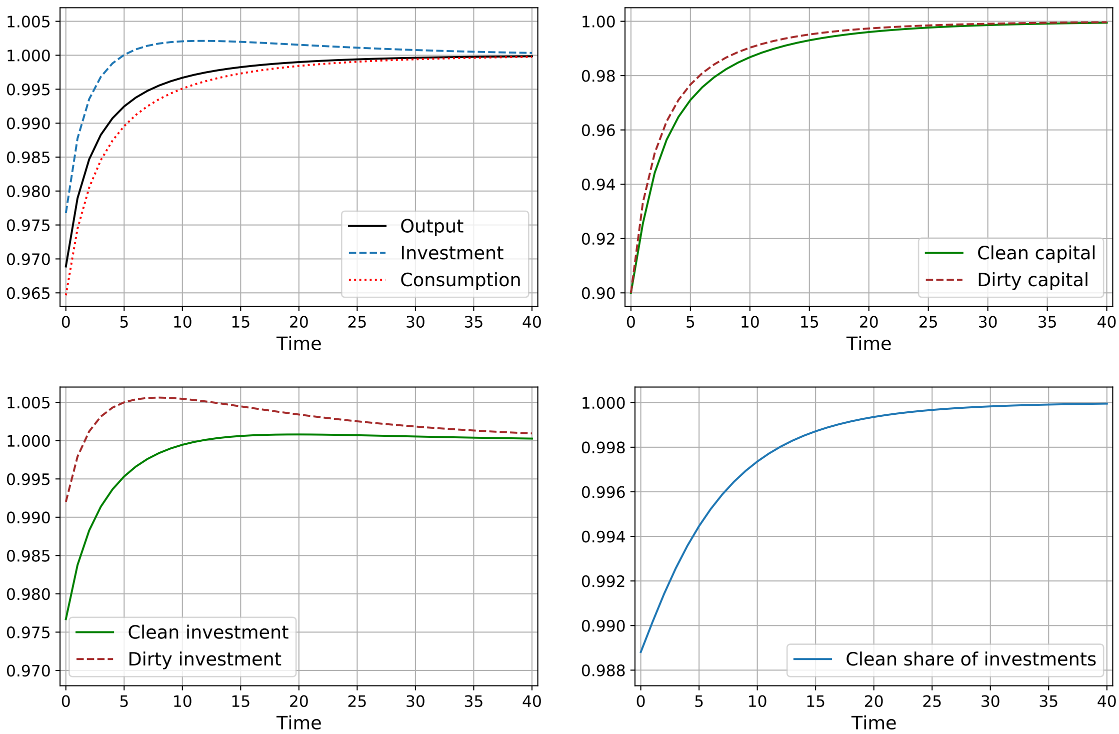

Figure B.4: $\theta = 1.5$

Notes. Relative changes in the named variable following an unexpected 10% loss in both types capital. The only difference with the simulation in the main text is the value of θ, here set to 1.5.