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Safeguarding macro-financial stability under carbon pricing and rapid energy transition

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Although the case for a swift climate transition is clear, its macro-financial viability remains uncertain. To shed light on the macroeconomic and financial response to deep mitigation trajectories controlled by carbon pricing, we soft-link a process-based integrated assessment model (the World Induced Technical Change Hybrid, WITCH) to a macro-financial agent-based model (the Dystopian Schumpeter Meeting Keynes, DSK). The hybrid framework allows us to translate energy systems transformations into macro-financial outcomes at business cycle frequency. We find that rapid transitions induced by fast-growing carbon prices significantly impact unemployment, inflation, and income distribution. Stabilization policies reduce these economic fluctuations, though not completely so in Paris-compatible scenarios. Our paper emphasizes the need for coordinated climate and macroeconomic policy during decarbonization. Additionally, it showcases how model integration can lead to a better understanding of the economic implications of low-carbon futures.

As countries commit to decarbonization plans, questions around implementation and robust policy design grow in importance. The current consensus is that the world possesses the technology and economic capacity to switch to low-carbon options in many sectors¹. However, much less is understood about the macroeconomic and financial repercussions of climate neutrality goals at the shorter time-scales of interest to policymakers^{2,3}. This is a major shortcoming of existing model-based assessments, given the importance of macroeconomic conditions for the political and public support of climate policies⁴ and for effective policy design aimed at smoothing the transition and making it inclusive.

The major causes of this limited capacity are methodological and disciplinary boundaries. Model-based assessments of decarbonization policies—especially those performed at the community science level—have focused on technological and sectoral strategies as the main outcome variables. Models supporting these assessments, including detailed-process Integrated Assessment Models (IAMs)⁵, typically feature a stylized representation of economic and financial dynamics⁶. Though some have quantified the implications of decarbonization for dimensions such as competitiveness, trade, and sectoral employment, many scenarios only use

changes in real GDP, typically at very low temporal frequency, to capture transition costs. Short-run dynamics and impacts on unemployment, balance sheets and the financial system, or inflation are typically not represented. Indeed, none of these macro-financial dimensions is reported in the 1100 scenarios assessed in the Intergovernmental Panel on Climate Change's Sixth Assessment Report. Moreover, fiscal or monetary policy responses to macroeconomic impacts induced by climate policy are not typically considered in ex-ante policy assessment. At the same time, such information is highly sought after by finance ministries and international organizations (e.g., the Network for Greening the Financial System, NGFS), and transition scenarios and their implications are becoming increasingly relevant for private financial sector agents^{7,8}.

On the other side, different macroeconomic models have been extended to accommodate energy and climate dimensions, providing insights into the effects of monetary and fiscal policy for the low-carbon transition, and on the repercussions of moving away from fossil-fuel energy for the macroeconomy. These models include extensions of the dynamic stochastic general equilibrium framework [DSGE; e.g., refs. 9–12], post-Keynesian ecological macroeconomic models [e.g., refs. 13–16],

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macroeconomic agent-based models [MABM; e.g., refs. 17–21], non-linear behavioral macroeconomic frameworks [e.g.²²] as well as network models [e.g., refs. 23–25]. However, the majority of these approaches lack detailed transition dynamics, such as those depicted by process-based IAMs and included in IPCC mitigation pathways. Indeed, they typically feature only a “green” and a “brown” sector.

This gap presents an opportunity for fruitful cross-fertilization between modeling methodologies, providing diverse yet complementary views on decarbonization dynamics. In this paper, we provide—to the best of our knowledge—the first coupling of a macroeconomic agent-based model and a process-based IAM. The two models used for the coupling are the DSK model, i.e., the “Dystopian Schumpeter Meeting Keynes”, which belongs to the “Keynes + Schumpeter” family of MABMs [see refs. 26–28], and the process-based IAM WITCH, “World Induced Technical Change Hybrid” [see refs. 29–31].

Specifically, we establish a one-way link in which WITCH generates the carbon tax trajectories and transition pathways that are subsequently fed into DSK.

This soft link allows us to combine the strengths of both approaches. Macroeconomic agent-based models offer comprehensive frameworks that integrate both long-term and short-term economic dynamics^{32,33}, encompassing real-financial interactions³⁴ and balance sheet relationships among economic agents³⁵. In principle, they enable the assessment of transition and climate costs at business cycle frequency, while also capturing growth implications and financial risks³⁶. Additionally, they report on a richer set of micro and macro variables than many other macroeconomic models (e.g., DSGEs), including unemployment, inflation, and distributional variables. Complementarily, IAMs offer a fine-grained depiction of decarbonization pathways, including the transformation of the energy and other emitting sectors, their mitigation costs, the investment requirements and the energy mix of the economy accounting for all major energy technologies.

Our modeling approach is the first comparable alternative to NFGS-based scenarios³⁷, which currently form the basis of most climate risk macro-financial analyses relevant to policymakers^{38–40}. Our proposed methodology complements existing NGFS approaches by introducing (i) full open access to data and code, (ii) disequilibrium dynamic adjustments, and (iii) energy-finance integration. These enhancements offer highly relevant policy analyses to a wide range of policymakers, such as ministries of finance, central bankers, and financial regulators.

Expanding on established research, our contribution builds upon the solid foundation of soft-coupled models developed in the mitigation literature, where they have been employed to investigate R&D investment strategies for decarbonization⁴¹, climate-induced financial instability^{42,43}, macroeconomic effects of climate shocks⁴⁴, housing renovation decisions⁴⁵, and provide stronger microfoundations to otherwise standard Computable General Equilibrium (CGE) models⁴⁶. Focusing on transition risks, refs. 47, 48 feed NGFS scenarios defined as carbon price and productivity shocks into a multi-country New Keynesian macro model (NiGEM), which is then linked to sectoral and financial models to perform stress tests. Closer to our approach is the contribution of ref. 49, who feed NGFS scenarios into a macroeconomic ABM calibrated for the Italian economy and endowed with a relatively simple energy sector. By comparison to the existing literature, our IAM-MABM approach offers several advantages by (i) incorporating disequilibrium adjustments, which highlight a greater need for stabilization policies and enhanced policy coordination; (ii) enabling the analysis of transition scenarios across more dimensions than those covered by NGFS; (iii) capturing energy sector imbalances more effectively, such as asset stranding due to over-capacity; (iv) providing a comprehensive understanding of energy sector disruptions within a fully-fledged macroeconomic framework.

We use the WITCH model to generate detailed transition pathways. This process-based integrated assessment model combines an inter-temporal Ramsey-type growth framework with a bottom-up representation of the energy sector. The model divides the world into 17 global regions, each playing a non-cooperative game to maximize welfare in response to climate policies. A key decision in this process is how to allocate R&D investments, which can be directed toward improving energy efficiency or developing carbon-free technologies.

The transition pathways produced by WITCH are then aggregated at the global level and fed into the DSK agent-based model, which depicts a single, aggregated economy representing the whole world. The DSK model depicts out-of-equilibrium economic dynamics, capturing both short-run fluctuations and long-run growth^{17, 50–52}. It includes seven types of agents interacting across five markets (see Fig. 1). Key variables from the WITCH-generated transition scenarios serve as inputs for the DSK model (see Fig. 1), allowing for an assessment of the macroeconomic implications of these transition pathways. We should point out that this soft-coupling approach necessarily treats some inputs as exogenous relative to the DSK—most notably policy variables. We return to this point in the “Results” and

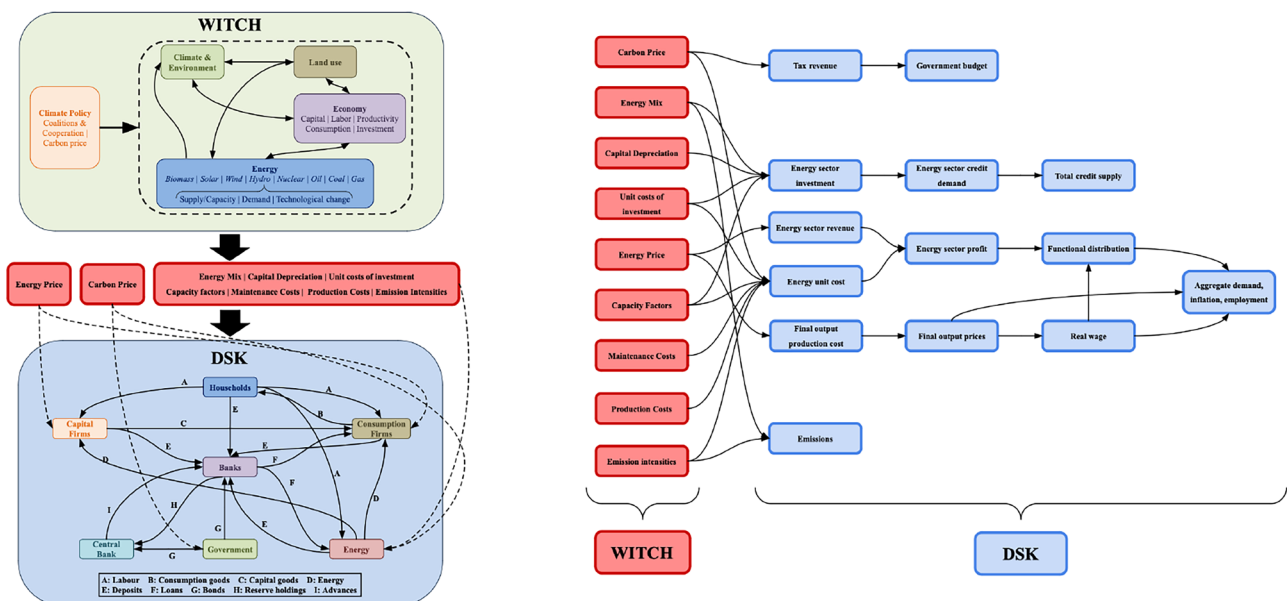


Fig. 1 | Coupling overview. Overview of the sectoral structure and inter-sectoral interactions depicted by DSK, the structure of the WITCH model, the list of variables from WITCH scenarios used as exogenous inputs, and their main transmission channels to DSK outputs.

“Discussion” sections, where we explain how our design mitigates this limitation and allows for a quasi-endogenous treatment of the carbon tax.

In this paper, we show that an *orderly*, i.e., low unemployment, and *just*, i.e., distributionally balanced, transition are mutually dependent, as the unemployment resulting from aggressive carbon pricing is influenced by how the tax burden is distributed between profit and wage incomes [see refs. 53, 54, for additional discussion.].

Furthermore, the unequal impact of the carbon tax on the energy sector presents a serious source of instability. While the carbon tax promotes profitability in renewable energy sectors, offering financial support for the transition, it simultaneously undermines profitability in fossil fuel-based sectors, rendering them more susceptible to bankruptcy. The government can mitigate these dynamics by using carbon tax revenues to manage aggregate demand. Redistributing revenues to wage earners can address distributional effects and limit negative macroeconomic impacts, compensating for wage losses and sustaining aggregate demand. We also find that the energy transition will require substantial credit provision for the build-up of renewable energy capacity and that fossil-intensive energy sectors will experience reduced profitability due to carbon pricing and the maintenance of costly stranded assets.

Our results contribute to the literature assessing the macroeconomic impacts of climate policies, regarding regressive effects of carbon pricing^{55–59} and the emergence of stranded assets^{3,16,25,60}. Empirical evidence regarding the macroeconomic effects of carbon pricing is somewhat mixed, with some studies finding no or even small positive effects on GDP^{61,62} and others predicting negative impacts in the short run⁵⁹. Model-based analyses often predict that aggressive carbon pricing may reduce GDP and employment, but highlight that appropriate revenue recycling can mitigate these outcomes^{18,47,48,63–68}. Further, they suggest that coordinating climate, monetary and prudential policy can help smooth transition risks, though the desirable mix of such instruments strongly depends on how emission-intensive sectors transform^{10,50,51,69}. This calls for a more fine-grained modeling of the energy sector, at the very least. Since the carbon price trajectories we examine manifest in relatively sudden increases in the price of energy, our work also contributes to the macroeconomic literature on energy price shocks^{19,70–73}. Finally, we contribute to the literature on MABMs^{32,33} and, in particular, to two sub-strands. The first regards the analysis of issues related to the green transition [e.g.^{74–77}] and energy price shocks^{19,78,79}. The second sub-strand regards the assessment of the macroeconomic consequences of changes in the distribution of income [e.g., refs. 80–83].

Results

Macro-financial impacts of the transition

We analyze three climate transition scenarios. The “Current Policy” (CP) scenario incorporates policies implemented by 2020 and serves as a baseline. The other two scenarios are designed to limit temperature increases to specific values by imposing carbon budgets from 2020 onward. One features a carbon budget of 1000 GtCO₂, leading to a 2 °C temperature increase (2 °C), and the other a carbon budget of 500 GtCO₂, leading to a 1.5 °C temperature increase (1.5 °C). In both cases, carbon budgets are met by imposing a global carbon tax, which we assume countries fully comply with for simplicity, while acknowledging that, in reality, political deviations from global climate agreements may occur.

The carbon tax is introduced gradually in a standard Hotelling fashion within the WITCH intertemporal optimization framework: the tax is introduced in 2025 and grows at the Ramsey growth rate (around 3–4 percent and declining over time) until globally, net-zero emissions are reached, after which it stays at the level required to keep global emissions at net-zero. Its initial value is chosen to meet the carbon budgets set. The initial hike in energy prices is therefore needed to induce a strong shift in the energy system to achieve the carbon budget, and the reduction over time is due to technical progress, notably in renewables, making it cheaper in the long run due to lower installation costs.

Another simplifying assumption is that we do not include climate-economy feedback in the form of climate-related shocks. This choice allows us to clearly isolate the effects of the carbon tax on the economy, which is the primary mechanism of interest in our analysis. Regarding the DSK policy setting, we initially assume that carbon tax revenues are entirely retained by the government and that the central bank adopts a single-mandate Taylor rule, i.e., it adjusts the interest rate to stabilize inflation (section 1.1.6 in SI); these assumptions will be relaxed in the policy experiments.

For the sake of clarity, let us stress that the carbon tax designed within WITCH is endogenous to the decarbonization pathway undertaken by the energy sector. By feeding key energy variables—such as emission intensities and the energy mix—into the ABM, we ensure that the energy sector dynamics in DSK remain consistent with the carbon tax at every point in time. Moreover, our fiscal and monetary policy experiments reinforce this consistency by making the broader policy mix explicitly endogenous to the macroeconomic dynamics unfolding in DSK during the transition.

Figure 2 shows the energy mix and price dynamics for each transition scenario. Keeping temperature in line with the goals of the Paris Agreement purely through a carbon price leads to a temporary but sharp increase in energy prices. This is especially the case for the most stringent climate target of 1.5 °C where fossil fuels are phased out rapidly during this decade (Fig. 2, panel e). In WITCH, the energy system can include the carbon capture and storage associated with oil, gas, and biomass technologies. As targets become more stringent, carbon capture and storage is introduced to reduce unabated emissions and to balance residual emissions.

The energy price shock induced by climate policy leads to a series of macroeconomic adjustments and fluctuations that emerge from the DSK properties. Figure 3 illustrates these adjustments by comparing scenarios. The main macroeconomic outcome is that of temporary stagflation (Fig. 3a–c) and low wage shares (Fig. 3d). Unemployment and low economic growth emerge during this decade in the Paris-compliant scenarios; the negative impacts on the real economy are accompanied by periods of high inflation. We should also highlight that before 2020 in both the 1.5 °C and 2 °C scenarios we observe a period of economic boom characterized by falling unemployment and high GDP. This occurs because, in WITCH, economic agents anticipate the future introduction of the carbon tax and begin investing in green energy technology. This investment stimulates economic activity before the carbon tax is implemented, resulting in a brief positive economic cycle.

Figure 4 delves into the mechanisms underlying the dynamics depicted in Fig. 3. We find that a key role is played by the wage share, which significantly declines during the early phase of the transition when energy prices are high. Moreover, its dynamics closely mirror the unemployment rate (Fig. 4a). By pooling all simulations across the three scenarios and calculating the quasi-elasticities of unemployment and the wage share with respect to the energy price, we find that high energy prices are associated with high unemployment and a low wage share (Fig. 4c, d).

Largely unchanged aggregate markups (assumed in the DSK model) imply that carbon pricing and energy price shocks shift aggregate income from labor to the government (via carbon tax revenue) and the “green” energy sectors, while firms’ income share remains unchanged. This also triggers a shift from labor income to dividend income, which is disproportionately saved rather than spent^{84–87}. The final effect is a lack of aggregate demand, leading to low employment and output.

As a result of perfect cost pass-through, an energy price surge induced by a rise in carbon prices is always inflationary on impact. The perfect cost pass-through assumption is motivated by the recent energy crisis due to the Russian invasion of Ukraine, where firms have generally been able to fully pass energy price shocks⁸⁸ on to final output prices and possibly even increase their mark-ups in the process, giving rise to so-called *sellers’ inflation* [e.g., refs. 89, 90]. Our assumption of full pass-through with largely constant markups can therefore be seen as qualitatively in line with available empirical observations and possibly even somewhat conservative.

In addition, nominal wage growth is pegged to the inflation rate (Equation 2 in SI). Higher inflation increases unit labor cost, which in turn

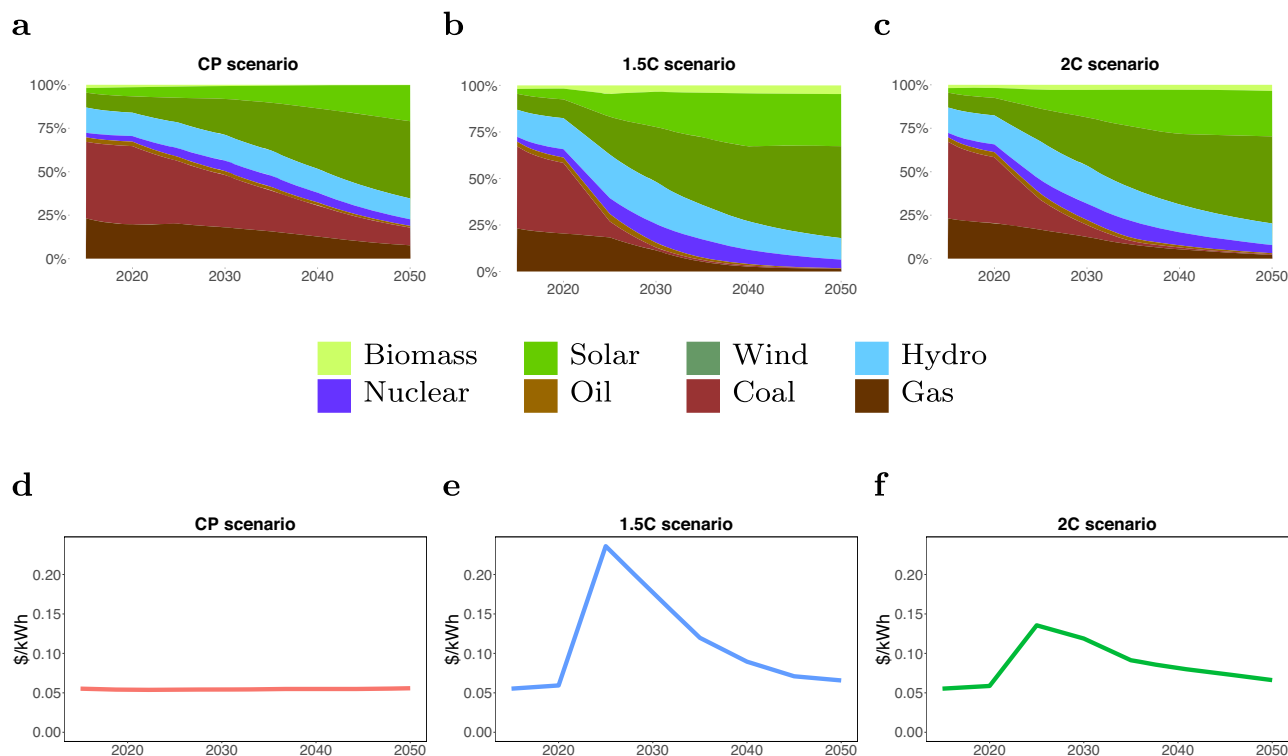


Fig. 2 | Energy price and transition dynamics. a–c energy mix, defined as the share of total energy produced by each technology, for the three WITCH scenarios. d–f energy price in (2005) dollars per kilowatt-hour in the three WITCH scenarios. x-axes always refer to years.

feeds back into the general price level. However, wages also respond to labor market conditions, growing more slowly (faster) when unemployment is high (low). During a stagflationary period, inflation dynamics are hence dampened by weak labor market outcomes. Figure 4b shows that inflation increases together with the energy price at first, but peaks while the latter is still growing and subsequently decreases before the energy price begins its downward trajectory driven by a rapidly growing share of renewables.

Figure 5 shows the adjustments in the energy sector, which exhibits a strong increase in credit demand (Fig. 5a). This is driven by the green sectors undertaking large investments (Fig. 5b, c) and by the fossil fuel sectors having to pay the carbon tax and sustain costly spare capacity (Fig. 5d, e). The consequent erosion of profitability affects financial stability, leading to an increase in defaults. Coal is especially affected, with default rates in this sector rising to 10–20% for 2 °C and 1.5 °C targets respectively (Fig. 5f). Differently, oil and gas are only marginally impacted. This result confirms that rapid mitigation may generate imbalances harming the financial stability of high-emitting sectors [e.g., ref. 15], but these risks appear to be concentrated in specific areas (i.e., coal).

The role of monetary and fiscal policies

The simulations shown above point to disruptive business cycle fluctuations arising from the carbon pricing needed to stabilize global warming. So far, however, we have not considered potential monetary and fiscal policy responses. The central bank (CB hereafter) follows a single-mandate Taylor rule aimed purely at inflation stabilization (section 1.1.6 in SI), and the government retains the entire carbon tax revenue.

To conduct a range of monetary and fiscal policy experiments, we relax these assumptions, allowing the CB to respond to unemployment and the government to redistribute carbon tax revenues. As was shown above, the dynamics generated by DSK in the 1.5 °C and 2 °C scenarios are qualitatively similar. We therefore conducted our policy analysis for the most stringent climate scenario (1.5 °C).

The alternative monetary policy rule modifies the single-mandate Taylor rule by adding an employment stabilization component that is

activated when the unemployment rate exceeds a threshold, leading the central bank to lower its interest rate. The central bank’s reaction to unemployment is governed by an exogenous parameter, measuring the strength of the central bank’s reactivity to high unemployment: the larger the CB’s reactivity to unemployment, the lower the interest rate in case of high unemployment. Effectively, we assume a *recession avoidance preference* for the CB [cf.⁹¹] with some degree of “recession tolerance”, i.e., the policy rate response to unemployment is not asymmetrical around zero, but instead around a positive threshold level [cf.⁹²]. We set the threshold level at 10%, as this high unemployment rate can be considered an alarming indicator of a severe recession in most countries.

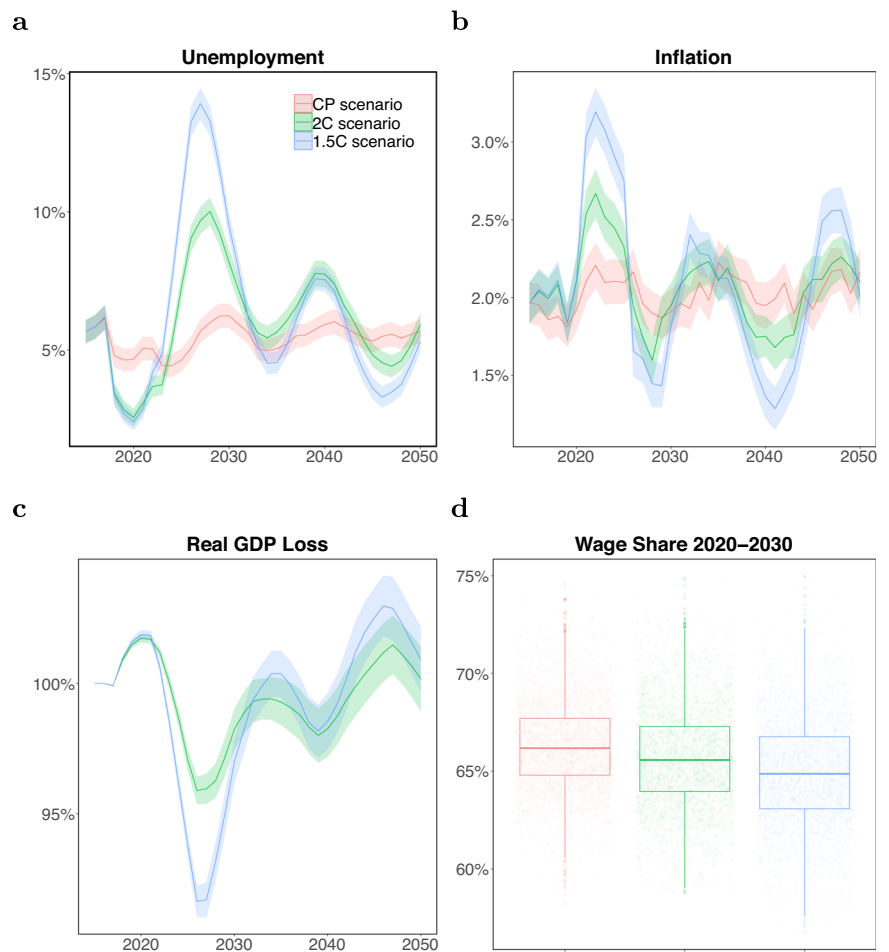
The fiscal policy experiment involves the redistribution of the carbon tax revenue to households. We assume that a share of current carbon tax revenue is distributed to households as a lump sum transfer. Moreover, we assume that this transfer is treated as being equivalent to labor income, and hence that the same propensity to consume applies to it.

Results from our policy experiments are summarized in Fig. 6. First of all, they suggest an important role for monetary-fiscal policy coordination to moderate the effects of the carbon tax. We focus on the most critical period, i.e., 2020–2040, which we split into two decades, and focus on unemployment and public debt-to-GDP ratios.

In the first sub-period, fiscal policy is highly effective in reducing unemployment (Fig. 6a). This is because, during this period, the carbon tax is high, resulting in large revenues to be redistributed. Monetary policy effects are instead negligible (Fig. S6 in SI). This is because, in 2020–2030, the policy rate does not change much across different CB reactivity levels to unemployment (Fig. S5 in SI). At the beginning of the transition phase, inflation rises faster than unemployment and hence dominates the Taylor rule. In 2030–2040, carbon tax revenues decline as emissions plummet, meaning that fiscal policy becomes less effective (Fig. S7 in SI). However, we observe a stronger role for monetary policy during this period (Fig. 6b).

In 2030–2040, inflation recedes, and so the employment stabilization effect dominates the Taylor rule, resulting in decreasing interest rates. However, we must account for the fact that central banks typically avoid

Fig. 3 | Macroeconomic impacts. Macroeconomic dynamics induced by different mitigation pathways. **a–c** each line represents averages across 300 simulations, shaded areas are 95% confidence intervals, each color is associated with a scenario; **c** GDP loss relative to the CP scenario obtained using the ratio between real GDP in the 2 °C and 1.5 °C scenarios relative to real GDP in the CP scenario; **d** box-plot showing the distributions of wage shares in 300 simulations for of each scenario, period 2020–2030.



abrupt changes in the policy rate; instead, they gradually adjust the policy rate towards a specific target. This behavior is captured by the implemented Taylor rule (Equations 57 and 76 in SI). As a result, the policy rate responds with a certain lag after unemployment reaches its safeguard level and remains relatively low even after unemployment drops below this level (Fig. S6 in SI). These two effects together determine the efficacy of monetary policy in the second phase of the transition.

We also find that inflation is not responsive to monetary policy during the transition, meaning that lowering the policy rate to fight unemployment does not produce additional inflationary pressure (Fig. S6 in SI). This is because inflation during the transition is driven by the energy price, which is exogenous to the policy rate. In the case of cost-push shocks, the main channel through which monetary policy could stabilize inflation is through expectation anchoring. However strong such a channel might be in the real world, it is absent from our model, meaning that we may underestimate the inflationary costs of an expansionary monetary policy along the transition.

The complementarity between fiscal and monetary policy, hence, stems from the fact that they are effective at limiting unemployment during different phases of the transition. Figure 6c illustrates their complementarity by pooling simulation data across phases. It shows that the average unemployment rate for the full 2020–2040 period is lowest when fiscal policy redistributes a high share of carbon tax revenue and monetary policy is expansionary. In addition, monetary-fiscal policy coordination also has relevant effects on the public budget (Fig. 6d, e, f). In particular, a lower policy rate will tend to lower the cost of servicing public debt in the latter phase of the simulation, hence creating fiscal space. Additionally, we observe that carbon tax revenue redistribution has a largely neutral effect on public debt. When carbon revenue is not redistributed, this represents an additional source of general revenue for the government. At the same time, however, declines in GDP and

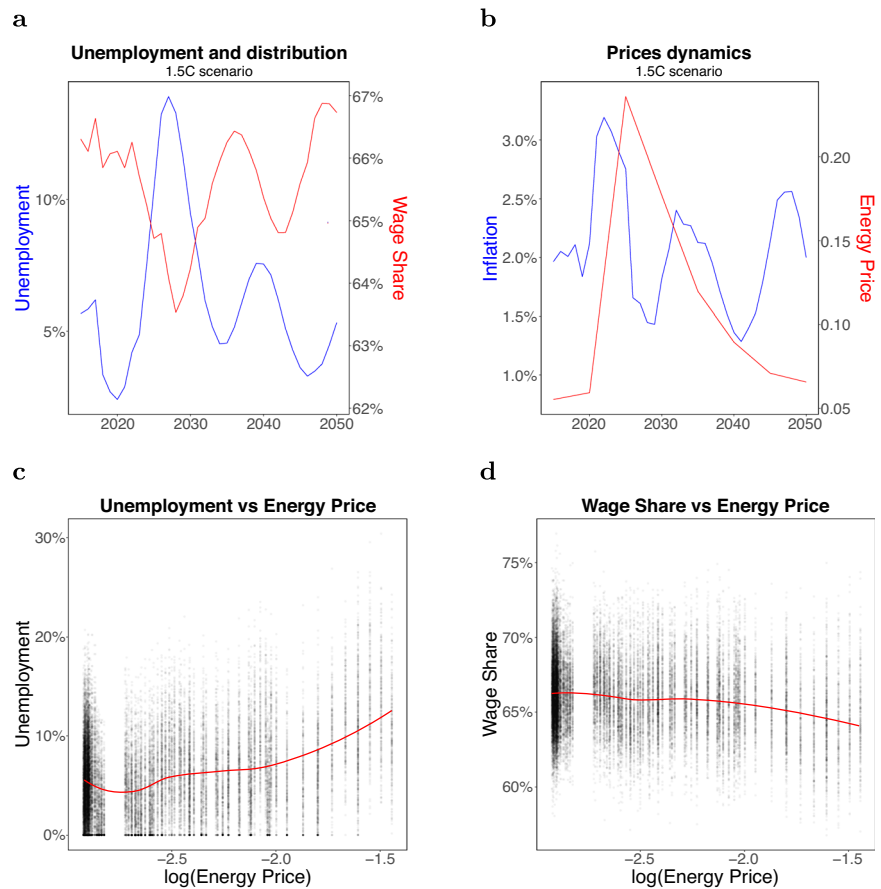
employment imply that other tax revenues will tend to decline, while outlays for unemployment benefits increase.

Discussion

Mitigation pathways, such as those reviewed in IPCC reports¹, offer a detailed assessment of decarbonization dynamics that all key sectors should undergo to meet certain climate targets. However, in their current status, they fail to provide an informative picture of the imbalances that such a process can create at the macro-financial level. Further, they are silent on the behavior of macroeconomic aggregates at the time scale (e.g., quarterly or annual frequency) that is relevant for designing stabilization policies accompanying climate ones. This study combined the strengths of two complementary modeling approaches, IAM and MABM, to shed light on the macroeconomic and financial implications of mitigation scenarios. Process-based IAMs generate transition pathways with great technological detail, while the strength of MABMs lies in the joint depiction of short and long-run out-of-equilibrium economic dynamics, distributional feedback effects, and real-financial interactions. This, combined with MABMs' capacity to handle a wide range of relevant economic variables, renders the IAM-MABM link a valuable instrument for refining the estimation of transition costs across various dimensions and transmission channels.

By simulating detailed transition scenarios generated by the WITCH IAM in the DSK MABM, we showed that ambitious mitigation trajectories guided by carbon pricing—as the vast majority of pathways in the literature—induce perils to macro-financial stability. Indeed, we showed that scenarios compatible with 2 ° and 1.5 °C tend to generate high unemployment and high inflation, resembling dynamics typical of so-called “stag-flationary” episodes. The source of the instability lies in the rapid transformation of the energy sector and its connection to the financial system. Our results point to the emergence of costly physical stranded assets in the fossil

Fig. 4 | Distributional impacts. Macroeconomic and distributional effects along 1.5 °C pathways. **a** blue and red lines represent averages across 300 simulations of the 1.5 °C scenario, the red line is the wage share (right), blue line is the unemployment rate (left); **b** blue and red lines represent averages across 300 simulations of the 1.5 °C scenario, red line is the energy price (right), blue line is the inflation rate (left); **c** scatterplot of unemployment and logarithm of the energy price, results pooled across 300 simulations of each scenario, period from 2015 to 2050, red line is a non-linear interpolation; **d** scatterplot of wage share and logarithm of the energy price, results pooled across 300 simulations of each scenario, period from 2015 to 2050, red line is a non-linear interpolation.



fuel-intensive sectors [see also refs. 15, 16], which contribute to an erosion of profitability of these sub-sectors during the transition. These decreases in profitability, in turn, result in an increased need for external finance as well as a higher rate of defaults. However, such risks concentrate in the coal sector, while gas and oil face much lower exposure.

Further, we showed that an orderly (low unemployment) and just (low labor share losses) are not independent: they need to align. Indeed, the price of energy can be viewed as a distributional variable, and shifts in functional income distribution resulting from climate policy can have undesired macroeconomic consequences. In particular, our results suggest that unless corrective policy action is taken, transition pathways guided by carbon prices are associated with temporary periods of high inflation and high unemployment. This volatility has detrimental consequences for the feasibility of decarbonization. These results point to the need (i) to account for ampler policy packages within mitigation pathways [e.g., ref. 18], (ii) to report climate policy strength beyond carbon pricing.

Conducting a battery of fiscal and monetary policy experiments, we showed that redistribution of carbon tax revenue can play an important role in limiting the negative macroeconomic effects of carbon pricing during the early phase of the transition. Expansionary monetary policy, on the other hand, was found to be more effective during the later stages of the transition, suggesting a positive role for monetary-fiscal policy coordination.

Overall, our study emphasizes the importance of incorporating a macro-financial dimension into the analysis of mitigation pathways. This addition is essential for a more comprehensive assessment of the viability of decarbonization trajectories and the effectiveness of underlying climate policies. We demonstrate that integrating macroeconomic models with integrated assessment models is a promising approach, although several limitations must be addressed in future research. Specifically, adopting a more disaggregated perspective at the country or macro-regional level is essential to offer clearer insights into practical policymaking. Our soft-link

approach also entails limitations for certain avenues of analysis, notably the design of the carbon tax. While our main exercise is intended to assess the macroeconomic consequences of carbon tax trajectories generated by an IAM once implemented in a full-fledged macroeconomic ABM, a natural extension would be to explore a hard coupling of the two models. This would allow the carbon tax to become endogenous to the economic dynamics generated by the ABM itself. We view our contribution as a necessary foundation for this line of research, paving the way towards full IAM-ABM integration.

Online methods

This study integrates an agent-based macroeconomic model and a process-based integrated assessment model to assess the materiality of transition risks along ambitious (deep) mitigation pathways. Detailed descriptions of the two models can be found in ref. 52 (DSK) and ref. 30 (WITCH). Additionally, a thorough discussion of key model features, including necessary extensions to the DSK framework for coupling with WITCH, is provided in Section 1 of the SI. In this section, we outline the main model features relevant to our analysis.

The economic core of the DSK model is formed by two vertically integrated agent-based firm sectors, namely consumption good firms and capital good firms (C-Firms and K-Firms hereafter). K-Firms produce machines characterized by heterogeneous labor productivities, energy efficiencies and emission intensities. To produce them, K-Firms use production techniques which are also heterogeneous in terms of labor productivity, energy efficiency and emission intensity. New capital goods and production techniques are the product of K-Firms' R&D, which determines long-term growth.

C-Firms use machines, labor, and energy to produce a homogeneous consumption good. C-Firms buy machines to match expected demand. Firms' activities are financed through retained earnings and, in the case of C-

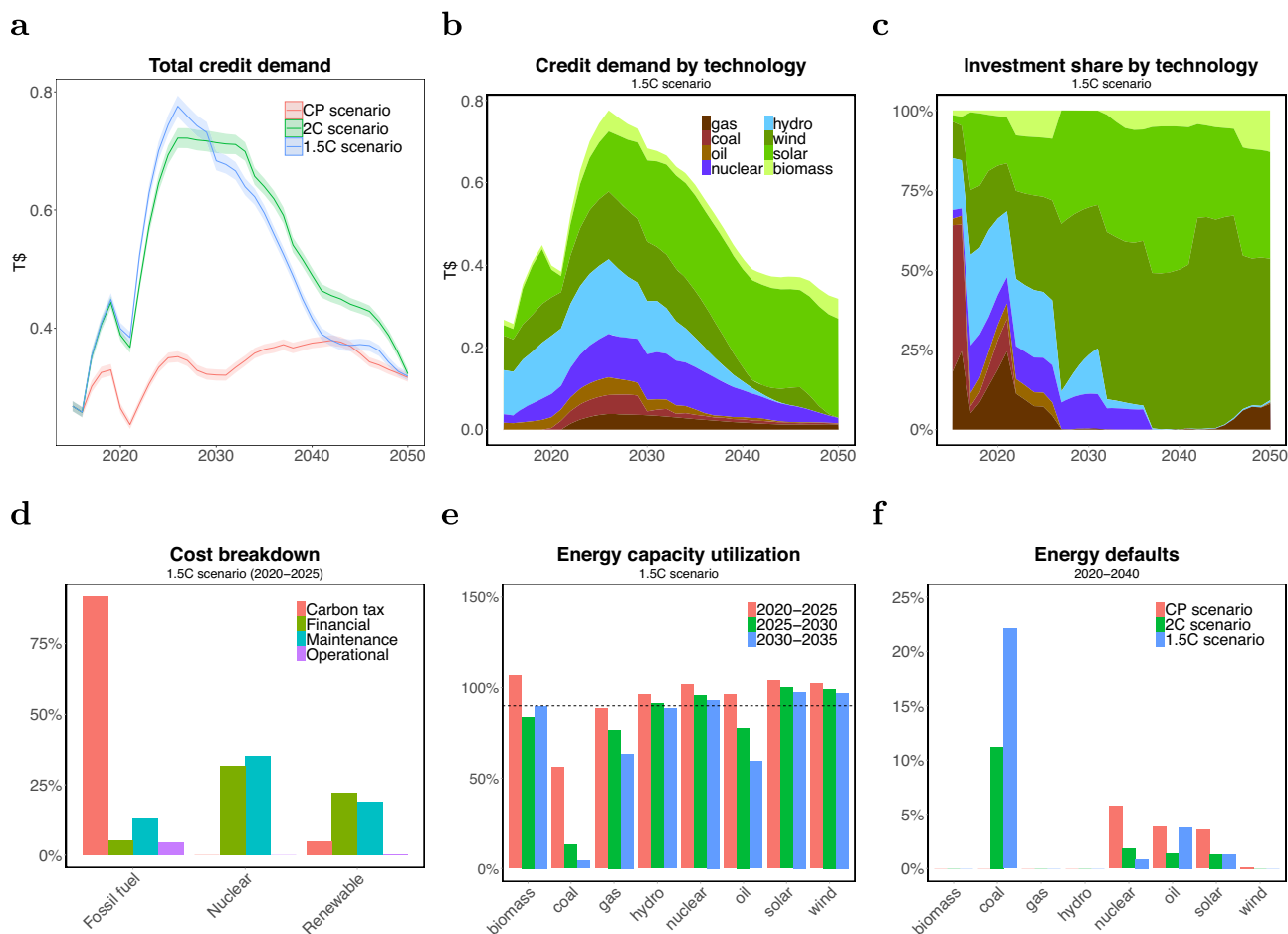


Fig. 5 | Energy sector adjustment. Energy sector-finance link, asset stranding and energy sector imbalances in 1.5 °C pathways. **a–f** averages across 300 simulations; **a** total credit demand of the energy sector across scenarios, expressed in 2022 US T\$. Shaded areas represent 95% confidence intervals; **b** energy sector credit demand disaggregated by sub-sectors, 1.5 °C scenario, expressed in 2022 US T\$; **c** investment disaggregated by energy sub-sector, 1.5 °C scenario, expressed as a share of total investment in the energy sector; **d** energy sector costs broken down by cost type and

disaggregated by technology-groups. Costs are expressed in proportion to revenues and refer to the 1.5 °C scenario for the time window 2020–2025; **e** capacity utilization and the maximum potential production, the horizontal dotted line marks target capacity utilization, which is set to 90%; **f** defaults disaggregated by energy sub-sector expressed as the average ratio of defaulted debt to total debt across simulations, grouped by scenarios, period 2020–2040.

Firms, loans from the banking sector. Households consume and receive income in the form of wages for supplied labor, interest on deposits, dividends from firms, banks and the energy sector, as well as unemployment benefits and occasional government transfers (like redistributed carbon tax revenues). The government collects taxes and spends on unemployment benefits, transfers, and the bailout of failing banks, while the central bank sets the policy rate. The DSK model also includes an energy sector, which supplies the firm sector with the energy needed for production, invests in physical capital and finances its activities using internal funds and bank credit.

The consumption and capital goods sectors, as well as the banking sector, consist of multiple and heterogeneous agents. We leverage the MABM framework to agentify the WITCH energy sector into eight macro-agents, each representing a distinct energy technology. Households are modeled as an aggregate entity. Table S2 in SI shows the transaction flow matrix of the model, summarizing the transactions between sectors and how these are financed.

The balance sheet and transaction flow matrices (section 1, Tables S1 and S2 in SI) can be used to derive the accounting identities that must be satisfied for the model to be formally stock-flow consistent. To ensure stock-flow consistency during simulations of the model, all transaction flows and balance sheet items are explicitly tracked. At the end of each simulation period, the model performs a series of checks at the agent,

sectoral and aggregate levels to ensure that no accounting identities have been violated during the period.

The WITCH model is an integrated modeling framework that captures the interactions among climate change, energy systems, and economic growth. It combines a macroeconomic model with a detailed energy system. The macroeconomic (top-down) aspect uses an intertemporal optimization strategy that incorporates macroeconomic relationships and dynamics over time. Simultaneously, the energy system (bottom-up) component details the technology options available in the energy sector. This dual approach facilitates the cost-effective optimization of strategies to minimize global costs associated with achieving specific climate and energy targets, taking into account investment, operational costs, the repercussions of climate change, and policy instruments such as carbon pricing.

The model divides the world into distinct global regions and generates optimal mitigation pathways up to 2100. These pathways are obtained through a welfare maximization process that accounts for regional interactions and the strategic dynamics spawned by global externalities, employing an iterative method to achieve a non-cooperative Nash equilibrium.

WITCH is distinguished by its dynamic representation of R&D diffusion and innovation in energy efficiency and low-carbon technologies. It encapsulates the broad spectrum of externalities in climate and innovation policy, including the global sharing of knowledge and technology spillovers,

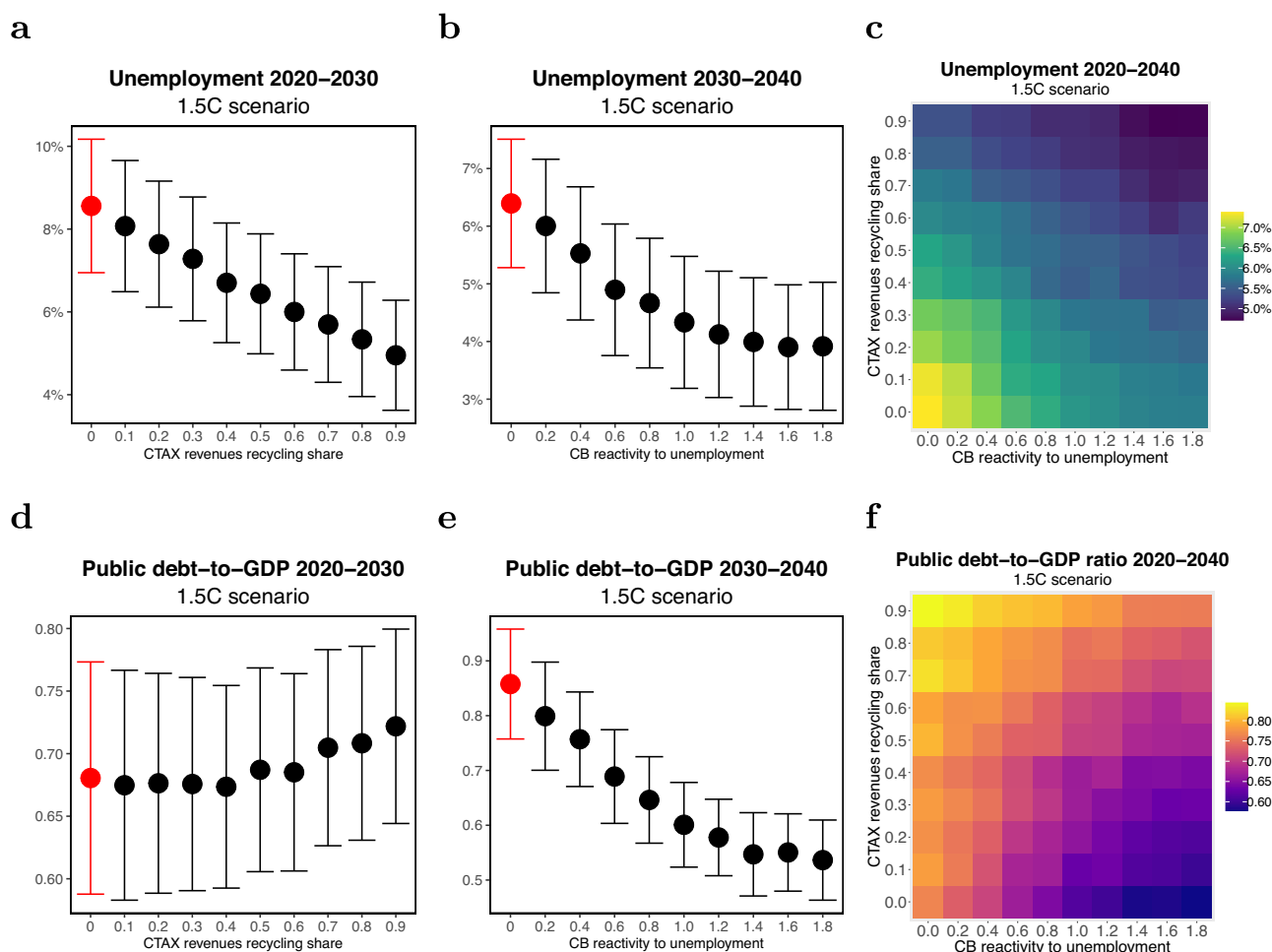


Fig. 6 | Fiscal-monetary policy coordination. Fiscal and monetary policy to stabilize the transition in 1.5 °C pathways. **a, b** and **d, e** dots refer to averages across 50 simulations, with each dot representing a policy experiment, red dots refer to the baseline configuration, bars are 95% confidence intervals; **a** average unemployment rate, 2020–2030, 1.5 °C scenario, across fiscal policy experiments, i.e., different shares of redistributed carbon tax revenues; **b** average unemployment rate, 2030–2040, 1.5 °C scenario, across monetary policy experiments, i.e., different

degrees of CB reactivity to unemployment; **c** average unemployment rate, 2020–2040, 1.5 °C scenario, across monetary and fiscal policy experiments; **d** average public debt-to-GDP ratio, 2020–2030, 1.5 °C scenario, across fiscal policy experiments, normalized at 2015 value; **e** average public debt-to-GDP ratio, 2030–2040, 1.5 °C scenario, across monetary policy experiments, normalized at 2015 value; **f** average public debt-to-GDP ratio, 2020–2040, 1.5 °C scenario, across monetary and fiscal policy experiments, normalized at 2015 value.

which influence each country’s adoption of low-carbon technologies and energy productivity. This is based on regional energy research and development, capital stocks, and the global cumulative installed technology capacity.

From an economic point of view, the model simulates a single-sector economy, where output may be influenced by climate impacts (climate change impacts are not activated in this study), and costs related to fossil fuel use and greenhouse gas mitigation are accounted for. It employs a social planner perspective to optimize regional utility, including risk aversion to future consumption levels. A CES function represents the production of goods using capital, labor, and energy services.

The energy sector within the WITCH model covers a broad spectrum of primary energy sources, conversion technologies, and consumption sectors. It includes diverse energy carriers, from fossil fuels to renewables, and technologies, from power generation to transportation, representing technological advancements and energy efficiency gains over time.

The scenarios generated for this study follow standard policy designs. The Current Policy scenario implements current national climate policies and extrapolates the same effort level across the century using regional carbon prices. Regulations and emission constraints are maintained throughout the century. The climate policies “2 °C” and “1.5 °C” aim for global net-zero emissions, following the design presented in ref. 93. Starting

from 2020, a global carbon tax is implemented to reduce CO₂ emissions. Once CO₂ emissions reach net zero, global emissions are maintained at this level until the end of the time horizon. Until the net-zero year, the carbon price is set to limit cumulative emissions to 1000 GtCO₂ for the “2 °C” scenario and 500 GtCO₂ for the “1.5 °C” scenario. Thereafter, the carbon price is adjusted to equal the emission market price to stabilize emissions at zero globally. More details about these two scenarios can be found in ref. 31 and ref. 94.

To couple the two models, we establish a one-way link from WITCH to DSK. Specifically, technology and cost-related variables for the energy sector, along with energy and carbon prices from transition scenarios generated by WITCH, are fed into DSK (see Fig. 1). We chose these variables to partially replace the DSK energy sector with that of WITCH. The resulting energy-level variables — such as production, investment, and credit demand—emerge from the interaction between the two models. This interaction combines the microeconomic variables from WITCH (e.g., operation and maintenance costs, energy mix) with the macroeconomic variables from DSK (e.g., aggregated energy demand, financial conditions). Table 1 illustrates how the variables from WITCH and DSK are combined, along with the resulting outputs. For more detailed information, please refer to the SI.

Table 1 | WITCH-DSK coupling

Coupling output	WITCH	DSK	Coupling output
Coupled energy price	Energy price	Inflation	
Energy production	Energy mix	Aggregate energy demand	
Energy expenditures		Aggregate energy demand	Coupled energy price
Coupled carbon tax	Carbon tax	Inflation	
Capacity expansion		Target capacity utilization	Energy production
Capacity	Capital depreciation		Capacity expansion
Nominal investment	Unit costs of investment		Capacity expansion
	Capacity factor		
Fixed costs	Maintenance costs		Capacity
Operating costs	Production costs		Energy production
Emissions	Emission intensities		Energy production
Carbon tax payments			Emissions Coupled carbon tax
Credit demand		Loan refinancing	Operating costs
		Deposits	Fixed costs Nominal investment Carbon tax payments

The first column lists the variables that result from combining WITCH inputs with endogenously produced variables from DSK. The second and third columns indicate which variables from WITCH and DSK are used to produce a particular coupling output variable. The last column indicates that some coupling outputs are recombined with WITCH and/or DSK variables to produce additional coupling outputs.

The coupling required several harmonizations concerning variables and units of account. For example, the DSK output is rescaled in order to obtain the credit demand figure in Trillion 2022 US\$. We calculate the energy sector-wide nominal credit-investment ratio produced by the model for 2022 in the CP scenario. We then multiply that ratio by the empirically observed nominal “power sector investment”, as reported by the IEA *World Energy Investment 2023*⁹⁵, to infer the equivalent nominal credit demand expressed in Trillion 2022 US\$. Finally, we use this empirically inferred nominal credit demand for 2022 and its counterpart from the model to calculate a rescaling factor, which is applied to the simulated time series across all scenarios.

Other adjustments required by the coupling resulted in the capacity utilization occasionally and slightly exceeding 1. This is because the energy mix is an input taken from WITCH scenarios and, during the transition, some energy sub-sectors in DSK may not yet have obtained the entire capacity needed to satisfy the demand implied by the exogenous energy mix. Since such inconsistencies are small, we allow the respective sectors to exceed full capacity utilization and accommodate the demand implied by the energy mix taken from WITCH.

WITCH produces scenarios up to 2100. For the current exercise, we only examine their effect on DSK dynamics up to 2050, which is the phase during which the transition takes place in decarbonization scenarios. Since DSK is a single-region model, global-level variables from WITCH are used as inputs. Section 1.4 in the SI discusses the calibration and the empirical validation of the modeling framework used in this work.

Macroeconomic policies and climate policies run together in the coupled model. Climate policy is implemented in WITCH, while fiscal and monetary policies are set in DSK. Section 1 of the SI provides additional insights into the policy rules adopted. Section 2 in the SI discusses the transmission of the climate policy shocks at the macroeconomic level (see section 2.1) and provides additional results on the stabilizing effects of monetary and fiscal interventions (see sections 2.2 and 2.3, respectively).

Data availability

This study is based on numerical simulations using a soft-linked modeling framework that combines the DSK agent-based macroeconomic model with scenario inputs from the WITCH integrated assessment model. No new empirical datasets were collected or generated. All data underlying the figures and results are model-generated outputs produced from the

simulations described in the paper. To ensure transparency and reproducibility, the full model code, configuration files, scenario inputs, and scripts required to reproduce the results are provided in a dedicated replication package. This package includes the DSK-WITCH soft-link code, the JSON input files defining the policy scenarios, and instructions for compiling and running the model across scenarios. The replication package is currently stored in a publicly accessible repository (<https://doi.org/10.5281/zenodo.19182237>). Luca E. Fierro (fierro@iiasa.ac.at) and Francesco Lamperti (flamperti@santannapisa.it) are responsible for maintaining the replication materials.

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Competing interests

The authors declare no competing interests.

Additional information

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