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Beyond climate economics orthodoxy: impacts and policies in the agent-based integrated-assessment DSK model*

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Though climate physical and transition risks will likely affect socio-economic dynamics along any transition pathway, their unfolding is still poorly understood. This also affects the development of climate-change policies to achieve sustainable growth. In this paper, the authors discuss a series of results, assessing the materiality of climate risks for economic and financial stability and alternative policy pathways by means of the Dystopian Schumpeter meeting Keynes (DSK) agent-based integrated-assessment model. Their results suggest that the emergence of tipping points due to unmitigated physical risks will reduce long-run growth and spur financial and economic instability. Moreover, diverse types of climate shocks have a different impact on economic dynamics and on the chances of observing a transition to carbonless growth. While these results call for immediate and ambitious interventions, appropriate mitigation policies need to be designed. The authors' results show that carbon taxation is not the most suitable tool to achieve zero-emission growth, given its serious transition costs. On the contrary, command-and-control regulation and innovation policies to foster green investments are the key elements of the most promising policy mix to put the economy on a green growth pathway. Overall, their results contradict the standard tenets of cost–benefit climate economics and suggest the absence of any trade-off between decarbonization and growth.

Keywords: *climate policy, climate risks, macroeconomic dynamics, agent-based modeling*

JEL codes: *C63, Q40, Q50, Q54*

1 INTRODUCTION

The most recent reports of the Intergovernmental Panel on Climate Change (IPCC) indicate that the impacts of a 2°C increase in global temperature would be considerably more

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severe than previously estimated (IPCC 2021). This implies a larger reduction of global greenhouse-gas emissions to mitigate the physical risks of a warming climate. However, notwithstanding widespread evidence that climate impacts are already mounting (Coronese et al. 2019; IPCC 2021) and will likely destabilize the whole Earth system (Steffen et al. 2015; 2018) under current emission pathways, the economic assessment of climate change remains largely anchored to old-style modeling techniques delivering extremely conservative estimates. To provide a stark example, in a survey published in the *Journal of Economic Perspectives*, Tol (2009: 33) wrote that there is ‘agreement that the welfare effect of doubling the atmospheric concentration of greenhouse gas emissions on the current economy is small – few percentage points of GDP. ... [R]oughly equivalent to a year’s economic growth.’ A decade later, the 2018 Nobel Prize lecture by William Nordhaus emphasized that the optimal degree of global warming, which maximizes human welfare across the next century, amounts to about 3°C above the pre-industrial level in 2100 (Nordhaus 2019). While criticized on a number of empirical and theoretical grounds (Stanton et al. 2009; Pindyck 2013), these assessments brought about two substantial policy implications. First, as long as climate policy has to be assessed through cost–benefit analysis, the lower the economic consequences of climate change, the lower the desirability of timely, ambitious, and aggressive interventions aimed at shifting the economy to a sustainable growth path. Second, as long as mitigation can be approximated by an ordinate response to price signals, climate policy boils down to the design of a suitable carbon tax balancing emissions’ abatement costs and avoided climate damages.

In this paper, we challenge the dominant view about the economic effects of climate impacts and climate policies by discussing a series of simulation results obtained with the *Dystopian Schumpeter meeting Keynes (DSK)* agent-based integrated-assessment model (Lamperti et al. 2018a; 2019a; 2020a; 2021). The DSK model is an out-of-equilibrium evolutionary simulation laboratory that accounts for coupled climate-economy evolution. The model can be employed to assess the economic consequences of uncontrolled climate change taking into account the presence of heterogeneous microeconomic climate impacts and the emergence of tipping points. Moreover, the model allows us to study the likelihood of achieving a transition towards green growth pathways and the risks and opportunities nested in the choice of climate policy instruments.

The DSK model is an agent-based simulation laboratory (Fagiolo/Roventini 2017; Dosi/Roventini 2019) representing a global economy co-evolving with climate change. In particular, the model comprises heterogeneous and interacting consumption- and capital-good whose production requires energy and labor inputs and it may need credit provided by a banking sector. Anthropogenic emissions arise from production of goods and energy. Cumulated emissions are linked to temperature increases through a single climate model. The model provides a stochastic microfoundation of climate damages, which are modeled as a series of heterogeneous shocks affecting several features of firms, consumers, and energy plants. As the size and frequency of the shocks depend on global warming, the aggregate climate effects on macroeconomic dynamics endogenously emerge from decentralized agents’ production activities and impacts.

The DSK model is able to reproduce a rich set of micro and macro stylized facts. Simulating the unfolding of climate-economy interactions along carbon-intensive futures – as mirrored by business-as-usual scenarios compatible with a Representative Concentration Pathway 8.5 delivering global warming at the end of the century beyond 3°C – returns way higher economic risks than those of the standard impact assessment literature (Ciscar et al. 2012; Nordhaus 2017; 2018). The negative impacts of climate change are magnified by the financial system via firms’ bankruptcies possibly triggering banking crises (Lamperti et al. 2019a; 2021). Our results provide evidence of a substantial lack of isomorphism

between the effects of micro- and macro-level shocks, as is typical of complex systems (Lamperti et al. 2018a; 2020a). Different types of shocks exert heterogeneous effects on output growth, the unemployment rate, financial instability, and the likelihood of economic crises. Most relevantly, uncontrolled warming is found to induce possible shifts in the growth dynamics of the economy towards a regime characterized by stagnation and high volatility. Overall, our analysis of the DSK model calls for immediate and strong climate policy aimed at mitigating the size and pace of global warming.

We then study decarbonization policies in the complex economic system provided by the DSK model. Simulation experiments show the relevance of transition risks stemming from a disordered decarbonization (in line with Mercure et al. 2018b; Lamperti et al. 2019d; Kanzig 2021; Semieniuk et al. 2021). However, the macrofinancial consequences of a rapid transition intimately depend on the enforced policy mix. The DSK model shows that carbon taxation is not an effective tool to achieve zero-emission growth trajectories. While extremely high carbon taxes are requested to trigger a fast-enough decarbonization process to comply with the Paris Agreement, they drastically increase the risk of a large unemployment crisis caused by a surge in energy prices, large drops in investments, and a rise in bankruptcy rates (Wieners et al. 2022). Contrarily, gradually increasing tax schemes are almost ineffective to tackle emission growth. In a nutshell, the standard role of carbon taxes internalizing environmental costs and triggering a green transition finds no support in our analysis. On the positive side, simulation results in Wieners et al. (2022) show that an ensemble of command-and-control regulation and green industrial and innovation policies is the best policy toolkit to support a rapid and orderly transition that puts the economy on a sustainable green growth pathway. In such a scenario, mild carbon taxation can be introduced to pay for the cost of the transition. Finally, combined financial policies can facilitate the decarbonization of the economy, minimizing financial and economic instabilities.

The DSK model nests in a broader modeling literature which is providing novel paradigms for the evaluation of climate impacts and climate policy, building on out-of-equilibrium dynamics and decentralized interactions (Mercure et al. 2016; Balint et al. 2017; Lamperti et al. 2019b; Hafner et al. 2020; Rising et al. 2022). For example, the DEFINE model offers a post-Keynesian aggregate framework often delivering similar and complementary results to DSK (Dafermos et al. 2017; 2018); the EIRIN model uses a flexible stock–flow consistent framework to study the interaction of green fiscal and monetary policies which can be compared, in many respects, to DSK (Monasterolo/Raberto 2018; 2019); the E3ME-FTT-GENIE model delivers a finer view of global energy transformations and their macroeconomic consequences by merging a multi-country, multi-sector, out-of-equilibrium macroeconomic structure with a system dynamics view of technological change (Mercure et al. 2018a); the EURACE@Unige model has been enriched to study the complex interplay between energy, credit, and monetary/prudential policy (Ponta et al. 2018), while the EURACE@Unibi to assess the shape of low carbon transition in relation to technological and labor market dynamics (Hötte 2020). D’Orazio/Valente (2019) used an agent-based model (ABM) to study the role of finance to stimulate green innovations and their diffusion; instead, abstracting from technical change, Ciola et al. (2022) proposed the MATRIX ABM studying energy shocks and induced fluctuations in complex economic systems.¹

The rest of the paper is organized as follows. Section 2 briefly introduces the DSK model, its structure, and its main features. Section 3 provides a critical analysis of the

1. Our list is not exhaustive by any means; an updated survey of out-of-equilibrium climate-economy models is outside the scope of this paper.

macroeconomic consequences of global warming in a complex evolving economy, while Section 4 discusses the effects of climate policies on the outlook of a more or less rapid and smooth transition. Finally, Section 5 concludes.

2 AN INTEGRATED-ASSESSMENT AGENT-BASED MODEL

The DSK model couples an economy populated by heterogeneous, interacting firms and a climate model (see Figure 1). The economy and the climate are linked by multiple, non-linear feedbacks co-evolving over time. Production and energy generation lead to greenhouse-gas emissions, which affect temperature dynamics. The evolution of the climate generates microeconomic impacts that heterogeneously harm firms. Endogenous technical change affects both economic growth and climate change, creating new technologies for firms and energy plants with different levels of greenhouse-gas emissions.

The economy builds on the K+S model (Dosi et al. 2010; 2013) and is composed of two vertically separated industries, wherein firms are fed by an energy sector and financed by loans from banks – if needed. Capital-good firms invest in R&D and innovation, and to improve the productivity, energy, and carbon efficiency of their production techniques and of the machines they sell. Consumption-good firms invest in capital-goods and produce an homogenous final good, which is ultimately consumed by households. The banking sector, akin to Dosi et al. (2015), encompasses commercial banks that provide credit to firms, plus a single central bank running monetary and prudential policies. Banks are heterogeneous in their number of clients, balance-sheet structure, and lending conditions. Indeed, the model accounts for endogenous money, and banks supply credit according to their own financial conditions, behavioral attitude, and macroprudential regulations.

In the first version of the DSK model (Lamperti et al. 2018a), innovation processes follow the K+S family (Dosi et al. 2017): technical coefficients – labor productivity, energy efficiency, and carbon efficiency – randomly change as a consequence of successful firms' R&D investment. Wieners et al. (2022) introduce fossil fuels among the inputs available to capital-good firms which can choose how much to electrify their production.

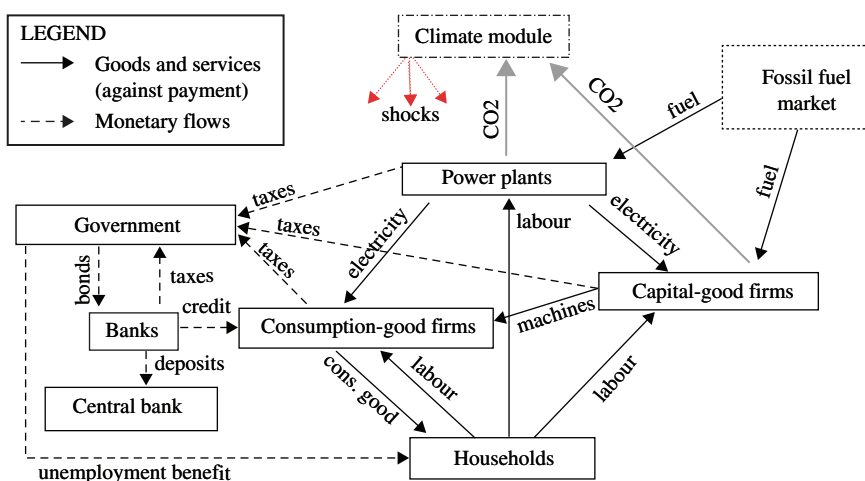


Figure 1 Schematic representation of the DSK model, adapted from Wieners et al. (2022)

More precisely, inspired by Nelson/Winter (1982), the process of technical change increases the potential combinations of electricity and fossil fuel use that are available to the firm, which then selects the most convenient recipe at available prices. Such dual structure of the model allows studying and calibrating both economies where manufacturing accounts for a relatively large fraction of fossil fuel use (for example, the US) or not (for example, France), and to account for full decarbonization of the whole productive structure (industry and power sectors).

The markets for capital and consumption goods are characterized by asymmetric information and imperfect competition wherein boundedly-rational firms adapt to a constantly evolving environment through behavioral heuristics grounded on trial-and-error learning schemes (Dosi et al. 2010). In the capital-good market, local interactions between capital- and consumption-good firms affect market dynamics, with the latter choosing the machine tools with the preferred quality–price–emissions combinations. In the consumption-good market, firms obtain a market share through a quasi-replicator dynamics: more competitive firms expand their share while firms with a relatively low competitiveness level shrink it. In the baseline configuration, firm competitiveness depends on unitary production costs and unfilled demand from customers (Lamperti et al. 2018a). Richer specifications are of course available. For instance, penalizing the competitiveness of carbon-intensive firms allows us to assess the economy-wide effects of households' preferences for greener goods (that is, goods with a lower environmental footprint; Bleda/Valente 2009; Peattie 2010) in a direct and controllable way.

Energy production is performed by a set of heterogeneous power plants featuring green (renewable) or brown (carbon-intensive) technologies. Such plants compete to produce homogeneous energy inputs that are demanded from firms. Endogenous technological change occurs along both the green and brown technological trajectories. In the first case, innovation reduces the cost of investing in additional green electricity generation capacity. In the second case, innovation improves the thermal efficiency of brown plants and reduces (but never eradicates) their emissions. Investments in new energy plants are decided by the energy firms on the basis of the lifetime costs of energy plants from alternative energy technologies. This implies that investments might dynamically lead to lock-ins in certain energy technologies, which would reflect an history of R&D activities and innovations along a prevailing technological trajectory. The energy market is competitive: plants submit production orders at their marginal production costs and the central authority subsequently ranks all orders and fixes production on a merit-order basis, that is, the cheapest plants are activated first and the ranking is followed until all the required production is reached. The price of energy is fixed in every period according to an additive mark-up over the marginal cost of the last activated plant. Investment in the energy sector can be associated with: (i) the replacement of old and obsolete plants; or (ii) capacity expansion. Replacement is due to the fact that all (brown and green) plants have a constant lifespan, while expansionary investments are needed to face an eventually increasing energy demand. In each period, investments are made of green or brown plants according to the relative cost of energy. The interactions between the dynamics of demand and investments determines the likelihood of a green transition or brown lock-ins in the power sector (Lamperti et al. 2020a).

Global warming reflects the dynamics of the stock of emissions in the atmosphere. We account for emissions from the industry and energy sectors, and assume that other non-modeled sources (for example, transport) follow the same relative changes that characterize the energy sector. The DSK models allow for two alternative climate modules: a simple one-equation climate box reflecting a carbon budget approach, and a more detailed climate module accounting for non-linear feedbacks and long-run downward temperature adjustments (Sterman et al. 2012).

The impact of climate change on economic dynamics is usually assessed in standard integrated-assessment models assuming aggregate fractional GDP losses, stemming from *ad hoc* damage functions, which express the percentage output loss for any level of temperature anomaly. By contrast, in the DSK model we employ a genuine bottom-up approach by modeling damages as micro shocks hitting workers' labor productivity and firms' energy efficiency, capital stock, or inventories. To do this, we use a stochastic *microscopic damage-generating function*, which models the direct impact of the weather on individual economic activities. At the end of each period, a random sample of climate-related shocks is constructed to affect agents through a multiplicative process.

In particular, in most of our applications, the microscopic damage-generating function – which is used to sample the shocks – takes the form of a beta distribution over the support $[0,1]$, whose density satisfies:

$$f(s; a, b) = \frac{1}{B(a, b)} s^{a-1} (1-s)^{b-1}, \quad (1)$$

where $B(\cdot)$ is the beta function and a, b are respectively the location and scale parameters. Both parameters are assumed to evolve across time, reflecting changes in climate variables:

$$a_t = a_0(1 + \log T_{m,t}) \quad (2)$$

$$b_t = T_{b_0} \frac{\sigma_{10y,0}}{\sigma_{10y,t}}, \quad (3)$$

where $\sigma_{10y,t}$ captures the average variability of surface temperature across the previous decade and a_0, b_0 are positive integers. Equations (2) and (3) shape the disaster-generating function as a right-skewed, unimodal distribution, whose mass shifts rightward as temperature increases, thereby raising the likelihood of larger shocks. The parameters a_0 and b_0 are usually tuned to match empirical data or to approximate the average shock in each time-step to a desired damage function (for example, DICE's quadratic damage function or Weitzman's sextic polynomial; see Weitzman 2009; Nordhaus 2017). Figure 2 shows the shape of the damage-generating function at two different levels of global warming.

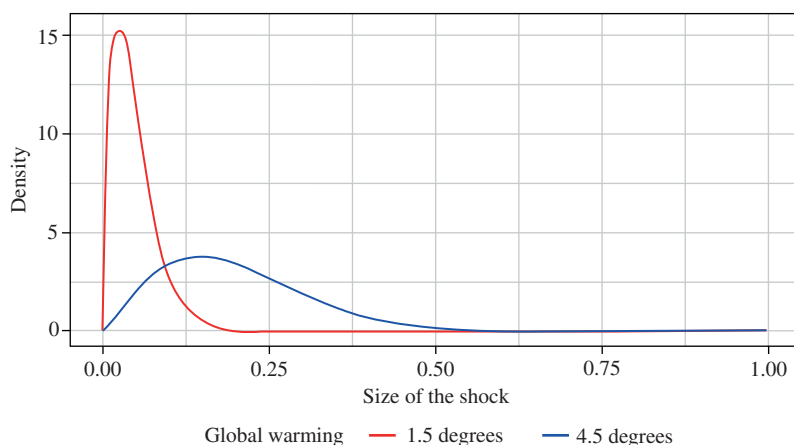


Figure 2 Examples of the damage-generating function at different levels of temperature anomaly

Once sampled, climate-related shocks are assumed to proportionally affect some of the features that characterize agents in the model. For example, when climate change is assumed to affect the productivity of labor, A , we obtain that $A_{i,t} = [1 - \text{shock}_{i,t}] \bar{A}_{i,t}$ for every firm i and time t , where $\bar{A}_{i,t}$ indicates the counter-factual value of i 's labor productivity in the absence of the climate damages, and $\text{shock}_{i,t}$ the corresponding climate shock. Similarly, shocks affecting capital stocks reduce the set of machines available to firms for production, while shocks to energy efficiency increase the amount of energy needed to manufacture goods.

2.1 Calibration, validation, and replication of stylized facts

As in every ABM,² the properties of the DSK have to be analysed via extensive computer simulations. Indeed, the DSK model is usually calibrated targeting a set of modern economies' properties (or moments) that a macrofinancial model running at global scale should desirably match. These include, among others, the relative growth rate of output, energy use, and emissions, as well as the relative volatility of consumption and investments with respect to output at business-cycle frequencies. Once these moments have been identified, the model is extensively explored in its business-as-usual scenario without climate damages: in this way, we wash out the role of climate damages in influencing the dynamic properties of the model. Next, simulated data are analysed in their ability to match the targeted properties, and the best-performing configuration of parameters is retained. In particular, we typically select the configuration that matches the highest number of qualitative properties and, in case of ties, we retain the one exhibiting the lowest relative distance from the quantitative targets, equally weighting the various moments. Sensitivity analysis is then used to inspect the robustness of results to slight changes in parameters' values and initial conditions.

The DSK model jointly generates endogenous growth and business cycles punctuated by major crises. Moreover, it reproduces a large ensemble of micro and macro stylized facts characterizing short- and long-run behaviors of developed and developing economies (see Table 1). At business-cycle frequencies output, investment and consumption series display the familiar 'rollercoaster' dynamics. In line with the empirical evidence, consumption is less volatile than GDP, while the fluctuations of investment are wilder. Recessions, their duration and the fiscal costs they cause qualitatively match the historical empirical distributions. Beyond business-cycle properties, the model reproduces fairly well the long-run positive cointegrating relationships between energy and output (see Ozturk 2010) and GDP and emissions (Triacca 2001; Attanasio et al. 2012).³ Financial cycles, proxied by firms' total debt, shows significantly ampler fluctuations than output. The real, financial, and energy parts of the economic system appear to be strongly correlated across downswings and, to a lesser extent, upswings. At the microeconomic level, in line with the empirical literature (see, for example, Dosi 2007), firms and energy plants display persistent heterogeneity in terms of productivity differentials, and energy and carbon efficiency, which hints at a genuine representation of heterogeneity within the DSK model. Overall,

2. We refer the reader to Fagiolo et al. (2019) and the literature review section in Lamperti (2018a; 2018b) and Lamperti et al. (2018b) for a broader overview of validation and calibration approaches for macroeconomics ABMs.

3. The interested reader will find additional details and a battery of cointegration tests in Lamperti et al. (2018a).

Table 1 Main empirical stylized facts replicated by the DSK model

Stylized facts	Empirical studies (among others)
<i>Macroeconomic stylized facts</i>	
SF1: Endogenous self-sustained growth with persistent fluctuations	Burns/Mitchell (1946); Kuznets/Murphy (1966); Zarnowitz (1985); Stock/Watson (1999)
SF2: Fat-tailed GDP growth-rate distribution	Fagiolo et al. (2008); Castaldi/Dosi (2009); Lamperti/Mattei (2018)
SF3: Recession duration exponentially distributed	Ausloos et al. (2004); Wright (2005)
SF4: Relative volatility of GDP, consumption, investments, and debt	Stock/Watson (1999); Napoletano et al. (2006)
SF5: Cross-correlations of macro variables	Stock/Watson (1999); Napoletano et al. (2006)
SF6: Pro-cyclical aggregate R&D investment	Wälde/Woitek (2004)
SF7: Cross-correlations of credit-related variables	Lown/Morgan (2006); Leary (2009)
SF8: Cross-correlation between firm debt and loan losses	Foos et al. (2010); Mendoza/Terrones (2012)
SF9: Pro-cyclical energy demand	Moosa (2000)
SF10: Synchronization of emissions dynamics and business cycles	Peters et al. (2012); Doda (2014)
SF11: Co-integration of output, energy demand, and emissions	Triacca (2001); Ozturk (2010); Artanasio et al. (2012)
SF12: Banking crises duration is right-skewed	Reinhart/Rogoff (2009)
SF13: Fiscal costs from recessions are fat-tailed	Laeven/Valencia (2012)
<i>Microeconomic stylized facts</i>	
SF14: Firm (log) size distribution is right-skewed	Dosi (2007)
SF15: Fat-tailed firm growth-rate distribution	Bottazzi/Secchi (2003; 2006)
SF16: Productivity heterogeneity across firms	Bartelsman/Doms (2000); Dosi (2007)
SF17: Persistent productivity differential across firms	Bartelsman/Doms (2000); Dosi (2007)
SF18: Lumpy investment rates at firm level	Doms/Dunne (1998)
SF19: Persistent energy and carbon efficiency heterogeneity across firms	DeCanio/Watkins (1998); Petrick (2013)
SF20: Firm bankruptcies are counter-cyclical	Jaimovich/Floetotto (2008)
SF21: Firm bad-debt distribution fits a power law	Di Guilmi et al. (2004)

we believe the model's ability to match stylized facts at various frequencies and across different modeled sectors can be regarded as a credible signal of its empirical validity.

3 REVISITING THE ECONOMIC CONSEQUENCES OF GLOBAL WARMING

3.1 Macroeconomic impacts as emergent properties of complex system dynamics

To repeat, in the DSK model, macroeconomic fluctuations as well as long-run growth trajectories are endogenously evolving properties that emerge from the interactions of households, firms, banks, energy plants, and the overall socio-ecological environment.⁴ By systematically comparing the properties of the system with and without the effects of climate change, one can study the macrofinancial effects of global warming on the economy, as well as the complex co-evolution of the climate and economic systems. Here, we focus on output growth, unemployment rate, likelihood of crises (that is, prolonged periods of negative growth), financial instability (as proxied by the frequency of banking insolvencies), shape of the transition, and debt dynamics to characterize the status of the system.⁵

Following such a simulated counter-factual approach and purposely targeting a relative 'extreme' scenario characterized by a high temperature anomaly (+4.5°C in 2100) and no climate policy (akin to representative concentration pathways (RCPs) 8.5), Lamperti et al. (2018a) showed the emergence of climate tipping points: after an initial relatively tranquil period characterized by negligible climate impacts, the magnitude and frequency of climate shocks sharply rises, leading to a new regime characterized by stagnant growth, higher unemployment, and depressed wages (see Table 2). When the banking system is taken into account, the impact of climate shocks is magnified (see Lamperti et al. 2019a; more on that below).⁶

We also find that the economic response to global warming is extremely dependent on the impact channel (see Table 2). Labor productivity shocks are way more damaging than those to either capital stocks, which mainly mirror increased weather extremes and natural disasters, or energy efficiency. In particular, labor productivity impacts considerably dampen the long-run growth of the economy by weakening the Schumpeterian innovation engine. Put differently, damages targeting firms' stock of machines increase the volatility of the business cycles, which reflects in the substantially magnified likelihood and magnitude of crises. The latter effects mainly stem from higher lumpiness of investments, supply bottlenecks, and sharpened financial fragility. Finally, as will be discussed in more detail below, energy efficiency shocks annihilate the chances of observing a green transition towards sustainable growth.

4. This is well in tune with the vast majority of the macroeconomic agent-based literature. See Fagiolo/Roventini (2012; 2017), Gatti et al. (2018), and Dosi/Roventini (2019) for details.

5. The shape of the transition is examined through: (i) the transition likelihood, as proxied by the share of runs featuring low-carbon energy sources permanently overcoming 85 percent of the energy mix; and (ii) the transition speed, as proxied by the number of simulation steps needed for low-carbon energy sources to reach 50 percent and 90 percent of the energy mix.

6. In both Lamperti et al. (2018a) and Lamperti et al. (2019a) the disaster-generating function of the DSK model (see equations (1), (2), and (3)) is tuned such that the average climate shock matches the aggregate loss determined by the damage function of Nordhaus (2014); this is also consistent with several micro-level impact studies (for example, Somanathan et al. 2021). However, the variance of the shocks is modeled differently in the two studies; we refer the reader to the original manuscripts for additional details.

Table 2 Macroeconomic consequences of different scenarios of climate damages in a business-as-usual scenario

Climate shocks directly affecting:				
	Labor productivity	Capital stock	Energy efficiency	Labor productivity and capital stock
<i>DSK (2018)</i>				
Short-run growth	mildly reduced	mildly positive	unaffected	mildly reduced
Long-run growth	strongly reduced	reduced	mildly reduced	strongly reduced
Likelihood of crises	increased	strongly increased	mildly increased	strongly increased
Unemployment	strongly increased	increased	mildly increased	strongly increased
<i>DSK (2019); multiple banks</i>				
Short-run growth	mildly reduced	mildly positive	–	mildly reduced
Long-run growth	strongly reduced	reduced	–	strongly reduced
Likelihood of crises	increased	strongly increased	–	strongly increased
Unemployment	strongly increased	increased	–	strongly increased
Financial instability	increased	mildly increased	–	strongly increased
Public debt (% GDP)	increased	mildly increased	–	strongly increased
<i>DSK (2020); endogenous low-carbon transition</i>				
Long-run growth	strongly reduced	–	mildly reduced	–
Likelihood of the transition	mildly increased	–	strongly reduced	–
Speed of the transition	mildly reduced	–	strongly reduced	–

Notes: Authors' analysis based on data collected in 2018, 2019, and 2020. Emissions and global warming compatible with RCP 8.5; in all studies the damage-generating function was calibrated to match the average shock with the loss predicted by the damage function of Nordhaus (2014).

Overall, the end-of-century value of global output produced by the DSK model in the presence of mounting climate impacts is significantly lower than its counter-factual without climate shocks. In particular we found that global GDP in scenarios with climate damages ranges between 10 percent and 84 percent of what would have been without climate change. This shows that micro-level heterogeneous climate shocks on the level of a certain variable induce severe macroeconomic impacts, adversely affecting the long-run growth dynamics of the economy. Our results are in line with a growing body of empirical evidence pointing to large adverse effects of temperature and precipitation variations on GDP and consumption growth (for example, Burke et al. 2015; Carleton/Hsiang 2016; Auffhammer 2018), and, by contrast, contradict the impact assessment literature grounded on computable general equilibrium models, which suggests minor effects of climate change on economic dynamics (for example, Tol 2002; 2009; Ciscar 2012). Relevantly, the results of the DSK model provide a microfoundation of the climate growth-at-risk effects reported in Kiley (2021), wherein global warming is found to probably shift leftward and fatten the distribution of growth rates, especially for vulnerable economies.

3.2 Climate-induced financial instability

Beyond the effects on the real economy, the assessment of climate physical risks has gradually broadened its focus towards the financial system (Lamperti et al. 2019a; Monasterolo 2020; van der Ploeg 2020; Battiston et al. 2021). Lamperti et al. (2019a) studied in the DSK model how climate shocks to firms affect the banking sector, altering the solvency of financial institutions and, in turn, feed back to public finances and the whole macroeconomy (see Table 2). Results indicate that uncontrolled climate change will increase the frequency of banking crises substantially (+26–248 percent). Further, rescuing insolvent banks will cause an additional fiscal burden of approximately 5 percent to 15 percent of GDP per year and an increase of public debt to GDP by a factor of approximately two. In line with the discussion provided above, the impact channel is pivotal to our understanding of the effects of climate shocks. Indeed, when global warming is low and mainly impacts the capital stocks, firms are forced to increase their investments without suffering from lower productivity, which results in higher output growth and increased financial stability. However, the picture reverses completely after global warming passes tipping points above 1.5°C: the capital stock shocks amplify the adverse effect of climate change on productivity by spurring bankruptcy rates, enlarging the stock of non-performing loans, and cutting back the supply of credit to the real economy, thus establishing a vicious cycle. Indeed, Lamperti et al. (2019a) suggest that around 20 percent of the growth slowdown induced by climate-related damages is attributable to the deterioration of banks' balance sheets provoked by firms' increased defaults on their debt obligations. While macroprudential regulation is deemed as potentially useful to fight climate risks (Campiglio et al. 2018; D'Orazio/Popoyan 2019), analyses with the DSK model suggest some degree of effectiveness as well as the need to couple them with climate-oriented credit policies (Lamperti et al. 2021) and broader mitigation efforts targeting the energy sector (Wieners et al. 2022).

The literature on the financial consequences of climate damages is rapidly developing, both on theoretical and empirical grounds. The DSK model was not the sole one to be applied to the assessment of such risks. For example, Dietz et al. (2016) built on the DICE model to document a skewed distribution of climate-induced losses in the value of financial assets along with a business-as-usual emissions path, with the 99th percentile amounting to an 18.9 percent write-down of the value of global financial assets. Under a

mild mitigation scenario, Dafermos et al. (2018) exploited the ecological macroeconomic DEFINE model (Dafermos et al. 2017) to show that climate damages to capital stocks seriously harm the solvency and leverage of financial institutions, sharply reducing GDP growth from 2.5 percent to about 1.5 percent at the end of the twenty-first century. More recently, Gourdel et al. (2021) and Dunz et al. (2021) used the EIRIN stock-flow consistent model to assess how climate physical, transition, and health risks compound, affecting macrofinancial stability. Such a stream of contributions effectively hint that leaving out the financial system from climate-economy integrated assessments may lead to an underestimation of climate impacts and a fundamental misunderstanding of the mechanisms behind the propagation of climate risks in a complex evolving economy.

3.3 The effects of climate impacts on the transition to sustainable growth

While the literature analysing low carbon transitions and mitigation pathways is large and variegated, there is a knowledge gap on how climate change can affect the likelihood and speed of the decoupling between economic growth and fossil-fuel use, and the ensuing macroeconomics effects. On the one side, this reflects the fact that the joint analysis of physical and transition risks is still in its infancy (Monasterolo 2020; NGFS 2021; Semieniuk et al. 2021). On the other, there is a long-lasting distance between studies of impact and mitigation assessment. However, recent empirical evidence pushes towards a coupled focus: for example, Lin et al. (2019) found that extreme temperatures boost investments into gas- and oil-fired power plants, as they are more flexible to be operated during weather anomalies.

In Lamperti et al. (2020a), the DSK model has been extended to account for endogenous transitions in the power sector to renewable energy sources and the interaction between climate impacts and the evolution of the energy mix. As summarized in Table 2, once climate damages are factored in, the likelihood of the green transition depends on how climate change affect agents in the model. When climate shocks are modeled as aggregate output losses, as commonly done in the majority of general-equilibrium climate-economy models, climate shocks do not affect the probability of carbon decoupling. However, in the presence of heterogeneous climate impacts hitting firms via different channels, the results are more complex. More specifically, negative shocks to energy efficiency are found to slow down the transition, whereas shocks reducing labor productivity accelerate it. Both effects interact with the dynamics of energy demand and prices, which in turn affect the investment of energy firms in green and dirty technologies. Indeed, if energy efficiency is reduced by climate shocks, the energy demand to produce a given output will increase, thereby inducing the energy industry to adapt its generation capacity. Since fossil-fuel technologies start with a lower lifetime production cost, expansionary investment will favor such a technological trajectory. Dynamically, this increased spending in R&D activities aimed at improving the efficiency of brown plants will create a vicious cycle impeding the shift to low-carbon technologies. This 'brown' lock-in turns out to dominate the dynamics, notwithstanding the penalizing effect the merit order market mechanisms exert on brown plants. By a similar token, shocks to labor productivity induce an increasingly sharp contraction in industrial production, wages, and final demand (see also Lamperti et al. 2018a; 2019a; and Table 2 in the present paper). In the presence of a merit order activation protocol (see Section 2), the lower energy demand will induce an increase in the share of green plants' production in the energy mix, which will further stimulate green R&D and improve the competitiveness of low-carbon technologies. When green technologies fill their initial technological gap, the transition starts unfolding and, further, self-sustains as long as the

marginal cost of green plants remains below those of brown ones. Overall, our results imply that the success and effectiveness of policies supporting sustainable growth – such as carbon tax and green subsidies – likely depends on the different channels through which climate damages affect the economy. In line with the most recent evidence, showing that climate impacts are likely larger than previously thought (IPCC 2021), future research will need increasingly strong and synergic integration between climate policy analysis and impact assessment.

4 THE DARK AND BRIGHT SIDES OF CLIMATE POLICY

To cut emissions, economies must reduce their carbon intensity and, given currently prevailing technologies, this implies a decisive shift away from fossil-fuel energy and related physical capital. In an adverse scenario, the transition to a low-carbon economy occurs either late or abruptly, with the costs of such a transformation being potentially high and systemic (Battiston et al. 2017; Mercure et al. 2018b; van der Ploeg 2020; Semieniuk et al. 2021). Indeed, policymakers increasingly emphasize the need of finding the right balance between a rapid transition and the macroeconomic frictions it entails (Carney 2015; NGFS 2019), as well as the long-run growth opportunities it can generate (Mercure et al. 2021). However, while there is widespread agreement about the urgency of climate action to mitigate risks from uncontrolled climate change, the evidence on the suitable policy package to induce an effective and orderly transition is scarce (NGFS 2019; Stern/Stiglitz 2021), and the excessive reliance on policy instruments characterized by low political acceptability, such as carbon pricing, brings about concerns for the transition outlook (Patt/Lilliestam 2018; Pezzey 2019; Rosenbloom et al. 2020). Hence there is an open debate concerning how to achieve a rapid and orderly transition, whether it will induce risks for economic stability or spur new growth opportunities, and whether it will dampen public finances or not.

Further, there is a lively discussion on the suitable modeling framework to study the trade-offs between alternative climate policies (see, among others, Farmer et al. 2015; Stern 2016; Balint et al. 2017; Hafner et al. 2020). Intuitively, such a debate is intimately related to the right policy mix for the green transition: adopting the lens of cost–benefit analysis and marketable impacts directly points to the design of climate policy as an optimal carbon tax; put differently, recognizing the complexity of economic behavior opens the doors to additional trade-offs, potential opportunities, and richer policy schemes (for example, Acemoglu et al. 2012; Lamperti et al. 2020b; Mercure et al. 2021; Stern/Stiglitz 2021).

Using the DSK model as a simulation laboratory, Lamperti et al. (2020a; 2021) and Wieners et al. (2022) extensively study alternative climate policy combinations within a complex evolving economy in persistent disequilibrium (see Table 3). In particular, Lamperti et al. (2020a) investigate the effects of price-based incentives (fossil-fuel taxes and feed-in tariffs) in shaping the likelihood and timing of a transition to low-carbon energy technologies. Lamperti et al. (2021) shift the focus to the financial sector and explore the role of credit market policies in sustaining the decarbonization of the industry sector. In both studies, the economy is evaluated in the presence and absence of climate impacts, which proxies the size of physical risks during the transition (or, in other words, a more or less delayed mitigation process). Therefore, the results allow us to infer the influence of micro-level damage on the effectiveness of the policy instrument. Contrarily, Wieners et al. (2022) engage in a systematic comparison of the climate policy schemes, allowing the maintenance of global warming within the 2°C threshold, and evaluate the risks and opportunities of each policy combination during the transition.

Table 3 Macroeconomic consequences of different climate policies with respect to a business-as-usual (no policy) scenario

Policy	Emission growth		Output growth		Financial stability	Deficit
	Energy	Industry	Short-run	Long-run		
<i>DSK (2020); endogenous low-carbon transition</i>						
Fossil-fuel tax	mildly red.	–	inc.	mildly inc.	–	red.
Feed-in tariff	mildly red.	–	inc.	mildly inc.	–	inc.
<i>DSK (2021); multiple banks</i>						
Green Base II (GB)	mildly red.	–	mildly red.	mildly inc.	Unaffected	mildly red.
Carbon risk adjustment (RA)	mildly red.	–	red.	red.	Decreased	unaffected
Green credit easing (CG)	mildly red.	–	mildly inc.	inc.	strongly inc.	inc.
GB + RA + CG	red.	–	mildly inc.	strongly inc.	strongly inc.	mildly red.
<i>DSK (2022); industry electrification</i>						
Const. (low) carbon tax (T)	mildly red.	unaffected	mildly red.	mildly red.	mildly inc.	mildly red.
Const. (high) carbon tax	strongly red.	red.	strongly red.	strongly red.	strongly red.	red.
DICE-like carbon tax	mildly red.	unaffected	strongly red.	strongly red.	strongly red.	red.
Sub. green plants (C)	red.	unaffected	inc.	unaffected	mildly inc.	mildly inc.
Sub. green R&D	mildly red.	unaffected	inc.	mildly inc.	unaffected	mildly inc.
Ban on fossil fuel use (B)	strongly red.	red.	mildly red.	unaffected	mildly red.	inc.
Electrification standard (E)	unaffected	strongly red.	strongly red.	red.	mildly red.	mildly inc.
B + C + E	strongly red.	strongly red.	mildly red.	unaffected	unaffected	inc.
B + C + E + T	strongly red.	strongly red.	mildly red.	unaffected	unaffected	unaffected

Note: Authors' analysis based on data collected in Lamperti et al. (2020a; 2021); Wieners et al. (2022). Red. = reduced; inc. = increased; const. = constant; and sub. = subsidy; in some simulations, Lamperti et al. (2020a; 2021) use a damage-generating function calibrated to match the average shock with the loss predicted by the damage function of Nordhaus (2014); Wieners et al. (2022) do not include climate damages.

4.1 The fallacy of carbon taxation

Climate policy is too often associated only with carbon pricing, either framed through cap and trade systems or direct carbon taxation. While the idea of putting a price on carbon is particularly intriguing for its simplicity, its possible implementation comes with a series of issues that make it inadequate to the scope of decarbonizing an entire economy within a limited timeframe, at least if not coupled with other policy interventions (Hepburn et al. 2020). Hence, carbon pricing is often disregarded by policymakers (Peñasco et al. 2021). Nonetheless, the vast majority of the integrated assessment literature reduces climate policy to carbon pricing, focusing either on cost-effective mitigation pathways (for example, Bosetti 2021) or on the social cost of carbon (Nordhaus 2017). Given the general equilibrium structure of traditional integrated assessment models, the risk of losing our understanding of the macrofinancial consequences of carbon taxation, especially when it needs to be very high, is considerable.

To shed light on the debate, in Wieners et al. (2022) we analyse a number of carbon tax schedules within the DSK model. In particular, we consider carbon taxes increasing the fossil-fuel price, either gradually – mimicking the policies suggested by either cost-benefit (for example, DICE) or cost-effective IAMs (for example, those reviewed by IPCC) – or by a constant wedge.⁷ The results are crystal clear. On the one hand, excessively low carbon taxation proves to be completely ineffective at triggering the green transition in both the power and the industry sectors. Indeed, we find that the relative likelihood of complying with the 2°C target relying only on carbon taxes below 100 percent of fossil-fuel price approaches zero. These results point to the difficulty to overcome inertia in the process of technology search and adoption by simply raising the carbon price. On the other hand, high carbon prices are found to foster economic instability, inducing a sharp increase of the unemployment rate just after policy implementation and a surge in firms' bankruptcies, which translates into a transitory yet long recession. This result is in line with recent evidence from a post-Keynesian ecological macroeconomic model, which Dafermos/Nikolaïdi (2019) used to show how carbon taxation decreases firms' profitability and access to credit. While revenue recycling schemes directed towards either firms or households soften such adverse effects, they do not eliminate them. Putting these two results together, in Wieners et al. (2022) we find that the exponentially increasing carbon pricing often advocated in DICE and other mainstream integrated assessment models (see, for example, Nordhaus 2014; 2019) is found to couple the negative sides of inefficiency of low initial carbon price with the economic instability brought by aggressive carbon price increases in the second half of the twenty-first century. These negative conclusions are related to the very functioning of the electricity market with a merit order activation protocol (Lamperti et al. 2020a). In such a market, carbon taxes increase the costs of fossil-fuel plants, which in turn raises the electricity price as long as the most expensive plant used for power generation is subject to taxation. Price-based incentives in the form of fossil-fuel taxes and feed-in tariffs work relatively well at redirecting investments. However, they induce a pass-through effect on firms' production costs during the whole transition and need to be disproportionately large to produce sensible reduction in emission growth. For this reason they can hardly be considered a viable strategy.

7. Specifically, we test policies that raise the fossil-fuel price by a factor ranging from 1 to 15, which allows the studying of carbon prices coherent with IPCC scenarios limiting temperature anomaly to 2°C as well as more aggressive policies. When modeling increasing rates, we consider exponential tax schedules following the same fossil-fuel price trajectories as Nordhaus's (2017) DICE model. Details in Wieners et al. (2022).

4.2 Command-and-control and innovation climate policies

Beyond carbon pricing, there are different climate policies focusing on quantities, regulation, innovation, nudging, social influence, information disclosure and mixed approaches (for example, Hepburn 2006; Peñasco et al. 2021). In Wieners et al. (2022), we tested a large ensemble of combinations, including subsidies to green power plant construction, R&D subsidies to low-carbon technologies, regulation banning of fossil-fuel power plants, and standards imposing electrification, as well as different forms of carbon taxation (see Table 3). This study complements the ecological macroeconomic assessments of policy combinations for the transition (for example, Mercure et al. 2018a; Dafermos/Nikolaidi 2019; Monasterolo/Raberto 2019; Rengs et al. 2020), offering a bottom-up perspective encompassing endogenous technical change in all sectors. The major focus was a multi-dimensional comparison of alternative schemes. Results show that command-and-control policies (with a grace period) forbidding fossil-fuel plant construction and the use of fossil fuel in the industry sector are effective in fostering investment in low-carbon technologies both in the energy and manufacturing sectors, thus triggering the green transition. Both policies are implemented as regulations establishing a ban to be enforced after a grace period of 25 years, with non-compliant firms being fined and forced to leave their respective markets.⁸ Public subsidies for green plant construction and green R&D further (i) accelerate the transition in the power sector, which is crucial to sustain the adoption of electrification-based solutions within industry, and (ii) sustain labor demand. Indeed, experiment $B + C + E$ (see Table 3) – which combines the fossil-fuel ban, public construction subsidies, and electrification standards – shows a strong potential for emission growth reduction while increasing growth and maintaining macrofinancial stability, though affecting public deficit. However, the overall cost induced by non-tax-based policies on the public budget is low (estimated around 1.5 percent (0.5–3 percent) of GDP per year in a prototypical developed country). Nonetheless, a small carbon tax can be added to the policy mix to further speed up the transition and neutralize its impact on the public budget (experiment $B + C + E + T$). Numerical simulations suggest that a constant carbon tax until 2100 can provide revenues to finance the innovation and green plant construction policies that are crucial in the early phase of the transition, while being sufficiently low as not to induce significant transition costs at the macroeconomic level.

Though policy combinations display sizable synergic effects, stand-alone implementation of single instruments reveals in their relative drawbacks, as also emphasized in Mercure et al. (2014) and Dafermos/Nikolaidi (2019). Regulation and standards tend to be effective in their respective sector of application, without significant spillover effects elsewhere in the economy. In such a framework, the length of the grace period granted to firms before policy is enforced has a relevant role: shorter (yet not too short) grace periods may increase financial stability, whereas longer ones are less effective. The effectiveness of regulation in the DSK model stems from its impact on the process of technological change, and not on relative prices, as in van den Bergh et al. (2021).⁹ Subsidies in the power sector stimulate investment – hence aggregate demand – during the transition, though their impact turned out to be negative on the public budget and only moderately

8. We assume that firms believe the policy announcement and adaptively strive to comply with the regulation; in particular, for what concerns the electrification regulation, firms are assumed to invest in R&D in the attempt to phase out the use of fossil fuel by the end of the grace period. The length of the grace period is the authors' preferred option after an extensive simulation exercise studying the effectiveness and side effects of different durations.

9. See also Lamperti et al. (2020b) for a comparison of price- vs quantity-based climate policy in a model of directed technical change.

successful at reducing emissions, in line with the results in Monasterolo/Raberto (2018), Dafermos/Nikolaïdi (2019), and Lamperti et al. (2020a).

To sum up, these results indicate that the best policy strategy to decarbonize an advanced fossil-fuel economy employ a set of regulatory interventions coupled with active and targeted innovation policy and very mild carbon pricing. Though policy instruments' interactions can make climate policy design a complex task (van den Bergh et al. 2021), we obtain a relatively simple and clear-cut prescription. Further, our evidence shows that there is no trade-off between rapid decarbonization and economic growth outlooks. On the contrary, coupling regulation with subsidies for green energy plant construction and a mild carbon tax mitigates transition frictions, neutralizes the adverse effects on public budgets, and stimulates employment growth during the energy transition, thereby delivering a win-win-win policy package. Indeed, our results corroborate the idea that one policy alone is not sufficient, does not perform the hard task of achieving the Paris Agreement target, and – by contrast – reinforces the literature insisting on policy combinations (for example, Mercure et al. 2018a).

4.3 Appropriate climate finance policies work

Following up the seminal speech by the ex-governor of the Bank of England – Mark Carney (2015) – scholars and policymakers have recently envisaged an active role of financial institutions and regulators in shaping both (i) climate risk-management (Campiglio et al. 2018; Battiston/Monasterolo 2020; Monasterolo 2020), and (ii) the transition to low-carbon technologies and production (Campiglio 2016; Monasterolo/Raberto 2018; D'Orazio/Popoyan 2019; Lamperti et al. 2019c; 2019d). However, the contribution of financial regulators and actors to the fight against climate change is still unclear. In Lamperti et al. (2021), we provide a novel perspective studying the impact of three new green financial policies, namely (i) *green Basel-type* capital requirements, (ii) *green credit guarantees*, and (iii) *carbon-risk adjustment* in credit ratings.

A green Basel II policy scheme excludes loans to green firms from banks' capital requirements regulation, thus relaxing the credit constraints of the former. More precisely, the macroprudential framework defines the total supply of credit, which is allocated to both green and brown firms on a pecking-order basis. Green credit easing is a form of public credit guarantee where the government 'backs' loans to green firms, thereby favoring financing of green projects (see Choi/Levchenko 2021 for a similar policy scheme, though directed towards a different industry). Finally, carbon-risk adjustment forces firms to disclose their level of emissions intensity together with their balance-sheet information (see, for example, Ameli et al. 2020), and we assume that such information is immediately observed by banks, which in turn use it in their credit rankings.¹⁰

Simulation results show that each of these policies is ineffective taken alone, as they either hamper growth, increase financial instability, or raise emissions growth. However, a policy mix comprising all of them solves the trade-offs, allowing the economy to enter a virtuous cycle. In short, while green Basel-type requirements spur growth by increasing credit supply and relaxing credit constraints, carbon risk adjustment and green (public) credit guarantee to deliver relevant emissions cuts in the industry sector, with the latter instrument also cushioning the fragility-enhancing effect induced by larger exposition to green yet possibly not sound firms. To conclude, simulation results point to the

10. In particular, we assume that banks rank firms on the basis of a composite indicator mixing credit risk and carbon risk; see Lamperti et al. (2021) for further details.

non-additivity of green financial policies. More generally, their role in achieving sustainable and resilient growth should be studied together with a more comprehensive policy package such as the one outlined in Wieners et al. (2022). For instance, Dafermos/Nikolaïdi (2021) suggest that differentiated capital requirements are particularly effective when coupled with green fiscal policy.

5 DISCUSSION AND CONCLUSIONS

Research in climate economics has blossomed since the early 2010s. At the crossroad between social, economic, engineering, and physical and climate science, models have a particular relevance, as they need to credibly project current economies in alternative distant futures and develop robust strategies to trigger the green transition and avoid the worst climate outcomes. Notwithstanding the large progress that has been made, we believe that the currently leading generation of general-equilibrium, integrated-assessment models employed to guide the assessment of the economic consequences of climate change and of climate policy is flawed. To rise up to the challenge, robust empirical evidence should be embedded in modeling frameworks capable of jointly capturing three elements: (i) mitigation dynamics, broadly representable by the evolution of the energy mix and the use of fossil fuels in the various parts of the economy; (ii) different climate policy schemes, possibly working through prices and quantities as well as social influence and behavioral factors; and (iii) the trade-offs emerging from realistic features of economic behavior, such as information asymmetries, financial constraints, and boundedly rational expectations, just to cite a few. In our view, the current state of the art in climate-economy modeling is not able to manage all these elements together.

Agent-based integrated-assessment models constitutes a promising route of research to jointly account for such open issues, as shown by the results produced by the so-called Dystopian Schumpeter meeting Keynes model (DSK; Lamperti et al. 2018a; 2019a; 2020a; 2021). The model is a simulation laboratory running at global scale comprising a manufacturing sector, an energy industry, a credit market, and a climate box. The model takes into account the continuous interactions between the economy and the climate and their co-evolution. The DSK is able to reproduce a rich ensemble of micro and macro empirical regularities and it is designed to run counter-factual experiments against a 'benchmark' scenario, which is typically a fictitious future with history-like growth properties and no climate impacts. As such, results should be always interpreted in deviation from the benchmark. The DSK model offers an evolutionary-inspired out-of-equilibrium alternative to the standard cost-benefit assessment of climate impacts, which boils down to the concept of optimal carbon taxation and, by contrast, allows the testing of a variety of climate, fiscal, monetary, and macroprudential policy.

In a series of papers, we obtained four main results with the DSK model. First, Lamperti et al. (2018a) and Lamperti et al. (2019a) provided a microfoundation of the aggregate economic losses from uncontrolled climate change in line with the recent empirical literature (Burke et al. 2015; Kiley 2021). After passing endogenous tipping points, the magnitude and volatility of climate shocks sharply increased, persistently hampering growth and spurring volatility. Moreover, different microeconomic climate shocks impacted the economy through diverse channels. Second, Lamperti et al. (2019a) showed that climate damages can reverberate back to the financial sector, exacerbating financial instability and inducing a negative feedback loop to the real economy through the credit channel. As a consequence, the financial sector magnifies the economic cost of uncontrolled climate change. While macroprudential and credit policies can attenuate such an impact, their

scope is relatively limited and their non-trivial effects should be carefully assessed (Lamperti et al. 2021). This corroborates the evidence in Dietz et al. (2016), Dafermos et al. (2018), and Dafermos/Nikolaïdi (2021). Third, Lamperti et al. (2020a) found that climate damages interact with the likelihood and shape of the low-carbon transition: climate impacts that increase energy demand are likely to delay the shift to green energy, while shocks reducing output growth tend to ease it. Fourth, in Wieners et al. (2022), we found that carbon-pricing policies are not effective mitigation interventions as they introduce a binding trade-off between economic growth and the decarbonization of the economy. On the contrary, a policy mix grounded on command-and-control regulation and subsidies for investments and R&D in green energy technologies is able to put the economy on a win–win–win sustainable growth pathway.

Our simulation results show that DSK has the potential to unleash a new generation of assessment of climate-economy co-evolution, wherein economic behaviors are more realistic, real-financial interactions explicitly modeled, and climate policy more exhaustively investigated. In that it provides new mitigation policy scenarios where a fierce fight of climate change – captured by the +1.5°C limit – is reconciled with innovation-driven sustainable economic growth. Given this fresh start, several challenges remain to be solved, starting with a more detailed representation of the available mitigation technologies and adaptation options and sectors (see, for example, the prospective coupling with a land-use model, Coronese et al. 2022), a serious multi-country setting with multiple interactions, a better accounting of inequalities, and improved empirical validation techniques. This constitutes the rich research agenda for the next developments of the DSK model.

REFERENCES

- Acemoglu, D., Aghion, P., Bursztyn, L., Hemous, D. (2012): The environment and directed technological change, in: *American Economic Review*, 102(1), 131–166.
- Ameli, N., Drummond, P., Bisaro, A., Grubb, M., Chenet, H. (2020): Climate finance and disclosure for institutional investors: why transparency is not enough, in: *Climatic Change*, 160(4), 565–589.
- Attanasio, A., Pasini, A., Triacca, U. (2012): A contribution to attribution of recent global warming by out-of-sample Granger causality analysis, in: *Atmospheric Science Letters*, 13(1), 67–72.
- Auffhammer, M. (2018): Quantifying economic damages from climate change, in: *Journal of Economic Perspectives*, 32(4), 33–52.
- Ausloos, M., Miśkiewicz, J., Sanglier, M. (2004): The durations of recession and prosperity: does their distribution follow a power or an exponential law?, in: *Physica A: Statistical Mechanics and its Applications*, 339(3–4), 548–558.
- Balint, T., Lamperti, F., Mandel, A., Napolitano, M., Roventini, A., Sapio, A. (2017): Complexity and the economics of climate change: a survey and a look forward, in: *Ecological Economics*, 138, 252–265.
- Bartelsman, E.J., Doms, M. (2000): Understanding productivity: lessons from longitudinal micro-data, in: *Journal of Economic Literature*, 38(3), 569–594.
- Battiston, S., Monasterolo, I. (2020): Assessing forward-looking climate risks in financial portfolios: a science-based approach for investors and supervisors, in: Jun, M., Caldecott, B., Volz, U. (eds), *Case Studies of Environmental Risk Analysis Methodologies*, Paris: NGFS, 52–72.
- Battiston, S., Mandel, A., Monasterolo, I., Schütze, F., Visentin, G. (2017): A climate stress-test of the financial system, in: *Nature Climate Change*, 7(4), 283–288.
- Battiston, S., Dafermos, Y., Monasterolo, I. (2021): Climate risks and financial stability, in: *Journal of Financial Stability*, 54, No 100867.
- Bleda, M., Valente, M. (2009): Graded eco-labels: a demand-oriented approach to reduce pollution, in: *Technological Forecasting and Social Change*, 76(4), 512–524.

- Bosetti, V. (2021): Integrated assessment models for climate change, in: *Oxford Research Encyclopedia of Economics and Finance*, Oxford: Oxford University Press, URL: <https://oxfordre.com/economics/view/10.1093/acrefore/9780190625979.001.0001/acrefore-9780190625979-e-572> (accessed 14 September 2022).
- Bottazzi, G., Secchi, A. (2003): Common properties and sectoral specificities in the dynamics of US manufacturing companies, in: *Review of Industrial Organization*, 23(3–4), 217–232.
- Bottazzi, G., Secchi, A. (2006): Explaining the distribution of firm growth rates, in: *The RAND Journal of Economics*, 37(2), 235–256.
- Burke, M., Hsiang, S.M., Miguel, E. (2015): Global non-linear effect of temperature on economic production, in: *Nature*, 527(7577), 235–239.
- Burns, A.F., Mitchell, W.C. (1946): *Measuring Business Cycles*, Cambridge, MA: National Bureau of Economic Research.
- Campiglio, E. (2016): Beyond carbon pricing: the role of banking and monetary policy in financing the transition to a low-carbon economy, in: *Ecological Economics*, 121, 220–230.
- Campiglio, E., Dafermos, Y., Monnin, P., Ryan-Collins, J., Schotten, G., Tanaka, M. (2018): Climate change challenges for central banks and financial regulators, in: *Nature Climate Change*, 8(6), 462–468.
- Carleton, T.A., Hsiang, S.M. (2016): Social and economic impacts of climate, in: *Science*, 353(6304), No aad9837.
- Carney, M. (2015): Breaking the tragedy of the horizon: climate change and financial stability, Speech given at Lloyd's of London, 29 September, 220–230.
- Castaldi, C., Dosi, G. (2009): The patterns of output growth of firms and countries: scale invariances and scale specificities, in: *Empirical Economics*, 37(3), 475–495.
- Choi, J., Levchenko, A.A. (2021): The long-term effects of industrial policy, Technical Report, National Bureau of Economic Research.
- Ciola, E., Turco, E.M., Gurgone, A., Bazzana, D., Vergalli, S., Menoncin, F. (2022): Charging the macroeconomy with an energy sector: an agent-based model, Technical Report, FEEM Working Paper.
- Ciscar, J.-C. (2012): The impacts of climate change in Europe (the Peseta research project), in: *Climatic Change*, 112(1), 1–6.
- Ciscar, J.-C., Saveyn, B., Van Regemorter, D. (2012): Economic modelling of climate impacts: a partial review, in: *Review of Business and Economic Literature*, 57(2), 144–157.
- Coronese, M., Lamperti, F., Keller, K., Chiaromonte, F., Roventini, A. (2019): Evidence for sharp increase in the economic damages of extreme natural disasters, in: *Proceedings of the National Academy of Sciences*, 116(43), 21450–21455.
- Coronese, M., Occelli, M., Lamperti, F., Roventini, A. (2021): AgriLOVE: agriculture, land-use and technical change in an evolutionary, agent-based model, Laboratory of Economics and Management (LEM), Sant'Anna School of Advanced Studies, Pisa, Italy, No 2021/35.
- Dafermos, Y., Nikolaidi, M. (2019): Fiscal policy and ecological sustainability: a post-Keynesian perspective, in: Arestis, P., Sawyer, M. (eds), *Frontiers of Heterodox Macroeconomics: International Papers in Political Economy*, Cham, Switzerland: Palgrave Macmillan, 277–322.
- Dafermos, Y., Nikolaidi, M. (2021): How can green differentiated capital requirements affect climate risks? A dynamic macrofinancial analysis, in: *Journal of Financial Stability*, 54, No 100871.
- Dafermos, Y., Nikolaidi, M., Galanis, G. (2017): A stock–flow–fund ecological macroeconomic model, in: *Ecological Economics*, 131, 191–207.
- Dafermos, Y., Nikolaidi, M., Galanis, G. (2018): Climate change, financial stability and monetary policy, in: *Ecological Economics*, 152, 219–234.
- DeCanio, S.J., Watkins, W.E. (1998): Investment in energy efficiency: do the characteristics of firms matter?, in: *Review of Economics and Statistics*, 80(1), 95–107.
- Dietz, S., Bowen, A., Dixon, C., Gradwell, P. (2016): 'Climate value at risk' of global financial assets, in: *Nature Climate Change*, 6(7), 676–679.
- Di Guilmi, C., Gallegati, M., Ormerod, P. (2004): Scaling invariant distributions of firms' exit in OECD countries, in: *Physica A: Statistical Mechanics and its Applications*, 334(1–2), 267–273.
- Doda, B. (2014): Evidence on business cycles and emissions, in: *Journal of Macroeconomics*, 40, 214–227.

- Doms, M., Dunne, T. (1998): Capital adjustment patterns in manufacturing plants, in: *Review of Economic Dynamics*, 1(2), 409–429.
- D’Orazio, P., Popoyan, L. (2019): Fostering green investments and tackling climate-related financial risks: which role for macroprudential policies?, in: *Ecological Economics*, 160, 25–37.
- D’Orazio, P., Valente, M. (2019): The role of finance in environmental innovation diffusion: an evolutionary modeling approach, in: *Journal of Economic Behavior and Organization*, 162, 417–439.
- Dosi, G. (2007): Statistical regularities in the evolution of industries: a guide through some evidence and challenges for the theory, in: Malerba, F., Brusoni, S. (eds), *Perspectives on Innovation*, Cambridge, UK: Cambridge University Press, 1110–1121.
- Dosi, G., Roventini, A. (2019): More is different ... and complex! The case for agent-based macroeconomics, Technical Report, Laboratory of Economics and Management (LEM), Sant’Anna School of Advanced Studies.
- Dosi, G., Fagiolo, G., Roventini, A. (2010): Schumpeter meeting Keynes: a policy-friendly model of endogenous growth and business cycles, in: *Journal of Economic Dynamics and Control*, 34(9), 1748–1767.
- Dosi, G., Fagiolo, G., Napoletano, M., Roventini, A. (2013): Income distribution, credit and fiscal policies in an agent-based Keynesian model, in: *Journal of Economic Dynamics and Control*, 37(8), 1598–1625.
- Dosi, G., Fagiolo, G., Napoletano, M., Roventini, A., Treibich, T. (2015): Fiscal and monetary policies in complex evolving economies, in: *Journal of Economic Dynamics and Control*, 52, 166–189.
- Dosi, G., Napoletano, M., Roventini, A., Treibich, T. (2017): Micro and macro policies in the Keynes+Schumpeter evolutionary models, in: *Journal of Evolutionary Economics*, 27(1), 63–90.
- Dunz, N., Essenfelder, A.H., Mazzocchetti, A., Monasterolo, I., Raberto, M. (2021): Compounding COVID-19 and climate risks: the interplay of banks’ lending and government’s policy in the shock recovery, in: *Journal of Banking and Finance*, No 106306.
- Fagiolo, G., Roventini, A. (2012): Macroeconomic policy in DSGE and agent-based models, in: *Revue de l’OFCE*, (5), 67–116.
- Fagiolo, G., Roventini, A. (2017): Macroeconomic policy in DSGE and agent-based models redux: new developments and challenges ahead, in: *Journal of Artificial Societies and Social Simulation*, 20(1), doi:10.18564/jasss.3280.
- Fagiolo, G., Napoletano, M., Roventini, A. (2008): Are output growth-rate distributions fat-tailed? Some evidence from OECD countries, in: *Journal of Applied Econometrics*, 23(5), 639–669.
- Fagiolo, G., Guerini, M., Lamperti, F., Moneta, A., Roventini, A. (2019): Validation of agent-based models in economics and finance, in: Beisbart, C., Saam, N.J. (eds), *Computer Simulation Validation*, Cham, Switzerland: Springer, 763–787.
- Farmer, J.D., Hepburn, C., Mealy, P., Teytelboym, A. (2015): A third wave in the economics of climate change, in: *Environmental and Resource Economics*, 62(2), 329–357.
- Foos, D., Norden, L., Weber, M. (2010): Loan growth and riskiness of banks, in: *Journal of Banking and Finance*, 34(12), 2929–2940.
- Gatti, D.D., Fagiolo, G., Gallegati, M., Richiardi, M., Russo, A. (2018): *Agent-Based Models in Economics: A Toolkit*, Cambridge, UK: Cambridge University Press.
- Gourdel, R., Monasterolo, I., Dunz, N., Mazzocchetti, A., Parisi, L. (2021): Assessing the double materiality of climate risks in the EU economy and banking sector, SSRN: 3939895.
- Hafner, S., Anger-Kraavi, A., Monasterolo, I., Jones, A. (2020): Emergence of new economics energy transition models: a review, in: *Ecological Economics*, 177, No 106779.
- Hepburn, C. (2006): Regulation by prices, quantities, or both: a review of instrument choice, in: *Oxford Review of Economic Policy*, 22(2), 226–247.
- Hepburn, C., Stern, N., Stiglitz, J.E. (2020): ‘Carbon pricing’ special issue in the European Economic Review, in: *European Economic Review*, 127, No 103440.
- Hötte, K. (2020): How to accelerate green technology diffusion? Directed technological change in the presence of coevolving absorptive capacity, in: *Energy Economics*, 85, No 104565.
- IPCC (2021): Climate Change 2021: *The Physical Science Basis, Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S.L., Péan, C., Berger, S., Caud, N., Chen, Y., Goldfarb, L.,

- Gomis, M.I., Huang, M., Leitzell, K., Lonnoy, E., Matthews, J.B.R., Maycock, T.K., Waterfield, T., Yelekçi, O., Yu, R., Zhou, B. (eds), Cambridge, UK and New York: Cambridge University Press.
- Jaimovich, N., Floetotto, M. (2008): Firm dynamics, markup variations, and the business cycle, in: *Journal of Monetary Economics*, 55(7), 1238–1252.
- Kanzig, D.R. (2021): The unequal economic consequences of carbon pricing, SSRN: 3786030.
- Kiley, M.T. (2021): Growth at risk from climate change, Technical Report, Board of Governors of the Federal Reserve System (US).
- Kuznets, S.S., Murphy, J.T. (1966): *Modern Economic Growth: Rate, Structure, and Spread*, vol. 2, New Haven, CT: Yale University Press.
- Laeven, L., Valencia, F. (2012): Systemic banking crises database: an update, IMF Working Papers 12/163, International Monetary Fund.
- Lamperti, F. (2018a): Empirical validation of simulated models through the GSL-DIV: an illustrative application, in: *Journal of Economic Interaction and Coordination*, 13(1), 143–171.
- Lamperti, F. (2018b): An information theoretic criterion for empirical validation of simulation models, in: *Econometrics and Statistics*, 5, 83–106.
- Lamperti, F., Mattei, C.E. (2018): Going up and down: rethinking the empirics of growth in the developing and newly industrialized world, in: *Journal of Evolutionary Economics*, 28(4), 749–784.
- Lamperti, F., Dosi, G., Napoletano, M., Roventini, A., Sapio, A. (2018a): Faraway, so close: coupled climate and economic dynamics in an agent-based integrated assessment model, in: *Ecological Economics*, 150, 315–339.
- Lamperti, F., Roventini, A., Sani, A. (2018b): Agent-based model calibration using machine learning surrogates, in: *Journal of Economic Dynamics and Control*, 90, 366–389.
- Lamperti, F., Bosetti, V., Roventini, A., Tavoni, M. (2019a): The public costs of climate-induced financial instability, in: *Nature Climate Change*, 9(11), 829–833.
- Lamperti, F., Mandel, A., Napoletano, M., Sapio, A., Roventini, A., Balint, T., Khorenzhenko, I. (2019b): Towards agent-based integrated assessment models: examples, challenges, and future developments, in: *Regional Environmental Change*, 19(3), 747–762.
- Lamperti, F., Mazzucato, M., Roventini, A., Semieniuk, G. (2019c): The green transition: public policy, finance, and the role of the state, in: *Vierteljahrshefte zur Wirtschaftsforschung (Quarterly Journal of Economic Research)*, 88(2), 73–88.
- Lamperti, F., Monasterolo, I., Roventini, A. (2019d): Climate risks, economics and finance: insights from complex systems, in: Ulivi, L.U. (ed.), *The Systemic Turn in Human and Natural Sciences*, Cham, Switzerland: Springer, 97–119.
- Lamperti, F., Dosi, G., Napoletano, M., Roventini, A., Sapio, A. (2020a): Climate change and green transitions in an agent-based integrated assessment model, in: *Technological Forecasting and Social Change*, 153, No 119806.
- Lamperti, F., Napoletano, M., Roventini, A. (2020b): Green transitions and the prevention of environmental disasters: market-based vs. command-and-control policies, in: *Macroeconomic Dynamics*, 24(7), 1861–1880.
- Lamperti, F., Bosetti, V., Roventini, A., Tavoni, M., Treibich, T. (2021): Three green financial policies to address climate risks, in: *Journal of Financial Stability*, 54, No 100875.
- Leary, M.T. (2009): Bank loan supply, lender choice, and corporate capital structure, in: *The Journal of Finance*, 64(3), 1143–1185.
- Lin, C., Schmid, T., Weisbach, M.S. (2019): Climate change, operating flexibility and corporate investment decisions, Technical Report, National Bureau of Economic Research.
- Lown, C., Morgan, D.P. (2006): The credit cycle and the business cycle: new findings using the loan officer opinion survey, in: *Journal of Money, Credit and Banking*, 38(6), 1575–1597.
- Mendoza, E.G., Terrones, M.E. (2012): An anatomy of credit booms and their demise, Technical Report, National Bureau of Economic Research.
- Mercure, J.-F., Pollitt, H., Chewpreecha, U., Salas, P., Foley, A.M., Holden, P.B., Edwards, N.R. (2014): The dynamics of technology diffusion and the impacts of climate policy instruments in the decarbonisation of the global electricity sector, in: *Energy Policy*, 73, 686–700.
- Mercure, J.-F., Pollitt, H., Bassi, A.M., Viñuales, J.E., Edwards, N.R. (2016): Modelling complex systems of heterogeneous agents to better design sustainability transitions policy, in: *Global Environmental Change*, 37, 102–115.

- Mercure, J.-F., Pollitt, H., Edwards, N.R., Holden, P.B., Chewpreecha, U., Salas, P., Lam, A., Knobloch, F., Vinales, J.E. (2018a): Environmental impact assessment for climate change policy with the simulation-based integrated assessment model E3ME-FTT-GENIE, in: *Energy Strategy Reviews*, 20, 195–208.
- Mercure, J.-F., Pollitt, H., Vinales, J.E., Edwards, N.R., Holden, P.B., Chewpreecha, U., Salas, P., Sognaes, I., Lam, A., Knobloch, F. (2018b): Macroeconomic impact of stranded fossil fuel assets, in: *Nature Climate Change*, 8(7), 588–593.
- Mercure, J.-F., Sharpe, S., Vinales, J.E., Ives, M., Grubb, M., Lam, A., Drummond, P., Pollitt, H., Knobloch, F., Nijse, F.J. (2021): Risk-opportunity analysis for transformative policy design and appraisal, in: *Global Environmental Change*, 70, No 102359.
- Monasterolo, I. (2020): Climate change and the financial system, in: *Annual Review of Resource Economics*, 12, 299–320.
- Monasterolo, I., Raberto, M. (2018): The EIRIN flow-of-funds behavioural model of green fiscal policies and green sovereign bonds, in: *Ecological Economics*, 144, 228–243.
- Monasterolo, I., Raberto, M. (2019): The impact of phasing out fossil fuel subsidies on the low-carbon transition, in: *Energy Policy*, 124, 355–370.
- Moosa, I.A. (2000): Cyclical asymmetry in energy consumption and intensity: the Japanese experience, in: *OPEC Review*, 24(1), 53–59.
- Napolitano, M., Roventini, A., Sapio, S. (2006): Are business cycles all alike? A bandpass filter analysis of Italian and US cycles, in: *Rivista Italiana degli Economisti*, 1, 87–118.
- Nelson, R., Winter, S. (1982): *An Evolutionary Theory of Economic Change*, Cambridge, MA: Harvard University Press.
- NGFS (2019): NGFS First Comprehensive Report: a call for action – climate change as a source of financial risk.
- NGFS (2021): Scenarios in action: a progress report on global supervisory and central bank climate scenario exercises, Technical Report, Network for Greening the Financial System.
- Nordhaus, W. (2014): Estimates of the social cost of carbon: concepts and results from the DICE-2013R model and alternative approaches, in: *Journal of the Association of Environmental and Resource Economists*, 1(1/2), 273–312.
- Nordhaus, W.D. (2017): Revisiting the social cost of carbon, in: *Proceedings of the National Academy of Sciences*, 114(7), 1518–1523.
- Nordhaus, W. (2018): Evolution of modeling of the economics of global warming: changes in the DICE model, 1992–2017, in: *Climatic Change*, 148(4), 623–640.
- Nordhaus, W. (2019): Climate change: the ultimate challenge for economics, in: *American Economic Review*, 109(6), 1991–2014.
- Ozturk, I. (2010): A literature survey on energy–growth nexus, in: *Energy Policy*, 38, 340–349.
- Patt, A., Lilliestam, J. (2018): The case against carbon prices, in: *Joule*, 2(12), 2494–2498.
- Peattie, K. (2010): Green consumption: behavior and norms, in: *Annual Review of Environment and Resources*, 35, 195–228.
- Peñasco, C., Anadón, L.D., Verdolini, E. (2021): Systematic review of the outcomes and trade-offs of ten types of decarbonization policy instruments, in: *Nature Climate Change*, 11(3), 257–265.
- Peters, G.P., Marland, G., Le Quere, C., Boden, T., Canadell, J.G., Raupach, M.R. (2012): Rapid growth in CO₂ emissions after the 2008–2009 global financial crisis, in: *Nature Climate Change*, 2(1), 2–4.
- Petrick, S. (2013): Carbon efficiency, technology, and the role of innovation patterns: evidence from German plant-level microdata, Technical Report, Kiel Institute for the World Economy.
- Pezzey, J.C.V. (2019): Why the social cost of carbon will always be disputed, in: *Wiley Interdisciplinary Reviews*, 10(1), No e558, URL: <https://onlinelibrary.wiley.com/doi/pdf/10.1002/wcc.558>.
- Pindyck, R.S. (2013): Climate change policy: what do the models tell us?, in: *Journal of Economic Literature*, 51(3), 860–872.
- Ponta, L., Raberto, M., Teglio, A., Cincotti, S. (2018): An agent-based stock–flow consistent model of the sustainable transition in the energy sector, in: *Ecological Economics*, 145, 274–300.
- Reinhart, C.M., Rogoff, K.S. (2009): *This Time is Different: Eight Centuries of Financial Folly*, Princeton, NJ: Princeton University Press.

- Rengs, B., Scholz-Wäckerle, M., van den Bergh, J. (2020): Evolutionary macroeconomic assessment of employment and innovation impacts of climate policy packages, in: *Journal of Economic Behavior and Organization*, 169, 332–368.
- Rising, J.A., Taylor, C., Ives, M.C., Ward, R.E. (2022): Challenges and innovations in the economic evaluation of the risks of climate change, in: *Ecological Economics*, 197, No 107437.
- Rosenbloom, D., Markard, J., Geels, F.W., Fuenfschilling, L. (2020): Opinion: why carbon pricing is not sufficient to mitigate climate change – and how ‘sustainability transition policy’ can help, in: *Proceedings of the National Academy of Sciences*, 117(16), 8664–8668.
- Semieniuk, G., Campiglio, E., Mercure, J.-F., Volz, U., Edwards, N.R. (2021): Low-carbon transition risks for finance, in: *Wiley Interdisciplinary Reviews: Climate Change*, 12(1), No e678.
- Somanathan, E., Somanathan, R., Sudarshan, A., Tewari, M. (2021): The impact of temperature on productivity and labor supply: evidence from Indian manufacturing, in: *Journal of Political Economy*, 129(6), 1797–1827.
- Stanton, E.A., Ackerman, F., Kartha, S. (2009): Inside the integrated assessment models: four issues in climate economics, in: *Climate and Development*, 1(2), 166–184.
- Steffen, W., Richardson, K., Rockström, J., Cornell, S.E., Fetzer, I., Bennett, E.M., Biggs, R., Carpenter, S.R., De Vries, W., De Wit, C.A., Folke, C., Gerten, D., Heinke, J., Mace, G. M., Persson, L.M., Ramanathan, V., Reyersand, B., Sörlin, S. (2015): Planetary boundaries: guiding human development on a changing planet, in: *Science*, 347(6223), 1259855.
- Steffen, W., Rockström, J., Richardson, K., Lenton, T.M., Folke, C., Liverman, D., Summerhayes, C.P., Barnosky, A.D., Cornell, S.E., Crucifix, M., Donges, J.F., Fetzer, I., Lade, S.J., Scheffer, M., Winkelmann, R., Schellnhuber, H.J. (2018): Trajectories of the earth system in the anthropocene, in: *Proceedings of the National Academy of Sciences*, 115(33), 8252–8259.
- Sterman, J., Fiddaman, T., Franck, T., Jones, A., McCauley, S., Rice, P., Sawin, E., Siegel, L. (2012): Climate interactive: the c-roads climate policy model, in: *System Dynamics Review*, 28(3), 295–305.
- Stern, N. (2016): Current climate models are grossly misleading, in: *Nature*, 530(7591), 407–409.
- Stern, N., Stiglitz, J.E. (2021): The social cost of carbon, risk, distribution, market failures: an alternative approach, Working Paper No 28472, National Bureau of Economic Research.
- Stock, J.H., Watson, M.W. (1999): Business cycle fluctuations in US macroeconomic time series, in: Taylor, J.B., Woodford, M. (eds), *Handbook of Macroeconomics*, vol. 1, part A, Amsterdam: Elsevier, 3–64.
- Tol, R.S. (2002): Estimates of the damage costs of climate change, part 1: benchmark estimates, in: *Environmental and Resource Economics*, 21(1), 47–73.
- Tol, R.S. (2009): The economic effects of climate change, in: *Journal of Economic Perspectives*, 23(2), 29–51.
- Triacca, U. (2001): On the use of Granger causality to investigate the human influence on climate, in: *Theoretical and Applied Climatology*, 69(3–4), 137–138.
- Van den Bergh, J., Castro, J., Drews, S., Exadaktylos, F., Foramitti, J., Klein, F., Konc, T., Savin, I. (2021): Designing an effective climate-policy mix: accounting for instrument synergy, in: *Climate Policy*, 21(6), 745–764.
- Van der Ploeg, F. (2020): Macro-financial implications of climate change and the carbon transition, Presented at the Session ‘Implications of Fundamental Global Changes for Central Banks’ of the ECB Forum on Central Banking, 11–12 November.
- Wälde, K., Woitek, U. (2004): R&D expenditure in G7 countries and the implications for endogenous fluctuations and growth, in: *Economics Letters*, 82(1), 91–97.
- Weitzman, M.L. (2009): On modeling and interpreting the economics of catastrophic climate change, in: *The Review of Economics and Statistics*, 91(1), 1–19.
- Wieners, C., Lamperti, F., Buizza, R., Dosi, G., Roventini, A. (2022): Macroeconomic policies to stay below 2°C with sustainable growth, Technical Report, LEM Working Papers, forthcoming.
- Wright, I. (2005): The duration of recessions follows an exponential not a power law, in: *Physica A: Statistical Mechanics and its Applications*, 345(3), 608–610.
- Zarnowitz, V. (1985): Recent work on business cycles in historical perspective: a review of theories and evidence, in: *Journal of Economic Literature*, 23(2), 523–580.