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

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

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Abstract

Though climate physical and transition risks will likely affect socio-economic dynamics along any transition pathways, their unfolding is still poorly understood. This also affects the development of climate-change policies to achieve sustainable growth. In this paper, we 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. Our results suggest the emergence of tipping points wherein physical risks under unmitigated emissions 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. Our results show that carbon taxation is not the most suitable tool to achieve zero-emission growth given its huge economic costs. On the contrary, command-and-control regulation and innovation policies to foster green investments is the best policy mix to put the economy on a green growth pathway. Overall, our results contradict the standard tenets of cost-benefit climate economics and suggest the absence of any trade-off between decarbonization and growth.

JEL codes: C63, Q40, Q50, Q54

Keywords: climate policy, climate risks, macroeconomic dynamics, agent-based modelling.

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1 Introduction

The most recent IPCC report indicates that the impacts of a 2°C increase would be considerably more 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) 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. [...] roughly 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 degrees Celsius above the preindustrial 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., 2018, 2019, 2020, 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 heterogenous microeconomic climate impacts and the emergence of tipping points. Moreover, the model allows 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 and Roventini, 2017; Dosi and 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 series of heterogenous 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 three degrees - returns way higher economic risks than those of standard impact assessment literature (Nordhaus, 2017, 2018; Ciscar et al., 2012). The negative impacts of climate change is magnified by the financial system via firms bankruptcies possibly triggering banking crises (Lamperti et al., 2019, 2021). Our results provide evidence of a substantial lack of isomorphism between the effects of micro and macro level shocks, as it is typical of complex systems (Lamperti et al., 2018, 2020). Different types of shocks exert heterogeneous effects on output growth, 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 disorderled decarbonization (in line with Kanzig, 2021; Semieniuk et al., 2021; Mercure et al., 2018; Lamperti et al., 2019). However, the macro-financial 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 a 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 which put the economy on a sustainable green growth pathway. In such a scenario, mild carbon taxation can be introduce 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 modelling literature which is providing novel paradigms for the evaluation of climate impacts and climate policy, building on out-of-equilibrium dynamics and decentralized interactions (Balint et al., 2017; Lamperti et al., 2019; Hafner et al., 2020; Rising et al., 2022; Mercure et al., 2016) 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 respect, to DSK (Monasterolo and 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 macroeconometric structure with a system dynamics view of technological change (Mercure et al., 2018,?); 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 labour market dynamics (Hötte, 2020). D'Orazio and Valente (2019) used an 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 agent-based model studying energy shocks and induced fluctuations in a complex economic systems.[1]

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

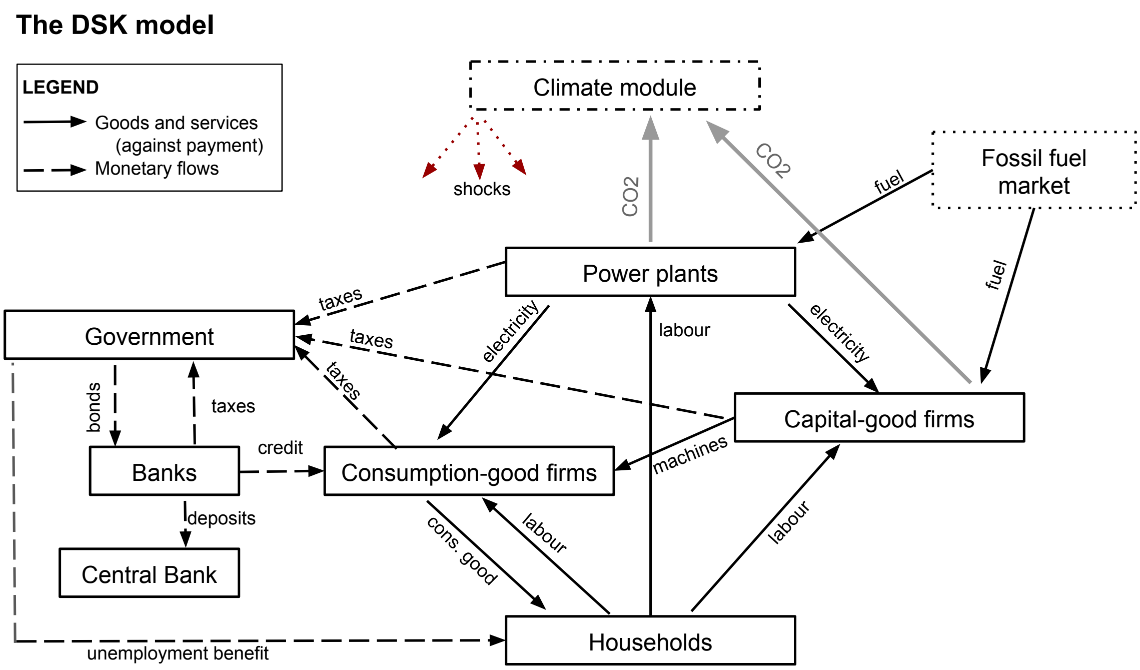
The *Dystopian Schumpeter meeting Keynes* (DSK) model couples an economy populated by heterogeneous, interacting firms and a climate model (see Figure 1). The economy and the climate are linked by multiple, non-linear feedbacks co-evolving over time. Production and energy generation lead to greenhouse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

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

climate change creating new technologies for firms and energy plants with different level of greenhouse gases emissions.

The economy builds on the K+S model (Dosi et al., 2010, 2013) and is composed by 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 innovate and to improve 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 own financial conditions, behavioural attitude and macroprudential regulations.

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



In the first version of the DSK model (Lamperti et al., 2018), innovation processes follow the K+S family (Dosi et al., 2017): technical coefficients - labour productivity, energy efficiency and carbon efficiency - randomly change as a consequence of successful firms' R&D investment. Wieners et al. (2022) introduces fossil fuels among the inputs available to capital-good firms which can choose how much to electrify their production. More precisely, inspired by Nelson and 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 (e.g., the US) or not (e.g., 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 boudedly-rational firms adapt to a constantly evolving environment through behavioural 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 lower competitiveness level shrink it. In the baseline configuration, firm competitiveness depends on unitary production costs and unfilled demand from customers Lamperti et al. (2018). Richer specifications are of course available. For instance, penalizing the competitiveness of carbon-intensive firms allows to assess the economy-wide effects of households' preferences for greener goods (i.e., goods with a lower environmental footprint; Bleda and 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 reduce (but never eradicate) their emissions. Investments in new energy plants are decided by the energy firm 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, then, the central authority ranks all orders and fix production on a merit-order basis, i.e. 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 markup over the marginal cost of the last activated plant. Investment in the energy sector can be associated to 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 life-time, 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., 2020).

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 (e.g. transports) follow the same relative changes that characterize the energy sector. The DSK models allows 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 temperature downward 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. On the contrary, in the DSK model, we employ a genuine bottom-up approach by modeling damages as micro shocks hitting workers' labor productivity, firms' energy efficiency, capital stock or inventories. To do so, 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 though 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:

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

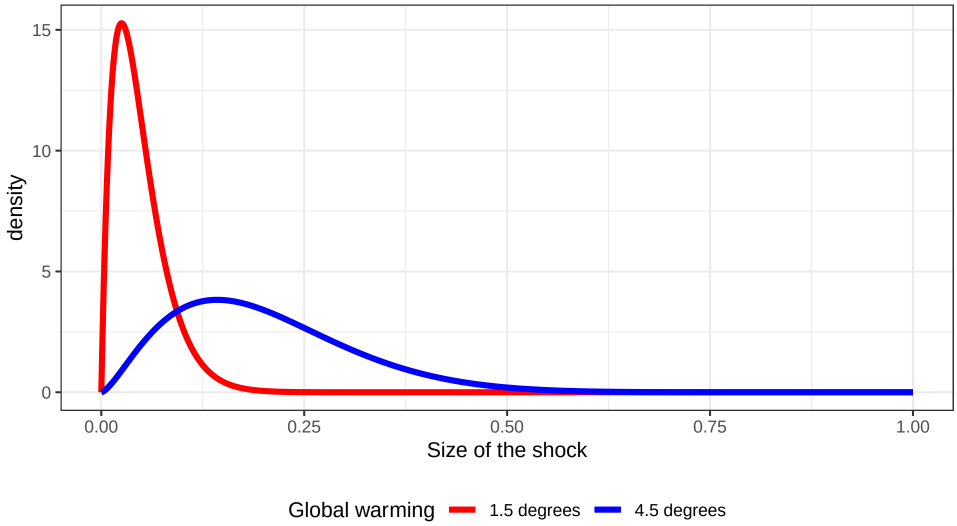
where $B(\cdot)$ is the Beta function and a, b are respectively the location and scale parameters. Both parameters are assumed to evolve across time reflecting changes in climate variables:

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

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

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 (e.g. DICE's quadratic damage function or Weitzman's sextic polynomial; see Nordhaus, 2017 and Weitzman, 2009). 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 labour, 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 counterfactual value of i's labour productivity in absence of the climate damage 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.

Calibration, validation and replication of stylized facts. As in every agent-based model,[2] the properties of the DSK have to be analyzed via extensive computer simulations. Indeed, DSK model is usually calibrated targeting a set of modern economies' properties (or moments) that a macro-financial 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 cycles 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 analyzed 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' value and initial conditions.

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

Table 1: Main empirical stylized facts replicated by the DSK model.

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

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 cycles frequencies output, investment and consumption series display the familiar "roller-coaster" dynamics. In line with the empirical evidence, consumption is less volatile than GDP, while the fluctuation 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 co-integrating 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 are strongly correlated across down-swings and, to a lower extent, upswings. At the microeconomic level, in line with the empirical literature (see e.g., Dosi, 2007), firms and energy plants display persistent heterogeneity in terms of productivity differentials, energy and carbon efficiency, which hints to a genuine representation of heterogeneity within the DSK model. Overall, 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] The interested reader finds additional details and a battery of co-integration tests in Lamperti et al. (2018).

3 Revisiting the economic consequences of global warming

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 macro-financial 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 (i.e. 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 high temperature anomaly (+4.5 degrees in 2100) and no climate policy (akin to RCP 8.5), Lamperti et al. (2018) 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., 2019, 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). Labour productivity shocks are way more damaging than those to either capital stocks, which mainly mirrors increased weather extremes and natural disasters or energy efficiency. In particular, labour productivity impacts considerably dampen the long-run growth of the economy by weakening the Schumpeterian innovation engine. Differently, damages targeting firms' stock of machines increase the volatility of the business cycles, which reflects in 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 it will be discussed in more details below, energy efficiency shocks annihilate the chances of observing a green transition towards sustainable growth.

Overall, the end-of-century value of global output produced by the DSK model in presence of

[4]This is well in tune with the vast majority of the macroeconomic agent based literature. See Fagiolo and Roventini (2012, 2017); Dosi and Roventini (2019); Gatti et al. (2018) 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% 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% and 90% of the energy mix.

[6]In both Lamperti et al. (2018) and Lamperti et al. (2019) the disaster generating function of the DSK model (see equations 1, 2, 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 (Somanathan et al., 2021, e.g.). However, the variance of the shocks is modelled 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. Authors' analysis based on data collected in Lamperti et al. (2018, 2019, 2020). Lab. Prod.: labour productivity; Cap. Stock: capital stock; Energy. Eff.: energy efficiency. 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).

	Climate shocks directly affecting:			
	Lab. Prod.	**Cap. Stock**	**Energy Eff.**	**Lab. Prod. and Cap. Stock**
DSK (2018)				
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
DSK (2019); multiple banks				
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
DSK (2020); endogenous low carbon transition				
Long-run growth	strongly reduced	-	mildly reduced	-
Likelihood of the transition	mildly increased	-	strongly reduced	-
Speed of the transition	mildly reduced	-	strongly reduced	-

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% and 84% of what would have been without climate change. This shows that micro-level heterogenous climate shocks on levels translates in severe macroeconomic impacts on growth dynamics. Our results are in line with a growing body of empirical evidences pointing to large adverse effects of temperature and precipitation variations on GDP and consumption growth (e.g. Burke et al., 2015; Auffhammer, 2018; Carleton and Hsiang, 2016) and, by contrast, contradict the impact assessment literature grounded on computable general equilibrium models, which suggests minor effects of climate change on economic dynamics (e.g. Tol, 2009, 2002; 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 likely shift leftward and fatten the distribution of growth rates, especially for vulnerable economies.

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 (Battiston et al., 2021; Lamperti et al., 2019; Monasterolo, 2020a; van der Ploeg, 2020). Lamperti et al. (2019) studied in the DSK model how climate shocks to firms affect the banking sector, altering the solvency of financial institutions and, in turns, feed-back to public finances and the whole macro-economy (see Table 2). Results indicate that uncontrolled climate change will increase the frequency of banking crises substantially (+26-248%). Further, rescuing insolvent banks will cause an additional fiscal burden of approximately 5% to 15% of

GDP per year and an increase of public debt to GDP by a factor of approximately 2. 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 pass tipping points above 1.5 degrees: 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. (2019) suggest that around 20% of the growth slowdown induced by climate-related damages is attributable by the deterioration of banks' balance sheets provoked by firms' increased defaults on their debt obligations. While macro-prudential regulation is deemed as potentially useful to fight climate risks (Campiglio et al., 2018a; D'Orazio and Popoyan, 2019a), analyses with the DSK model suggests 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 the theoretical and the empirical grounds. The DSK model was not the sole 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 a 18.9% 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% to about 1.5% at the end of the 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 macro-financial stability. Such a stream of contributions effectively hint that leaving out the financial system from climate-economy integrated assessment 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.

The effects of climate impacts on the transition to sustainable growth. While the literature analyzing low carbon transitions and mitigation pathways is large and variegate, 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 (NGFS, 2021; Semieniuk et al., 2021; Monasterolo, 2020a). On the other, there is a long-lasting distance between studies of impact and mitigation assessment. However, recent empirical evidences 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. (2020), 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 presence of heterogenous 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 accelerates it. Both effects interact with the dynamics of energy demand and prices, which in turns affect the investment of energy firm 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 increases spending in R&D activities aimed at improving the efficiency of brown plants will create a vicious cycles 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 exerts on brown plants. By a similar token, shocks to labour productivity induce an increasingly sharp contraction in industrial production, wages and final demand (see also Lamperti et al., 2018, 2019, and Table 2). In presence of 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 stimulates 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 stronger 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 transformation being potentially high and systemic (van der Ploeg, 2020; Mercure et al., 2018; Battiston et al., 2017; Semieniuk et al., 2021). Indeed, policymakers increasingly emphasize the need of finding the right balance between a rapid transition, 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 (Stern and Stiglitz, 2021; NGFS, 2019), and the excessive reliance on policy instruments characterized by low political acceptability, such as carbon pricing, brings about concerns for the transition outlook (Patt and 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 other, Balint et al., 2017; Farmer et al., 2015; Stern, 2016; 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; differently, recognizing the complexity of economic behavior opens the doors to additional trade-offs, potential opportunities and richer policy schemes (e.g. Acemoglu et al., 2012; Lamperti et al., 2020; Stern and Stiglitz, 2021; Mercure et al., 2021).

Using the DSK model as a simulation laboratory, Lamperti et al. (2020, 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. (2020) 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 presence and in 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 inferring the influence of micro-level damages on the effectiveness of the

Table 3: **Macroeconomic consequences of different climate policies with respect to a business as usual (no policy) scenario.**. Authors' analysis based on data collected in Lamperti et al. (2020, 2021); Wieners et al. (2022). Fin. Stab. stands for financial stability; Red. for reduced; inc. for increased.; const. for constant and sub. for subsidy; in some simulations, Lamperti et al. (2020, 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.

	Emission growth		**Output growth**			
Policy	**Energy**	**Industry**	**Short-run**	**Long-run**	**Fin. Stab.**	**Deficit**
DSK (2020); endogenous low carbon transition						
fossil-fuel tax	mildly red.	-	inc.	mildly inc.	-	red.
feed-in tariff	mildly red.	-	inc.	mildly inc.	-	inc.
DSK (2021); multiple banks						
green Basel 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.
DSK (2022); industry electrification						
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.	midly 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

policy instrument. Contrarily, Wieners et al. (2022) engage in a systematic comparison of the climate policy schemes allowing to maintain global warming within the 2°C threshold, and evaluate the risks and opportunities of each policy combinations during the transition.

The fallacy of carbon taxation. Climate policy is too often associated only to 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 limited time, at least if not couple with other policy interventions (Hepburn et al., 2020). Hence, carbon pricing is often disregarded by policy makers (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 (e.g. Bosetti, 2021) or on the social cost of carbon (Nordhaus, 2017). Given the general equilibrium structure of traditional integrated assessment models, the risk to loose our understanding of the macro-financial 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 analyze 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 (e.g. DICE) or cost-effective IAMs (e.g. 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 both in the power and industry sectors. Indeed, we find that the relative likelihood of complying to the 2°C target relying only on carbon taxes below 100% 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 finds in line with recent evidence from a post-Keynesian ecological macroeconomic model, which Dafermos and Nikolaidi (2019) used to show how carbon taxation decrease firms' profitability and access to credit. While revenues recycling schemes directed towards either firms or household 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 e.g. Nordhaus, 2019, 2014) 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 on the century. This negative conclusions are related to the very functioning of the electricity market with merit order activation protocol (Lamperti et al., 2020). In such a market, carbon taxes increase costs of fossil-fuel plants, which in turns raise 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 though 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.

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 (e.g. 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 fossil fuel power plants, 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 (e.g. Mercure et al., 2018; Monasterolo and Raberto, 2019; Dafermos and Nikolaidi, 2019; Rengs et al., 2020), offering a bottom-up perspective encompassing endogenous technical change in all sectors. The major focus was a multi-

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

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 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 (i) sustain labour demand. Indeed, experiment B+C+E (see Table 3) - which combines fossil fuel ban, public construction subsidies and electrification standards - shows a strong potential for emission growth reduction while increasing growth and maintaining macro-financial stability, though affecting public deficit. However, the overall the cost induced by non-tax based policies on the public budget is low (estimated around between 1.5% [0.5%-3%] 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 not to induce significant transition costs at the macroeconomic level.

Though policy combinations display sizable synergic effects, stand-alone implementation of single instruments revels their relative drawbacks, as also emphasized in Mercure et al. (2014) and Dafermos and 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 being negative on the public budget and only moderately succesful at reducing emissions, in line with the results in Lamperti et al. (2020), Dafermos and Nikolaidi (2019) and Monasterolo and Raberto (2018).

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

[8]We assume that firms believe the policy announcement and adaptively strive to comply to 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 out of an extensive simulation exercise studying the effectiveness and side effects of different durations.

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

and very mild carbon pricing. Though policy instruments' intractions 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 plants construction and a mild carbon tax mitigates transition frictions, neutralizes the adverse effects on the public budget 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 difficulty fits the hard task of orderly achieving the Paris agreement target, and - by contrast - reinforce the literature insisting on policy combinations (e.g. Mercure et al., 2018).

Appropriate climate finance policies work. Following-up the seminal speech by the ex-governor of the Bank of England - Mark (Carney, 2015) - scholars and policy-makers have recently envisaged an active role of financial institutions and regulators in shaping both (i) climate risk-management (Campiglio et al., 2018b; Battiston and Monasterolo, 2020; Monasterolo, 2020b), and (ii) the transition to low-carbon technologies and production (Campiglio, 2016; D'Orazio and Popoyan, 2019b; Monasterolo and Raberto, 2018; Lamperti et al., 2019). 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 favouring financing of green projects (see Choi and Levchenko, 2021, for a similar policy scheme, though directed to a different industry). Finally, carbon-risk adjustment forces firms to disclose their level of emission intensity together with their balance-sheet information (see e.g. Ameli et al., 2020) and we assume that such information is immediately observed by banks, which in turn use it in their credit ranking.[10]

Simulation results show that each of these policies is not effective 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 deliver relevant emissions cuts in the industry sector,

[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.

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 points to the non additivity of green 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 and Nikolaidi (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 in the last decade. At the crossroad between social, economic, engineering, 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 worst climate outcomes. Notwithstanding large progresses have been made, we believe that the currently leading generation of general-equilibrium, integrated-assessment models currently employed to guide the assessment of the economic consequences of climate change and of climate policy is flawed. To raise up to the challenge, robust empirical evidences 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, 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, 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., 2018, 2019, 2020, 2021). The model is a simulation laboratory running at global scale comprising a manufacturing sector, an energy industry, a 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 counterfactual 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, allow testing a variety of climate, fiscal, monetary and macro-prudential policy.

In a series of papers, we obtained four main results with the DSK model. First, Lamperti et al. (2018) and Lamperti et al. (2019) provided a micro-foundation of the aggregate economic losses from uncontrolled climate change il 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 increase persistently hampering growth and spurring volatility. Moreover, different microeconomic climate shocks impact the economy through diverse channels. Second, Lamperti et al. (2019) showed that climate damages can reverberate 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 impact, their scope is relatively limited and their not trivial effects should be carefully assessed (Lamperti et al., 2021). This corroborates the evidence in Dietz et al. (2016) and Dafermos et al. (2018); Dafermos and Nikolaidi (2021). Third, Lamperti et al. (2020) 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 the 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, a serious multi-country setting with multiple interactions, a better accounting of inequalities and improved empirical validation techniques. This constitute the rich research agenda for the next developments of the DSK model.

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