The Coalition of Finance Ministers for Climate Action

Are carbon-pricing policies enough? A brief agent-based modeling assessment

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Introduction

Over the past two decades, carbon pricing has been the primary tool for policymakers to try to reduce greenhouse gas (GHG) emissions and accelerate the green energy transition (Santos, 2022). A critical assessment of its policy potential and limitations is essential for advancing to a low-carbon economy. Despite the growing governmental and academic attention given to climate change mitigation, engagement of the private sector in the green-energy transition remains insufficient, with global investments falling short of the required levels (Lamperti et al., 2019). In free-market economies, reducing GHG emissions is often a low priority for profit-driven entities, particularly as sustainable energy technologies have yet to match the economies of scale offered by fossil alternatives. Mobilizing institutions and businesses to accelerate the transition is indispensable for achieving global environmental objectives, such as those outlined in the Paris Agreement, which seeks to limit global temperature rise and mitigate its adverse effects.

The challenges in advancing the green-energy transition are also compounded by policymakers' limited understanding of the real-world impacts of their industrial and environmental policies. This is a knowledge gap caused largely by the structural limitations of current modeling frameworks. Traditional assessment models often rely on oversimplified assumptions that fail to capture the fundamental uncertainties of technological change, such as those inherent to the ongoing energy transition (Farmer et al., 2015). To more accurately evaluate the policy effects over long-term horizons and across economic and social dimensions, it is crucial to develop models that endogenously incorporate the inherent complexities. Modeling must move beyond unrealistic assumptions—like long-term equilibrium, incremental technological change, or perfect information—which often neglect critical factors such as agent heterogeneity, radical innovation, and bounded rationality. Even if these limitations are accepted as "reasonable simplifications", current models remain inadequate for addressing many pressing policy questions. Consequently, there is a growing need for a new generation of models capable of providing actionable insights, such as how to harness emerging technologies for spurring development, or to identify adequate policy mixes for decarbonizing while creating quality jobs.

This paper employs a data-driven, agent-based model (ABM), calibrated to replicate the long-term dynamics of the United States economy to evaluate these issues.

Agent-based models

ABMs have emerged as a relevant methodology for analyzing both micro and macroeconomic dynamics, offering modelers the flexibility to start from realistic assumptions and employ disaggregated data. The approach enables the statistical simulation of how relatively simple individual (micro) agents collectively generate the complex macroeconomic features of modern societies. A key strength of ABMs lies in their capacity to capture endogenous emergent phenomena—such as market structures, price formation, economic cycles, and diffusion of products and technologies—arising from individual interactions. ABMs are particularly effective in modeling the nonlinear and network aspects of long-term technological diffusion, making them well-suited for studying the green-energy transition, given its decentralized, systemic, and long-term nature (Shaifiei et al., 2012). The bottom-up dynamic is critical to the adoption of new technologies, such as renewable energy, which require timely and well-designed policies that effectively account for the microeconomic dimension to succeed.

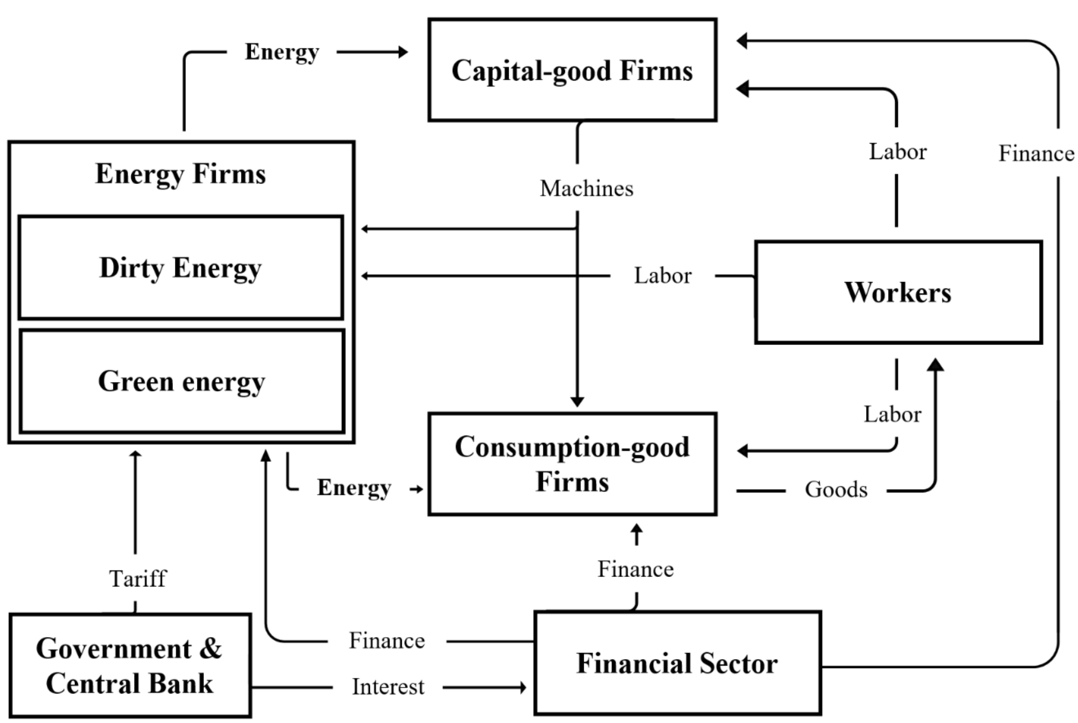
ABMs have been successfully used to analyze economic impacts of industrial policies, a feature largely missing in the current Integrated Assessment Models (IAMs) commonly used for evaluating energy transition policies (Bossetti et al., 2009). We argue that ABMs offer a valuable alternative to equilibrium-based approaches, enhancing the understanding of green-energy transition challenges, especially in developing countries where decarbonization is not the sole, or even the most urgent goal. Unlike Dynamic Stochastic General Equilibrium (DSGE) models, ABMs provide a bottom-up methodology with robust micro-foundations, grounded in realistic assumptions and empirical microeconomic evidence (Dosi and Roventini, 2019). This is crucial for modeling the development of new technologies, markets, and industries, which cannot be accurately represented as equilibrium systems, or precisely forecasted ex ante. A disequilibrium approach is better suited to capture the statistical probabilities—and uncertainties—of the structural changes involved in the transition to sustainable energy, particularly in emerging industries and economies. In a long-term analysis, precise forecasts are more often unrealistic; instead, under unpredictable structural change, complex systems theory suggests one should focus on the statistical probabilities of potential outcomes.

For policymakers and stakeholders, the ABM approach offers a probabilistic understanding of the possible future scenarios. While the exact opportunities and drawbacks of policies may remain uncertain, these models can help assess which policies are more likely to achieve desired outcomes and which may risk most significant failures. Traditional general equilibrium frameworks, by contrast, require policymakers to assign probabilities to (potentially unknown) outcomes ex ante, making decision-making less objective due to the wide range of possible scenarios to consider. Agent-based models invert this process, estimating policy risks and opportunities as outputs rather than inputs. Our research aims at developing ABMs as reliable, data-driven, and theoretically-sound platforms for analyzing climate change and the green-energy transition.

Our study

We employ the Keynes Meeting Schumpeter (K+S) micro-macroeconomic model (Dosi et al., 2010), calibrated with real U.S. data, to evaluate the medium- and long-term effects of carbon-pricing policies across the micro and the macroeconomic levels. The K+S model integrates Schumpeterian growth principles with a complex system of heterogeneous agents—firms, banks, and a government—combining supply- and demand-side dynamics. It captures Keynesian demand feedback loops across micro, meso (sectoral), and macro levels, reproducing endogenous growth, business cycles, and crises. The new model version includes an expanded, competitive energy sector with heterogeneous producers using different energy sources and emitting CO_2, based on micro-level decision rules (Lamperti et al., 2020). The model reproduces a wide range of macroeconomic (Dosi et al., 2015) and microeconomic stylized facts while ensuring full stock-flow consistency across all aggregation levels and time scales (Haldane and Turrell, 2019).

Figure 1. Interactions among agent categories in the energy-augmented K+S model

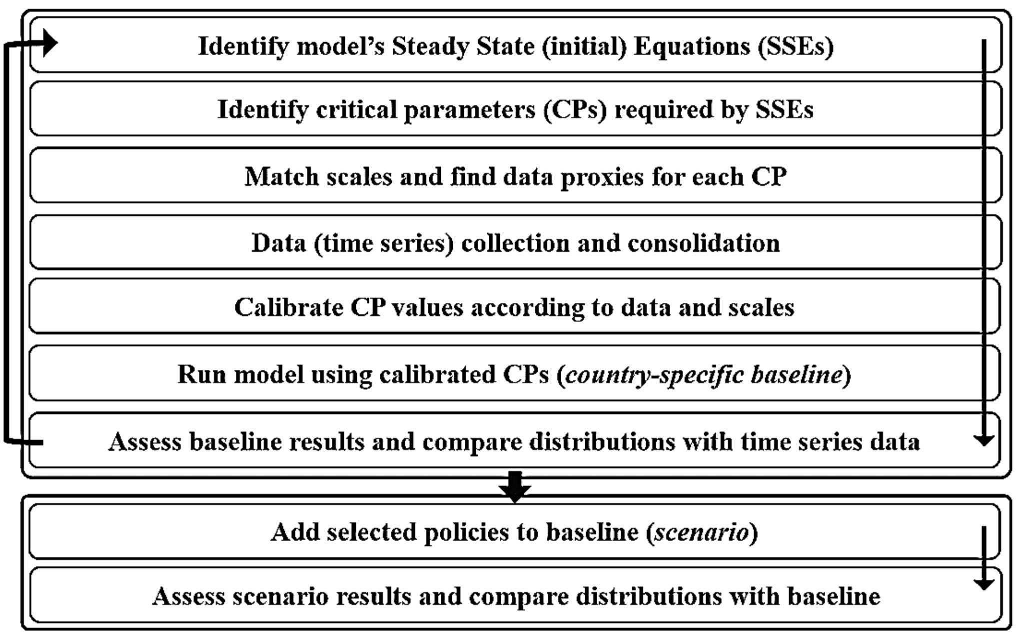


Source: Authors

The current version of the model represents a large, closed national economy organized as described in Figure 1. In it, capital-good firms invest in R&D to produce heterogeneous machines with evolving technology and productivity. Consumer-good firms apply machines and labor to produce goods for households. Both industrial sectors demand energy from suppliers in the energy sector who choose to operate based on fossil or sustainable sources, or a mix between the two. Banks finance firms' activities in the three sectors, while these hire or fire workers based on individual demand expectations. The central bank manages monetary policy, bails out failing banks, and enforces reserve requirements. The government taxes agents, pays unemployment benefits, sets a minimum wage, and maintains debt stability. CO_2 emissions from firms drive temperature changes, increasing the risk of climate shocks that may damage capital, destroy inventories, and reduce labor productivity.

The flexibility of the K+S model, as is characteristic of ABMs, allows a detailed calibration of the model parameters as well as an extensive validation of the results. This allows a robust representation of complex real-world economic systems such as industries or countries. Based on the literature (Dosi and Roventini, 2019; Fagiolo et al., 2019), which has advanced significantly in recent years, we employ a calibration strategy following the procedure outlined in Figure 2.

Figure 2. Protocol for calibration and validation of the energy-augmented K+S model



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The K+S model operates in discrete time (quarters), starting from a reference condition defined by the values for endogenous variables using steady-state equations (SSEs) and critical parameters (CPs). SSEs are used to set variable initial values to an unperturbed state at the beginning of the simulation ($t = 1$) from available micro and macroeconomic data. CPs are model parameters for which reasonably different values—mostly derived from empirical data—may lead to significant changes to the relevant model outputs. Thus, SSEs and CPs are the main instruments for applying empirical data to calibrate the model.

A set of CPs is identified from data and scaled down, as ABMs typically model only a fraction of the real-world agents because of computational constraints.[1] ABMs are designed to simulate predefined time horizons and the resulting time series are compared with empirical ones to ensure accurate parameter and initial condition calibration, by means of the iterative process depicted in Figure 2. After calibration, the model is simulated in a Monte Carlo experiment, with results undergoing output

[1] In cases where direct calibration (using real data) is impossible, indirect calibration is possible, as seen in Guerini and Moneta (2017). Parameter value adjustments are carried out as described in Grazzini et al. (2017) and Pangallo et al. (2024a; 2024b).

validation (Fagiolo et al., 2019). In this step, the aggregated and disaggregated properties of the model are contrasted with the empirical evidence. Finally, the model is assessed based on its ability to reproduce more qualitative stylized facts at each level of analysis (Haldane and Turrell, 2019).

To model the U.S. economy on the selected scale, 23 steady-state equations (SSEs) were identified, involving 48 initial parameters, 34 being calibrated using data from 1988 onward. The model performance was validated against real-world data from 2020. This enabled medium- and long-term projections, along with probability distributions, over 200 periods (50 years, 2020–2070) in a Monte Carlo (MC) experiment with 100 observations. MC results are presented as the median trajectory and the corresponding mean distribution over this time span. The process was repeated for two scenarios: a no policy "business as usual" baseline, and a steep carbon tax policy.[2] While the K+S model produces extensive results, this paper focuses on comparing (distributions of) projected emissions, along with some key economic and environmental variables, between the two scenarios.

Figure 3. Median trajectories of CO_2 emissions (left), and CO_2 atmospheric concentration (right), in thousands of tons, on vertical axes; time (number of periods) on horizontal axes

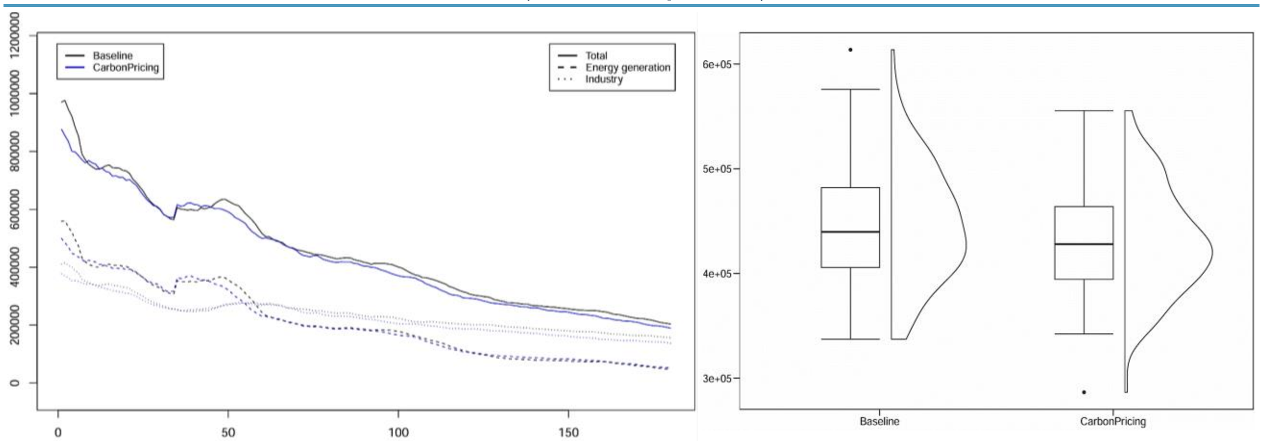

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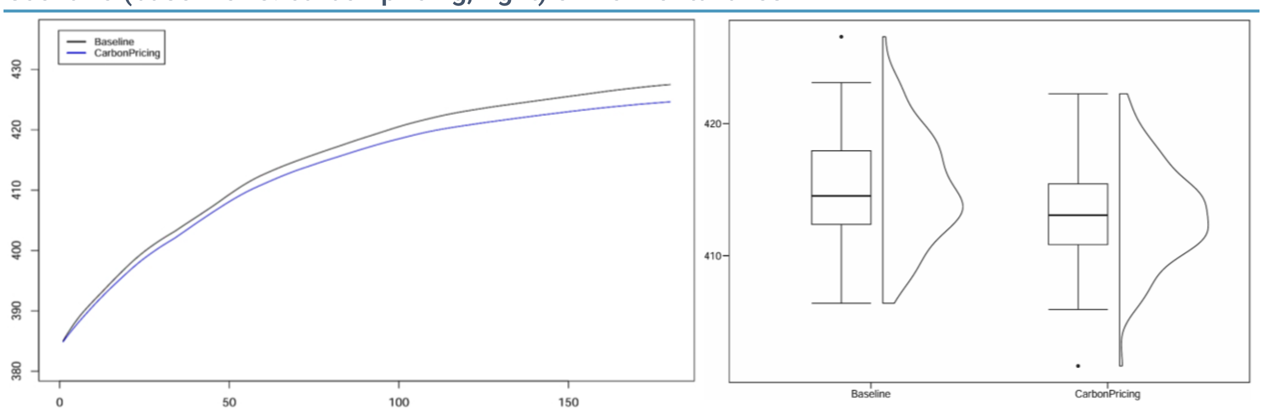
Figure 4. Median trajectories (left) and frequency distributions (right) of CO_2 atmospheric concentration, in parts per million (ppm), on vertical axes; time (number of periods, left) and policy scenario (baseline *vs*. carbon pricing, right) on horizontal axes



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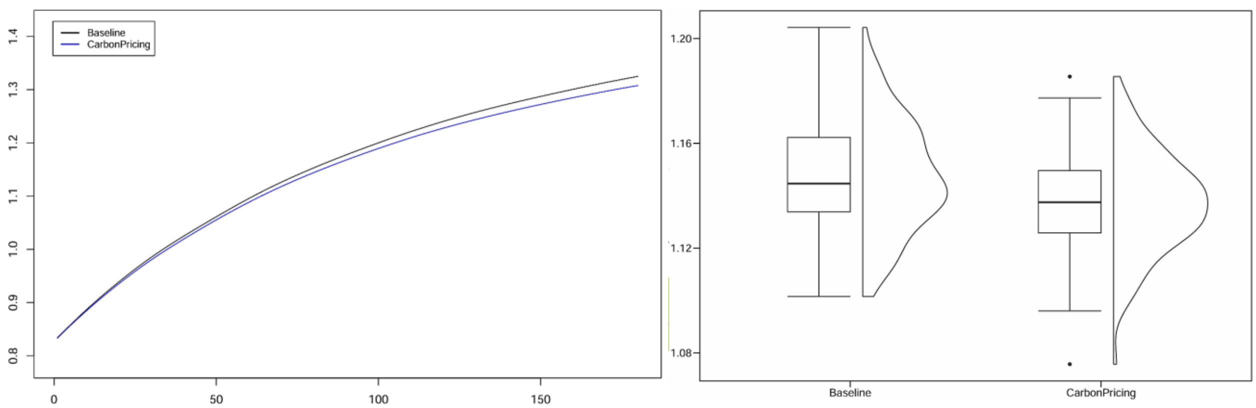
Figures 3 and 4 illustrate the ability of the K+S model to provide robust results not only in terms of the mean trajectories of variables over time but also in terms of probability distributions.[3] This allows the

2 Approximately US$168/ton in 2020, with a constant annual increase of 5%.

3 The time series plot depicts the MC median trajectory over time. The box plot represents the distribution quartiles, the median is indicated by the thick line, and outliers are represented by the dots. The two plots provide complementary perspectives on how the data are distributed within simulated "worlds".

model to indicate, rather than a single "exact" value, the most probable intervals for various phenomena and variables. Adopting the Paris Agreement (COP21) objectives as a reference—specifically, emission reduction targets and timelines—countries would need to reduce global emissions by 40–70% by 2050 to limit warming to 2°C. Considering the Nationally Determined Contributions (NDCs) of countries, the U.S. would need to reduce emissions by approximately 66% by 2035 compared with 2005 levels (United Nations Climate Change, 2019; Whiting, 2025). Our simulations indicate that even in a scenario with the widespread implementation of a progressively increasing steep carbon tax, emission reductions would more likely amount to about 34%. Not even in the most optimistic—and unlikely—case, does the NDC target seem achievable by the carbon pricing policies alone.

Figure 5. Median trajectories (left) and frequency distributions of temperature anomaly (right), in °C from preindustrial reference, on vertical axes. Time (left) and policy scenario (baseline vs. carbon pricing, right) on horizontal axes



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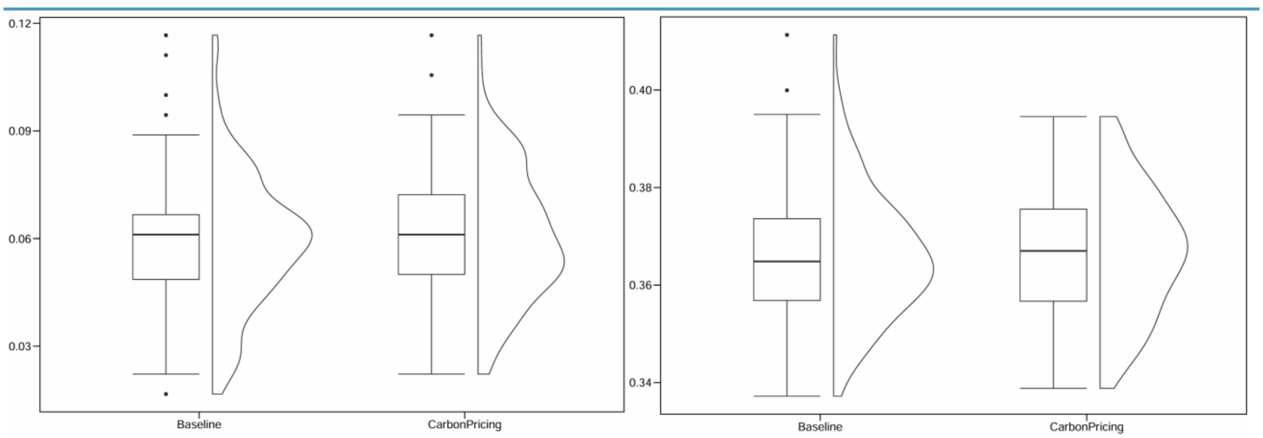
As a result of reduced CO_2 emissions and the consequent decline in atmospheric CO_2 concentration, Figure 5 indicates the trend for a smaller temperature increase in the carbon pricing scenario. This is led by the partial compensation of the reduced emissions because of higher long-term growth rates.[4]

Figure 6. Frequency distributions of the share of innovating firms in the energy sector (left) and in the capital-good sector (right) on vertical axes. Policy scenario (baseline vs. carbon pricing) on horizontal axes



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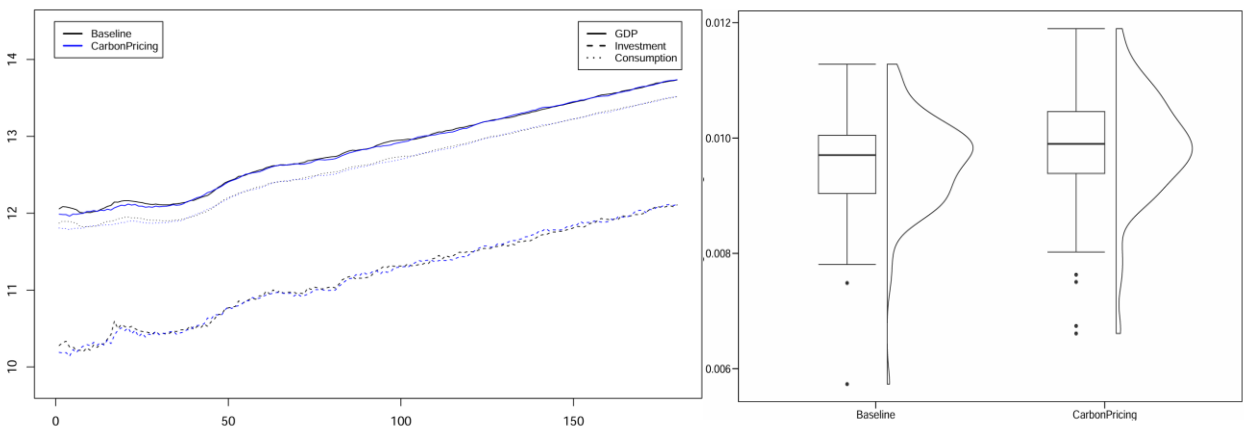
4 The energy-augmented K+S model keeps track of the temperatures rising, which may cause economic shocks by destroying capital and product inventories or decreasing worker productivity. To privilege the analysis of the strictly economic effects of the carbon-pricing policy, in the current report the climate feedback loop is disabled. The temperature rising effect will be introduced in a subsequent report. However, as expected, such inclusion further differentiates the positive macroeconomic impacts of the policy, even if the total emissions profile does not change significantly.

The environmental and macroeconomic benefits of the carbon pricing policy implemented in the model stem from individual and microeconomic decisions. The difference between results is subtle, yet statistically significant and economically relevant, as the increased adoption of green energy technologies by the energy producers and the higher rate of capital machine innovation spill over across the entire economy. As seen in Figure 6, although the medians of carbon-price innovation frequencies are only marginally higher in both cases, the data distribution reveals a greater concentration at higher probability of innovations, with signs of a rising bimodality—that is, the emergence of runs in which a new group of firms engage in significantly higher levels of innovation following the incentives. In the case of the energy sector, the carbon pricing scenario has a heavier upper tail and fewer outlier runs, indicating that "innovating more" is a more widespread and less occasional behavior of energy producers than in the baseline. A similar interpretation can be drawn for the capital goods sector, which shows a distribution with wider support and heavier lower tail in the baseline case.

Figure 7. Median trajectories of real GDP, investment and consumption (left), in log nominal currency on vertical axis and time on horizontal axis. Frequency distributions of real GDP growth rates (log, right) on vertical axis and policy scenario (baseline vs. carbon pricing) on horizontal axis



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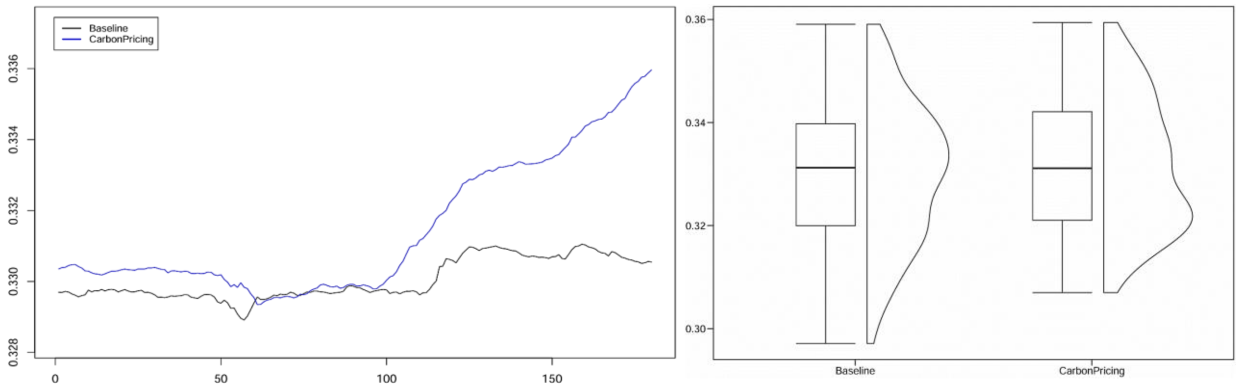
In the K+S model, higher innovation rates–driven by intensified innovative efforts resulting from increased capital-good sales–lead to higher and more stable long-term macroeconomic growth rates. This, in turn, reinforces the demand for better machines and spurs innovative efforts, as illustrated in Figure 7. The feedback loop, arising from the actions of individual firms and their interaction with the macroeconomic dimension, is absent in traditional modeling approaches. These approaches typically impose exogeneity on the macroeconomic structure and do not allow for endogenous non-obvious macro feedback, such as the carbon tax policy spillovers to capital-good innovation and consumption-good productivity.

Figure 8. Median trajectories (left) and distributions of frequency (right) of the thermal efficiency of fossil energy generation on vertical axes. Time (left) and policy scenario (baseline vs. carbon pricing, right) on horizontal axes



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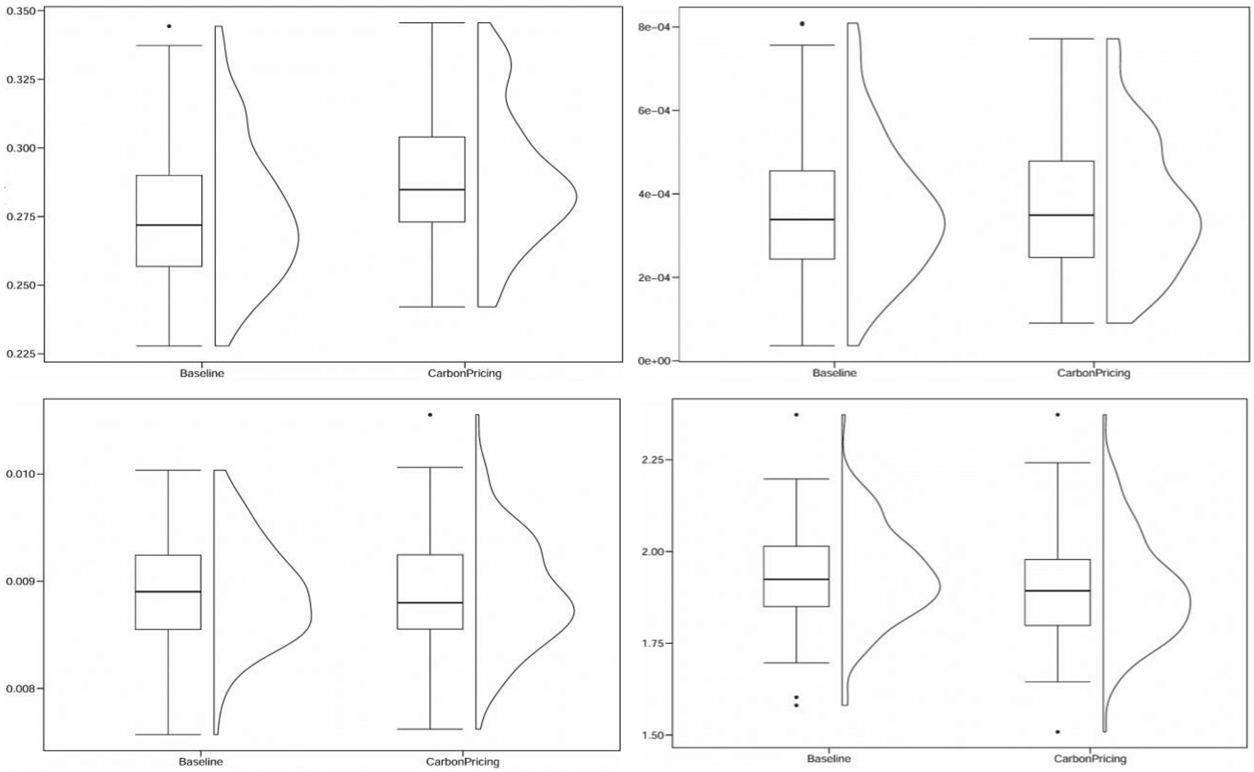
Additionally, as expected from an emission-penalizing policy, the deeper search for innovations in both the energy and the industrial sectors, plus the increased competitiveness of green sources lead to higher thermal efficiency of fossil fuel power plants (Figure 8). This effect supports the relative reduction of fuel consumption relative to the GDP growth, a known efficiency effect that, here, is produced endogenously, and not assumed ex ante. To conclude, the ABM analysis indicates that a carbon pricing policy, even if substantial, is unlikely to reduce emissions at a pace consistent with the required environmental goals. Nevertheless, the policy has significant and negative impacts on CO_2 emissions, both in the short and long term.

In summary, an incentive such as a carbon tax is unlikely to push economic agents to substantially change behavior or increase their innovative efforts in the long run. This seems true even for an increasing and substantial tax rate. However, it may raise the likelihood that agents reorganize technological strategies, whether through the development, acquisition, or use of newer clean machinery. Given this is one of the main channels which policy may act upon, focused policies directed on stimulating this behavior are probably more desirable and effective when compared with broader, "heavy-handed" policies like a carbon tax. This level of understanding is an example of how the micro-level distributional analysis, made possible by ABMs, may play a critical role in policy design and evaluation.

While the primary benefit of the tested policy lies in reducing emissions, it also significantly extends to other variables of importance to policymakers, such as a new government revenue source which can leverage further decarbonization policies such as subsidies for green technologies, retraining programs for displaced workers, or investments in the conversion of high-emission industries. By doing so, these funds can help offset adverse effects from a pure carbon tax policy on key macroeconomic variables. These can be observed in Figure 9 on employment, inflation, productivity, and real wages.[5] Again, we find distributions indicating a slightly increased likelihood, under the carbon pricing scenario, of runs with higher unemployment and inflation rates, and lower rates of productivity growth and real wages. This highlights the fact that such a policy will not produce only positive effects but may also lead to undesirable outcomes in key macroeconomic variables that are of great concern to policymakers. In this case, for instance, higher levels of innovation may generate technologies that require fewer workers, thereby increasing unemployment.[6] The higher level of economic activity, as seen in Figure 7, may result in increased price levels, reducing real wages that are already under pressure due to the weaker labor demand.

5 This model assumes a labor market that provides a uniform wage to all workers, in notional nominal currency units, for each worked time period. At the beginning of the simulation, the wage is equal to one.
6 "Unemployed" includes all the non-working population, which is different from usual measures of unemployment.

Figure 9. Distributions of frequency for unemployment rate (upper left), inflation rate (upper right) and labor productivity growth rate (per period, bottom left); real wages (log nominal currency per period, bottom right), on vertical axes. Policy scenario (baseline vs. carbon pricing) on horizontal axes



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In summary, environmental policies such as carbon pricing induce complex, intertwined structural changes across economic sectors. They drive broad and uneven macroeconomic impacts, possibly affecting employment, inflation, tax revenues, and public spending—all of which fall under the purview of Ministries of Finance. In this context, policymakers must move beyond concerns about fiscal neutrality and act strategically to ensure that monetary, fiscal, and budgetary instruments are aligned with long-term decarbonization and development objectives. However, just focusing on the usual macro-level policies may be insufficient. Deeper, more focused micro incentives to release agents from established technological lock-ins seem equally relevant. Without such integrated economic micro-macro governance, the environmental transition risks becoming socially and economically unsustainable.

Models designed to support policy formulation should be capable of capturing not only environmental average impacts, but also the macro- and microeconomic distributional effects associated with a given intervention. These should be analyzed in terms of both the causal mechanisms and the probability of occurrence, thereby providing a more comprehensive and policy-relevant understanding of the economic system. It is relevant to say here that such effects in many cases can only be observed "at the margin", as despite similar expected (mean) effects, the probability distributions become more skewed toward the worse realizations. This probabilistic approach not only strengthens policymakers' awareness of possible unintended consequences, but also allows some socioeconomic challenges to be addressed, fostering a more balanced and sustainable transition to a low-carbon economy.[7]

7 This model employs a centralized labor market. The natural progression for its evolution is the implementation of a decentralized labor market, enabling the assessment of environmental policy effects on various aspects of employment and income.

Ensuring a fair and effective low-carbon transition requires ministries of finance (MoFs) anticipating economic and social asymmetries. Our simulations show that even well-designed environmental policies, such as carbon pricing, may generate significant adverse side effects, including higher unemployment, declining real wages, or sectoral disruptions. These effects, if left unaddressed, can undermine both the legitimacy and efficacy of the transition efforts. MoFs, therefore, play a pivotal role in designing and financing complementary interventions, such as targeted transfers, industrial reconversion programs, and retraining initiatives. Fortunately, this expanded focus is recently being considered in initiatives like the Ecological Transformation Plan led by the MoF of Brazil.

Conclusion

This paper has aimed to briefly demonstrate the advantages of the K+S ABM model over more traditional analytical approaches. We have outlined the model calibration possibilities, and the procedures adopted to adjust the model to the U.S. economy. The results of this effort, as presented above, extend beyond the usual "precise" (and certainly unlikely) trajectories, and enable the evaluation of a carbon-price policy based on its probabilistic results, consistent with the fundamental uncertainty of the real economy, and the unpredictability inherent in long-term analysis. Thus, we observe that this kind of policy, despite being clearly insufficient in terms of emissions reduction, can offer some more nuanced economic benefits when observed at different levels of aggregation. From the individual micro level to the country macro level, including the environmental impacts, a comprehensive integrated analysis is made possible by the ABM approach.

ABMs like the one presented here allow Ministries of Finance to assess the likelihood of multiple outcomes, identify unintended effects, and design integrated policy mixes that mitigate risks while amplifying benefits and reducing costs. For the policymaker, this means more accurately targeting fiscal incentives, identifying sectors at risk of job displacement and loss, or evaluating the inflationary effects of technological shocks. Due to their modular structure, ABMs can be enhanced at various levels, allowing Ministries of Finance to represent different sectors, countries, and institutional settings in a unified setup that can evolve over time. ABMs offer not just insights for a single case, but a scalable analytical infrastructure for policymaking across changing contexts. In this sense, we are currently expanding the research to also calibrate the model for a developing country (Brazil) and integrating multiple country profiles in a unified international ABM. With this we believe even more fruitful collaborations with Ministries of Finance will become possible.

We close by arguing that a deeper understanding of microeconomic coordination and policy incentives are critical for fully understanding their effects on the economic, social, and environmental levels. This knowledge is crucial for the design of effective policies that are able to accelerate the green transition to the required pace. Future research must expand the model's scope to include the economic-environmental feedback mechanism, a more heterogeneous industrial base, detailed labor markets, and multiple countries in a global set-up.

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