The Coalition of Finance Ministers for Climate Action

Macroeconomic modeling of climate change: the E3ME model

Cambridge Econometrics

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Introduction

Ministries of Finance across the globe are constantly evaluating the costs, benefits, and impacts of climate policies and regulation. Meanwhile, the choice of analytical tools is vast and will be underpinned by different economic theories and/or assumptions which could make them more or less suitable for a particular piece of analysis. Deciding which tool is most appropriate for which questions can therefore be a daunting task for financial policymakers. Questions might range from weighing up commitment to climate action against other uses of resources, to understanding the options of different policy packages for decarbonization. Financial policymakers will also need to consider in parallel any wider interventions to support economic and social transitions to deliver climate action, e.g., reskilling needs. Having a tool that covers several aspects of decision-making can help address this dilemma. The global macroeconomic simulation model E3ME and its family of related models designed to incorporate new thinking in economics are one example of suitable tools for evaluation of the economic costs and benefits of climate change and climate action.

Theoretical foundations for a family of nonequilibrium macro-sectoral models

Since the use of computer-based models started to become popular with the rise of the digital age at the start of the 21st century, research studies have compared, contrasted, and explained different groups of models in an attempt to make their use and results more accessible and fit-for-purpose. (Souffron and Jacques, 2024; US Council of Economic Advisers, 2023; Sognnaes et al., 2021). It remains an important area of ongoing research and communication. In recent years, the breadth and complexity of macro-sectoral models has expanded further. From the European Commission's GEM-E3 and E-QUEST general equilibrium models, to the GCAM and MESSAGE integrated assessment models, and nonequilibrium simulation models such as E3ME, the choice available to financial policymakers is unprecedented.

The primary challenge with all macroeconomic modeling is the several levels of depth that modelers and policymakers need to unpack in attempting to understand uncertainties, which are integral to the real world and not necessarily built into computer models. Some uncertainties are well known and common to many models, e.g., the use of historical relationships as a basis for projections into the future (Lucas, 1976), which will likely be less representative over time. However, there are numerous uncertainties arising from the underlying model design, theoretical framework, and related assumptions that are more nuanced, and there is a greater risk of misinterpretation when communicating the modeling outputs. In the context of climate change, understanding the uncertainties specific to the chosen modeling approach is critical and highly consequential. Policy decisions taken today on climate change mitigation and adaptation will create path dependencies for future environmental outcomes. There are already several dimensions to policy design that need to be considered from the outset, whether geographic, temporal, or thematic. It could be argued that a broad understanding of different macroeconomic modeling approaches is an additional but necessary complexity for policymakers to understand if these approaches are used to build an evidence base for decision-making.

E3ME is a nonequilibrium macroeconometric model. The design principles of E3ME are that it is based on real-world data and real-world representation of human behavior. The model was co-developed by Professor Terry Barker in the 1990s and draws on the Cambridge tradition of post-Keynesian macroeconomics, following in the footsteps of John Maynard Keynes and Nobel Memorial Prizewinner Richard Stone. E3ME's theoretical foundation can be traced back to the Treatise on Probability (Keynes, 1921) and the General Theory (Keynes, 1936), and the model has continued to be developed to suit the needs of researchers and policymakers through major historical events such as the 2008–2009 financial crisis and the UNFCCC conference COP15 in Copenhagen.

Post-Keynesian economics rejects the assumptions made in neoclassical economics that there is perfect competition, individuals act rationally, and markets always clear where demand matches supply (otherwise known as market equilibrium). For this reason, E3ME is often described as a nonequilibrium model. While neoclassical theories remain most useful for determining economically optimal pathways for achieving environmental targets, they traditionally exclude considerations of technical, psychological, and socio-political uncertainties around complex long-term climate issues and how people actually behave. Alternative theories of economics that do consider these uncertainties, including post-Keynesian economics, are therefore an important complement.

In E3ME simulations, there is uncertainty. This leads to outcomes seen in the real world, such as involuntary unemployment. Similarly, investment is not constrained by savings, and borrowing between periods is possible. The key implication is that under certain policy conditions, it is possible to implement energy and climate policies without taking resources away from elsewhere in the economy and negatively impacting growth (European Commission, 2017).

By comparison, most macroeconomic models used to answer the same questions E3ME addresses tend to be equilibrium models; these include computable general equilibrium (CGE) models, which are the most commonly used analytical tool for long-term energy-environment-economy (E3) analysis. While the two families of models share similar characteristics, such as the use of national accounts and sector-level resolution, their views of uncertainty differ vastly, which affects how their results can be interpreted. In a CGE model, climate mitigation action necessarily entails a deviation from the optimal path (before the benefit of such action is considered), which means such action implies a trade-off against economic costs. By contrast, in E3ME, the same intervention creates additional demand, which is made possible by deploying previously under-used resources such as the economically inactive population.

Mercure et al. (2016) describe four areas of uncertainty that contribute to "'policy indecisiveness"' (where interventions may be delayed or disregarded due to the complexity of setting them):

(1) The rate of technology diffusion
(2) Macroeconomic impacts of low-carbon policies
(3) The scale and channels of energy-environment-economy interactions
(4) Anticipation of policy outcomes.

The first three of these areas of uncertainty are embedded in the theoretical framework of E3ME.

Meanwhile, the fourth can be explored through scenario and sensitivity analysis in E3ME modeling studies. For example, labor and financial market frictions fall into this group and have been central to discussions around policies generally, and E3ME analysis specifically, in the EU (European Commission, 2024).

Practical use and accessibility

Since its original development under a research program funded by the European Commission, the ongoing upkeep and evolution of E3ME has been made possible through projects led by or co-developed with the team of model developers at Cambridge Econometrics, a global economics consultancy. The E3ME model is licensed to research institutions, Government departments and universities across the globe for public policy analysis. Active users of E3ME include the South African Treasury, the World Bank, and the United Nations Economic Commission for Latin America and the Caribbean (ECLAC), who carry out in-house modeling simulations. These groups of users interact with the model through a web-based graphical user interface, and Cambridge Econometrics maintains the model code and database using specialist programming languages such as Python.

Over time, models that share certain characteristics with E3ME have also been developed, including:

- The SAMM macro-sectoral model for the Maltese Ministry for Finance and Employment
- A state-level model for Thailand (E3-Thailand) in collaboration with the World Bank
- A state-level model for India (E3-India) in partnership with the Regulatory Assistance Project (RAP)
- A state-level model for the United States (E3-US)

- The Framework for Modelling Economies and Sustainability (FRAMES), which was designed for data-scarce countries and first applied for fiscal reforms analysis in Bangladesh (The Ex'Tax Project, 2019).

Nevertheless, the E3ME model remains the most advanced within this family. It is both detailed and highly disaggregated. The structure of E3ME is based on systems of national accounts, with further linkages to energy demand and environmental emissions. All data is taken from national government or multilateral publications, such as those of the United Nations, International Labour Organization, and International Energy Agency. The labor market is also covered in detail, including both voluntary and involuntary unemployment.

In total, there are 33 sets of behavioral equations parameterized from an analysis of historical patterns using econometrics techniques. These equations cover household consumption, investment, international trade, prices, and energy demand, which span across several model dimensions (Cambridge Econometrics, 2022). These include:

- 71 global regions, including all G20 and EU Member States explicitly, plus a set of regions to meet global totals
- 43 economic sectors and 28 categories of household expenditure in each region, with additional detail in Europe
- Time series model output to 2050 on an annual basis
- 25 different users of 12 different fuel types.

The breadth of dimensions makes E3ME well-placed to explore the impacts of many different climate-related economic scenarios. The model runs produce a broad range of economic, energy and environment and societal indicators, which enables financially minded decision-makers to gain a comprehensive understanding of the impacts of different policy options and the trade-offs between them.

A final design feature of E3ME that supports macrofinancial decision-making is the link with Future Technology Transformation (FTT) sub-models. The FTT framework, introduced in 2013, revolutionized the treatment of technology development in E3ME by depicting technological progress using S-shaped diffusion curves with endogenous learning-by-doing effects, which are comparable with historical technology deployment trajectories (Mercure, 2012). This means the FTT models track the rate of deployment of each technology within a sector as part of the simulation; when a technology-specific policy is implemented, not only the deployment of that technology but also the whole system reacts. This notion, that scaled up deployment of new technologies leads to lower costs and allows innovators to respond to feedback by introducing improvements that further enhance their marketability and attractiveness, is important because it closely mimics how investors make decisions and the various stages of technological progress in real life (for example, the way in which the cost of solar and wind power generation have fallen in the past two decades).

FTT models exist for power generation, steel production, residential heating, and passenger car transportation sectors. They simulate the uptake of new technologies within sectors based on a combination of consumer demand, technology-specific costs and market conditions such as regulation, availability of financial support, and national and global deployment rates.

Taking the power generation sector as an example, the FTT-Power model covers 24 different types of power plants, covering:

- High-emissions technologies: coal, oil, and natural gas
- Commercially available low-emissions technologies: nuclear, solar photovoltaic (PV), concentrated solar, onshore wind, offshore wind, tidal, geothermal
- Emerging technologies: carbon capture and storage, solid biomass and biogas, combined heat and power (CHP) and hydrogen fuel cells

The FTT-Power model allows users to understand what mix of generation technologies would be deployed and the associated investment and electricity price implications of different combinations of subsidies, regulatory and innovation measures.

The unique features of E3ME, including the FTT sub-models, create an important basis for the design and implementation of quantitative analysis, as it allows a shift in scenario thinking from target setting, which is often formed only at the national or broad sector level, to incentive design, which requires an understanding of within-country, within-sector, and within-group behavioral patterns. This approach particularly resonates with the logical process of policymakers, whose task involves turning ambitions into human strategies and operational policy instruments.

Key policy/analytical questions

The type of research questions for which the model has been used to answer include

- Is climate action costly or inexpensive for the economy?
- To what extent can a carbon price policy reduce emissions? What are possible policy combinations, for example, with recycling of carbon revenues as financial support for low-carbon technologies, which could enhance the economic outcomes of such a policy?
- How are the price and income effects of switching from high-emissions to low-carbon technologies distributed across households, firms, and the Government?
- What sectors are likely exposed to major restructuring and job reallocation as a result of climate change, which may require Government support?
- Is it possible to reach net zero emissions without a certain technology (such as carbon capture and storage)?
- How would a change in the technology mix affect the cost of and demand for energy, particularly for households? Would this affect socio-economic groups differently?

Applications of E3ME and a policymaker's journey

Given the breadth and depth of E3ME's design, it has been widely used around the world at every stage of the policymaking process. Some key case studies are set out below.

Demonstrating a case for climate action

E3ME was one of the three macroeconomic models used by the European Commission Directorate-General for Climate Action to inform a landmark recommendation of the 90% emissions reduction target in the EU by 2040 (European Commission, 2024). Additionally, its analysis provided an evidence base for national governments to gain confidence and momentum in climate mitigation, such as modeling findings for India and Indonesia (Asia Society Policy Institute, 2022, 2023), which highlighted visible net benefits in GDP and employment terms from pursuing stronger decarbonization pathways.

E3ME has also been used to investigate the case for action in response to historical events such as the Covid-19 pandemic. Cambridge Econometrics collaborated with the United Nations Partnership for Action on Green Economy (PAGE) and used E3ME modeling to highlight positive effects on GDP, jobs, and emissions reductions in South Africa, where green policies strongly featured in the Government's economic reconstruction and recovery plan (Cambridge Econometrics, 2021).

Understanding the opportunities and trade-offs of different fiscal policy options and packages

E3ME can be used to explore a wide range of policy options, from environmental tax reforms to sector- and regional-specific financial support needs and global climate finance coordination.

For example, the International Renewable Energy Agency (IRENA) used E3ME analysis to evaluate policy packages that support the global transition to renewable energy sources. In addition to sectoral and economy-wide impacts, this research highlighted, at the national, regional, and global level, Government fiscal balances implications of an international climate fund much larger than current pledges for mitigating against negative social welfare impacts of a global energy transition in the Global South (IRENA, 2023).

In a study for the Italian Ministry of Economy and Finance and the European Commission, E3ME results were disaggregated into in-country regions to identify groups in society that may be more vulnerable to job displacement due to a green transition. This helped Italian policymakers to understand who might require social assistance to shift away from high carbon jobs, such as those in the refinery and chemicals industries in Sicilia, Puglia, and Lombardia (ICF et al., 2021).

Designing a well-balanced mix of financial and non-financial interventions.

Ultimately, the purpose of setting a course for action and exploring feasible policy options is to design suitable regulatory, market-based, and (re)distributive interventions, which all have financial implications and therefore are critical to 'MoFs' agendas. With innovation being explicitly represented in the model's behavioral responses, E3ME is capable of quantifying both economy-wide and sector-level investment needs for decarbonization. This analysis has been carried out for, e.g., Italy (ICF et al., 2021) and the United Kingdom (Cambridge Econometrics, 2020).

Furthermore, E3ME can be used to quantify potential damages from failing to meet the needs to transform and protect the economic system against climate change, e.g., through climate stress testing for the Central Bank of Hungary (Magyar Nemzeti Bank, 2021). Such damages may be tangible, in the form of output and job losses, or intangible, such as stranded assets and lower productivity, all of which are captured at least in parts of the existing E3ME structure.

Looking ahead

Recognizing the technical complexity that accompanies powerful models such as E3ME, ongoing efforts are focused on improving understanding of the approach and increasing accessibility for technically minded audiences. Annual E3ME summer schools and capacity-building activities are regularly attended by model users and stakeholders. Versions of the FTT models are publicly accessible (GitHub, 2024), as an example of future releases of similar standalone tool kits in the making.

As well as trying to make the models more accessible, there are plans to expand the range of insights they could produce. Recent developments have been focused on expanding FTT sub-models to more sectors and introducing new socio-economic dimensions such as inequality and skills indicators. A key priority for model development is to explicitly capture the presence of non-financial obstacles, such as skills shortages and finite material resources, and increase the resolution of fiscal balances and the financial sector. This will enable policy and decision-makers to use E3ME to address issues that are more complex and evolve over time, such as risks of stranded assets, opportunities for green fiscal reforms, climate-related costs of finance, and potential linkages between monetary and fiscal measures to manage the transition to net zero.

Among the plethora of options and in a world filled with uncertainty, E3ME, as a highly disaggregated and comprehensive model that links the economy, energy systems, the environment, and technologies together—a notable success in the family of post-Keynesian models—is a unique and versatile tool that invites MoFs to tap into at every step of their green finance journey.

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