Building a reduced-form macro-econometric model E3ME Lite for the evaluation of the multiple benefits of energy efficiency policy

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Executive Summary

This working paper describes the development of a reduced-form macro-econometric model, E3ME Lite, as part of the REFEREE Policy Assessment Tool. The E3ME Lite model was designed to complement and link with other models and calculations in the tool, which ultimately link together to provide a simulation tool which can estimate the impact of a wide range of policies in terms of stimulating changes in technology investment choices, and ultimately what such polices and choices mean in terms of four key impact areas – industrial productivity, socioeconomic development, air quality & wellbeing and environment & climate. These areas collectively are key parts of an assessment of the multiple benefits of energy efficiency – the Policy Assessment Tool provides an analysis of the impacts of energy efficiency and related policy across the European Union at the Member State level.

The E3ME Lite model is a simplified version of the E3ME model, a well-established and widely used macro-econometric model of the global economy. This working paper provides a detailed description of how the E3ME Lite model was constructed and integrated into the REFEREE Policy Assessment Tool framework. At its core, the E3ME Lite model was constructed through a large number of runs (>2,000) of the E3ME-FTT model, a large-scale global macro-econometric model owned and maintained by Cambridge Econometrics. By running the model twice for each combination of Member State and impact variable (with a 'low' and a 'high' impact), we were able to estimate parameters which capture the core socio-economic impacts of changes in technology decisions which were modelled 'live' in the Policy Assessment Tool (via the web-based user interface). This set of equations allowed outcomes from the FTT technology diffusion models (where user-decided policies are initially introduced) to be fed through the quantification of the different multiple benefits.

The model was designed to deliver a Policy Assessment Tool that could be used relatively quickly and easily by non-expert final users via a web browser; to do this, a number of design decisions had to be made, which traded off complexity for computation speed. As such, while the Policy Assessment Tool provides useful and actionable insights, it should be viewed as the starting point for an evaluation of the potential impacts of energy efficiency (quantified across multiple benefit streams), rather than the final end point for such an assessment.

1. Introduction

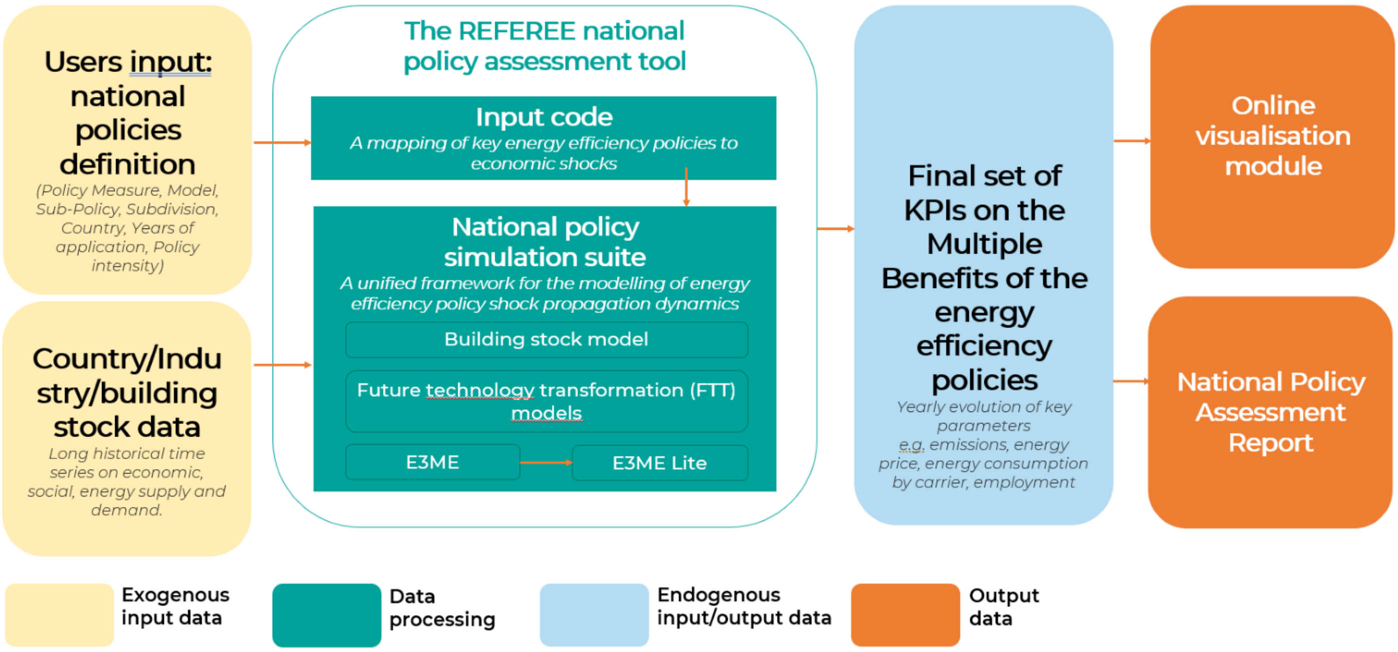
1.1. Objectives

As part of the European Union's Horizon 2020 research and innovation programme, under grant agreement NO 101000136, the REFEREE project developed the REFEREE Policy Assessment Tool, an intuitive and accessible online platform that empowers policymakers at all governance levels with actionable insights and data-driven solutions. The ultimate aim of the Policy Assessment Tool was to provide quantitative evaluations of the impact of different types of energy efficiency policy, described through a multiple benefits framework as first pioneered by the International Energy Agency (https://www.iea.org/reports/capturing-the-multiple-benefits-of-energy-efficiency).

This work involved a consortium of European institutions, and the hard-linking of 7 different models evaluating different aspects of energy efficiency policy. The integrated models and calculations covered the direct effects of energy efficiency policy, in terms of the take-up of different energy technologies (on both the supply- and demand-side) and the impacts on energy demand, and the follow-on impacts along four key impact areas – Industrial productivity, socioeconomic development, air quality & wellbeing and environment & climate.

The modelling framework is summarised in Figure 1 below.

Figure 1.1 The REFEREE national policy assessment tool framework



This paper focusses on the boxes at the bottom of the framework under the REFEREE national policy assessment tool. Specifically, it discusses the development and evolution of the E3ME Lite model, based upon the large-scale macroeconomic model E3ME, and its integration with the FTT suite of technology diffusion models that are used to simulate the direct impacts of energy efficiency policies.

The quantification of multiple benefits is not the focus of this paper; nonetheless, the final quantifications include a substantial focus on economic impacts (both through industrial productivity and socioeconomic development) – see the figure below. This highlights why the E3ME Lite modelling was such a key component of the modelling framework, and therefore presented such an interesting challenge in this project; without some form of macroeconomic model, the panel of indicators that could have been quantified would have been substantially reduced; yet macroeconomic models are typically large and complex – so a key challenge for the REFEREE team was finding a way to realise these socioeconomic outcomes but in a way that was computationally simple enough to be accessible through a web-based front end.

Table 1.1 The impact areas assessed in the national REFEREE Policy Assessment Tool

Impact areas	Indicators
Industrial productivity	Gross Value Added (GVA)
	Energy intensity
	Energy cost impact
	International competitiveness
	Labour productivity
Socioeconomic development	Gross Domestic Product (GDP)
	Employment
	Demand for skills
	Energy expenditure as a percentage of total expenditure by income quintile
	Energy demand by dwelling archetype
Air quality & wellbeing	Air pollution damage costs
Environment & Climate	Air pollution and emissions
	Fossil fuel consumption
	Fuel imports as a share of GVA
	Water used in electricity generation
	Material consumption
	Electricity generation

The rest of this paper sets out the underlying structure of the E3ME model, on which the E3ME Lite model is built, and the process by which the E3ME Lite model was then built. Then we set out how the E3ME Lite model was integrated into the FTT suite of technology diffusion. Finally, we conclude with an outline of the key strengths and weaknesses of the REFEREE Policy Assessment Tool, with a focus on the implications of the design decision choices made along the way.

2. Methodological Approach

2.1. The global macroeconomic model E3ME

The following introduction to the E3ME model is drawn from (Dwesar et al., 2022), the main manual for the E3ME model.

E3ME is a computer-based model of the world's economic systems, energy systems, and the environment. It was originally developed in the 1990s through the European Commission's research framework programmes and has been in a state of constant development and improvement ever since. The model is now widely used in Europe and beyond for policy assessment, forecasting, and research purposes. The acronym E3ME stands for Energy-Environment-Economy Macro-Econometric, reflecting the key properties of the model.

The rationale for E3ME is that it is not possible (or ethical) to carry out experiments at the macroeconomic level. However, policy makers understandably want to test new policies before implementing them on the whole population. Computer modelling therefore provides the next best option, acting as a laboratory for testing new policy (see discussion in Romanowska et al, 2021, p4). These policies are entered into the model as scenarios which are then compared to a no-policy baseline case.

However, to be useful, the model must provide a representation of reality that includes all the factors most relevant to the policy in question. It must reflect the observed reality to the greatest degree possible.

E3ME aims to meet this goal. The model provides a general macroeconomic framework, meaning that it covers the whole economy on a consistent basis (e.g., with no double counting). The linkages to the physical supply/demand of energy and material resources mean that the model is often used to assess the impacts of sustainable development policies (including climate policy) on the economy and the labour market. The addition of technology-focused FTT models in key energy-using sectors further enhances the range of policies that the model can address.

E3ME is a model that is based on empirical foundations. Its structure and parameterisation reflect the nature of economic activity as found in the real world. This approach takes E3ME away from the methodology commonly found in equilibrium-based approaches, which makes sweeping assumptions about human behaviour. It leads to an approach that is consistent with post-Keynesian macroeconomic thinking (King, 2015; Lavoie, 2014), complemented by more recent insights from complexity economics (Arthur, 1999; 2015; Kirman, 2018).

The most important properties of the E3ME model relate to the key principles listed above and its post-Keynesian theoretical foundations. However, the model is often referred to as a 'macro-econometric' tool. This description is accurate but may be confusing, as the term is also used to describe equilibrium-based tools with econometric parameters. Whilst E3ME is a non-equilibrium model, it uses an empirical approach to model human behaviour.

Human behaviour is what economists refer to as 'non-observable'. This does not mean that we cannot see it, instead that it cannot be measured in the same way as, for example, jobs or euros. Without a ready data source, human behaviour is inferred using econometric equations. These equations provide estimates of the historical responses to economic stimuli such as changes in prices, effectively trying to match cause and effect. They are the primary determinants of human behaviour in E3ME.

Figure 2.1 Linkages in E3ME

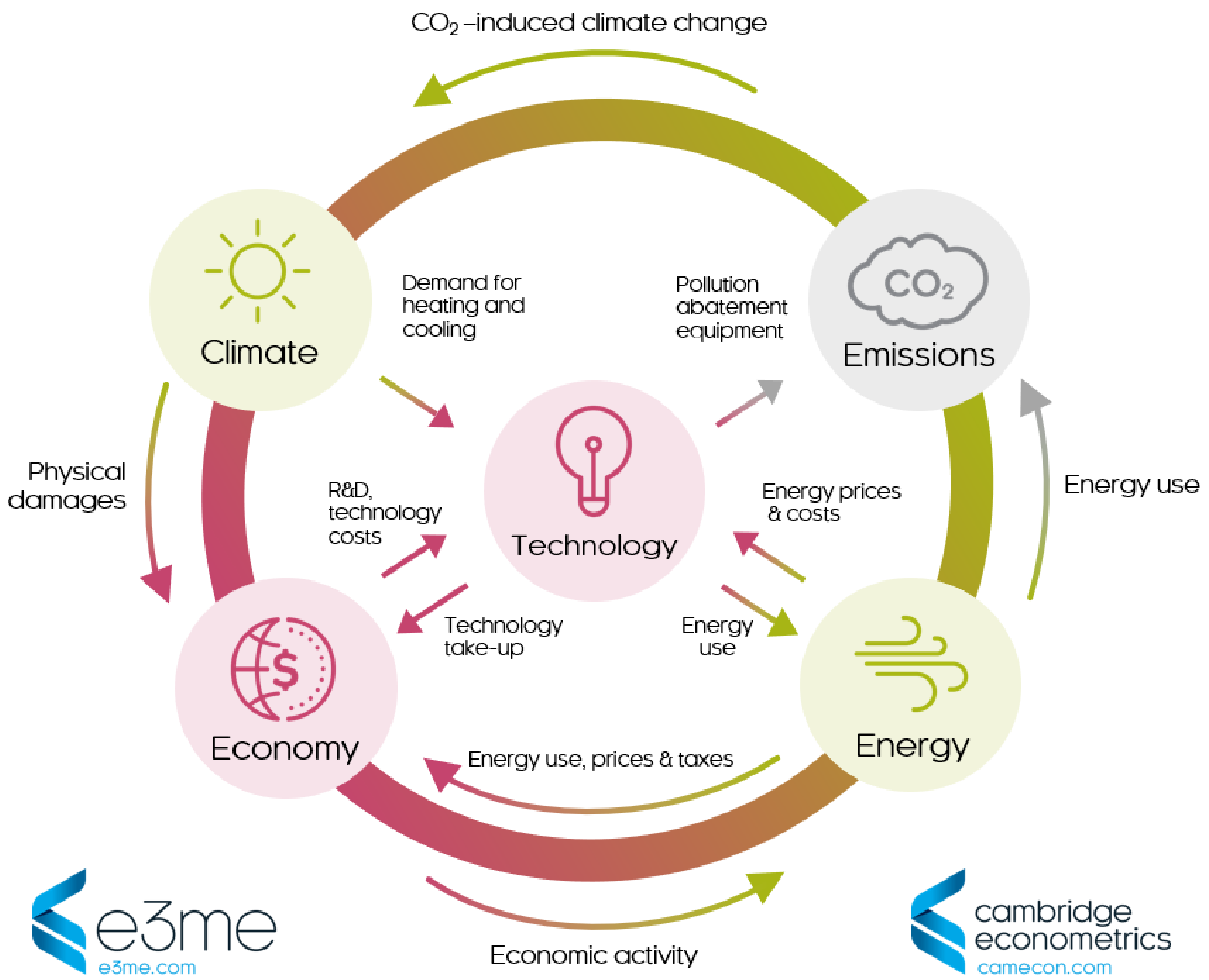


Figure 2.1 provides an overview of E3ME's basic structure. The different modules of E3ME are represented in the bubbles. The links between the modules show the key lines of causality and how the model maintains consistency between economic and physical units (as, for example, systems dynamics models do).

The structure of E3ME is based on the system of national accounts, with further linkages to energy demand and environmental emissions. The labour market is also covered in detail, including both voluntary and involuntary unemployment. In total there are 33 sets of econometrically estimated equations. These also include the components of GDP (consumption, investment, international trade), prices, energy demand, and materials demand. Each equation set is disaggregated by country and by sector.

2.2. The FTT technology diffusion models

The FTT models assess technology deployments. As described in Mercure and Salas (2012), the FTT models draw from the innovation literature and use a predator-prey approach to assessing competition (like the dynamic model in Goodwin, 1967). The direction and pace of technological innovation is driven by both rates of economic development and specific policy impacts.

Within each FTT model, investors are faced with several options to build new capacity (Mercure, 2012). New capacity is required to replace old capacity and to meet the changing demand (which is determined by E3ME). The decision-making core generates estimates of investor preferences by comparing the levelised costs between technology options on a pair-wise basis. This is conceptually equivalent to a binary logit model, which is parameterised by the measured technology cost distributions of several cost components. The costs include upfront investments (which can decline through learning effects), energy costs, and policy costs. Distributions of these costs indicate local variabilities as well as the heterogeneous character of investors, which stems from their different perceptions and outlooks.

The diffusion of technology follows a set of coupled non-linear differential equations, sometimes called 'Lotka-Volterra' or 'replicator dynamics'. These equations represent the better ability of larger or better-established industries to capture the market, the investor preferences, and the rate at which one technology can replace another technology. The key characteristics of FTT include path-dependency, sub-optimal decision-making, and non-marginal change in responding to external influences. The FTT framework produces the characteristic S-shaped curve often found in historic cases of technological diffusion.

The FTT models deployed in the REFEREE Policy Assessment Tool assess the deployment (and, in particular, the *change* in deployments in response to policy) of technologies related to;

- Road transport
  - Freight
  - Passenger cars
- Household heating and cooling
- Power sector
- Manufacturing industries (using process heating).

These models calculate, in each of these sectors, investment, consumption, average technology prices and fuel consumption. It is through these channels that policy decisions in each sector can lead to the realisation of multiple benefits; for example, policies which encourage the take-up of more energy efficient electrified technologies can be expected to change investment volumes (resulting from different investment decisions), fuel demand (through reducing demand for fossil fuels and increasing demand for electricity) and ultimately consumption. In the fully realised E3ME-FTT framework, these changes are modelled in detail as they pass through to the rest of the economy; the challenge of the REFEREE model decision process was how to represent them well enough to use them for the calculation of multiple benefits, but in a way that also could be realised rapidly enough to be used through a web-based interface.

2.3. Building E3ME Lite as a reduced form version of E3ME

The purpose of E3ME Lite is to translate the energy outcomes from running policy scenarios through the FTT models into various socioeconomic outcomes that then feed into the REFEREE Policy Assessment Tool.

The REFEREE Policy Assessment Tool aimed to allow individual users to assess the multiple benefits of different policies and policy packages. The macro econometric model E3ME is well suited to translating the impact of FTT into economic outcomes. However, due to the scale and complexity of E3ME's modelling framework, it is not practical to integrate the full E3ME model framework into the policy assessment tool.

E3ME Lite provides a smaller modelling framework that captures the detailed macro-economic policy responses that E3ME can generate without needing to replicate the full computation framework of the E3ME model. To do this, we generated a suite of parameters for all the required E3ME model outputs by carrying out various individual impact scenarios that cover each of the individual outcomes that would flow from FTT to E3ME. These parameters are then used to generate economic outcomes from any FTT policy scenario that is run in the Tool.

To achieve this, we ran through a variety of individual runs to mimic the model feedback from FTT outputs through to E3ME.

The channels through which FTT impacts feedback into E3ME are:

- Fuel demand (all FTT models)
- Electricity prices (Power)
- Investment (Power and Industrial heat)
- Consumer expenditure on equipment (Heat)

We developed scenarios that tested each of these shock across each of the fuels and fuel users and investment sectors that could be impacted. The aim ultimately then was to be able to link changes in these indicators through to the final impact areas quantified in the Policy Assessment Tool, covering industrial productivity, socioeconomic development, air quality & wellbeing and environment & climate. The estimation of parameters for each effect was achieved by taking runs for each individual shock element, and averaging the impact on each variable relative to size of variable shock averaged over the full scenario period (2023-2050). Each impact run was implemented twice at two different levels (one low and one high) to allow both validation of model parameter estimates and also help ensure we derive a reasonable average impact across a wide range of scales of impact that could be produced from the FTT suite of models. All impacts from FTT were modelled as additive and so no interaction between impacts or recursive feedbacks were considered.

Parameters were estimated for each Member State in isolation to avoid induced impacts linked to trade effects from changes taking place in other Member States.

Table 2.1 shows the total number of runs that need to be carried out for each an individual country.

Table 2.1 Number of total runs per feedback channel and impact sub-category

FTT feedback channel	Subcategories of impacts	Total runs
Fuel demand	6 fuels 10 Fuel Users	60 runs
Electricity price	None	1 Run
Investments	10 fuel users	10 runs
Consumer expenditure for heating technologies	None	1 Run

Below is the breakdown of the individual subcategories to be run.

6 fuels:

- Coal
- Gas
- Oil
- Middle distillates
- Electricity
- Biomass

10 Fuel Users:

- Power
- Households
- Road transport (Passenger)
- Road transport (Freight)
- Industry heat users groups
  - Chemicals
  - Non-metallic minerals
  - Food drink & tobacco
  - Non-ferrous metals, machinery, and transport equipment
  - Other industries

Each needed to be run per Member State.

Factoring in all permutations of impacts plus running the model in isolation for each Member State , a total of 2,017 runs were required (including a baseline run for reference). At 10-15 minutes per run, this required a total run time of 300 – 500 hours of computing time to run through. To speed up the process of preparing these runs, the E3ME model was run in parallel over several machines.

Once the runs were complete, there was an extensive checking process to review the modelled runs and check for notable outliers in terms of the key output variables. Parameters were then estimated from the validated runs, applying the averaging over time methodology set out above.

The key non-linearities within the framework are experienced in the way that policy impacts upon consumer/business behaviour, in terms of both the adoption of more energy efficient technologies and explicit reductions in energy demand, which are encapsulated in the FTT models. Our model framework has been designed from the start with this in mind; these models are called by the REFEREE Policy Assessment Tool, and as such these non-linearities are captured within the framework. Conversely, most of the resultant impacts captured in E3ME were largely linear in terms of how they scale as the scale of the change in technology deployment or energy demand changes. As such, the averaging technique used to estimate the final parameters is not expected to have skewed the parameters in a particular direction, or led to system under- or over-estimation of the parameters.

2.4. Linking the FTT technology diffusion models and the E3ME Lite model

Once the E3ME Lite model had been parameterised, the FTT models and E3ME Lite were linked, and in such a way as to capture the major sequential impacts from each model. Particular attention was played to the order in which the models were operated, in order to capture linkages between them. Specifically, there are interactions between the power generation sector and the take-up of different technologies; electricity prices are a function of electricity demand (since renewables and other low-cost technologies can play a greater role in setting prices when demand is lower), which changes the cost of operating electricity-based technologies (which tend to be more energy efficient) and therefore their competitiveness in the market and therefore the take-up of them. In return, the take-up of electrified technologies changes demand for electricity, which can further affect electricity prices. To address this, the modelling framework ensures that the power sector model, FTT:Power, is run after the other technology models, so that impacts of the take-up of new technologies can be fed through as demand for electricity, and play a role in determining the price for electricity across the wider economy within the E3ME Lite model. In scenarios where policies directly affect the power sector (such as mandated minimum shares for specific generation technologies), the FTT:Power model is run *first*, to ensure consistency with the policy, then the remaining FTT models are run, and finally FTT:Power is run *again*, to make sure that the impacts on electricity demand of the diffusion of energy-efficient technologies is captured.

Through this integrated framework, we are then able to simulate the impact of energy efficiency policies and measures upon a multiple benefits framework.

2.5. Limitations of the approach

The E3ME Lite model is by design a simplified emulation of the E3ME model response to FTT model responses. As such, is has several limitations. First the parameters are averaged over the whole estimation time period and so represent to average E3ME response to a give change in an FTT input variable and so does not account for how proportionality of impact would change over time and any impacts that propagate through lagged effects. Second, the impact of each FTT input is evaluated in isolation and then added together. This means that the approach cannot take account of any interaction effect from two inputs from FTT which may interact in the full E3ME model. Third, as the impacts are estimated as a percentage change in E3ME outputs from a corresponding change in an FTT input, it may not capture well the E3ME model response from extreme changes in FTT inputs, especially if values move toward zero. This is because this emulation approach cannot take account of cases hitting model boundaries. The estimation of parameters over a low and high change in FTT input does mitigate this slightly, but it still cannot mirror extreme cases fully.

3. Conclusions

The REFEREE Policy Assessment Tool was designed and developed in order to meet the ultimate goal of empowering policymakers at all governance levels with actionable insights and data-driven solutions. Specifically, it has delivered a modelling framework that can be readily accessed by stakeholders via an online interface, and policy levers that can be tailored into policy packages and run 'live' by those stakeholders, all within the same online interface. To facilitate this, a number of design decisions were taken. In particular, the macroeconomic analysis required to quantify the multiple benefits of energy efficiency had to achieved in a reduced form (compared to being run in a fully detailed macro-econometric model such as E3ME), and limits put on the iterations between the different stages of the model framework (specifically, between the FTT suite of technology diffusion models and the macroeconomic model E3ME Lite). These entail necessary compromises;

- The E3ME Lite model, although parameterised based upon more than 2,000 runs of the E3ME model, makes relatively strong assumptions about the linear nature of the econometric relationships that are parameterised, with just a single multiplicative parameter in each equation set, calculated as a time-agnostic average of two single E3ME runs. As such, while the parameters are estimated for individual equations relating to specific variables, broken down by type, and for each Member State, they are simplifications compared to the fuller econometric equation set contained within a more detailed and complex model.

- The full E3ME-FTT model framework, owned and maintained by Cambridge Econometrics, solves the technology diffusion and economic parts simultaneously. However, this drastically increases the complexity of the model, and therefore the run time. It was necessary, in the REFEREE Policy Assessment Tool, to simplify this process by running the different sub-models in a linear sequence, allowing for the most important feedbacks between each to be captured in the final quantifications of multiple benefits. This means that a user can specific a set of policy inputs and then run the model in a manageable amount of time (typically 5-10 minutes).

The trade-offs in such decisions are clearly set out above – but it is essential to highlight that the main benefit of such choices is to deliver a modelling framework that ultimately can be used as intended – by a non-expert user, through a web interface, with the ability to design and implement policy inputs and then run them in the model, achieving results in terms of the impacts of these policies on the multiple benefits of energy efficiency within a manageable amount of time (typically 5-10 minutes). All design decisions taken throughout the design and implementation of the Policy Assessment Tool were taken in service to this ultimate goal.

It is important to understand that these simplifications and design choices place some limitations on the way that the results of the model can be used. However, the concise approach adopted in the Policy Assessment Tool can be further supported through more detailed analysis. Some of these approaches have been developed and implemented in other parts of the REFEREE project; such as the implementation of case studies in selected municipalities, which help to illustrate the real challenges and trade-offs faced by energy efficiency policymakers. Furthermore, models and approaches exist to support more nuanced, detailed and fully-formed quantitative modelling exercises, either through the development of in-house expertise within key agencies (such as the European Commission or Member State governments) or the use of consultants with the relevant expertise and tools. The REFEREE Policy Assessment Tool should therefore represent a starting point for the analysis of the impact of potential energy efficiency policy, rather than a final end point.

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