Cambridge Econometrics

E3ME Model Manual

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clarity from complexity

Model Manual

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Preface and Summary

Acknowledgement

The E3ME model is developed and maintained by the modelling team at Cambridge Econometrics. Any errors in this manual are the responsibility of the team.

The FTT models have been developed by teams led by Jean-Francois Mercure (Exeter University). The energy cost supply curves in the model were developed by Jean-Francois Mercure and Pablo Salas.

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Acronyms

Conventions adopted in the manual

ADB	Asian Development Bank
AMECO	Annual Macroeconomic database (DG Economic and Financial Affairs, European Commission)
ARIMA	Auto-Regressive Integrated Moving Average
ASEAN	Association of Southeast Asian Nations
CAS	Complex Adaptive Systems
CE	Cambridge Econometrics
CEE	Central and Eastern Europe
CFC	Chlorofluorocarbons
CGE	Computable General Equilibrium
COMETR	Competitiveness effects of environmental tax reforms
DE	Domestic Extraction
DMC	Domestic Material Consumption
DMI	Domestic Material Input
DSGE	Dynamic Stochastic General Equilibrium
E3	Energy-Environment-Economy
E3ME	Energy-Environment-Economy Macro-Econometric Model
E3MG	Global Energy-Environment-Economy Model
EC	European Commission
ECF	European Climate Foundation
ECM	Error Correction Model

EDGAR	Emissions Database for Global Atmospheric Research
ESA	Eurostat system of national accounts
ETS	Emission Trading Scheme
EU	European Union
EURACE	European Accreditation of Engineering
FDI	Foreign direct investment
FTT	Future Technology Transformations
GDP	Gross Domestic Product
GEM	General Equilibrium Model
GHG	Greenhouse gas
GTAP	Global Trade Analysis Project
GVA	Gross Value Added
HERMES	Macro-sectoral model by the Federal Planning Bureau
HFC	Hydrofluorocarbons
ICT	Information and communications technology
IDIOM	International Dynamic Input-Output Model software package
IEA	International Energy Agency
ILO	International Labour Organization
IMF	International Monetary Fund
IO	Input-output
IPCC	Intergovernmental Panel on Climate Change
IRENA	International Renewable Energy Agency
JOULE	Joint Opportunities for Unconventional or Long-term Energy supply model (R&D elements)
KLEMS	EU level analysis of capital (K), labour (L), energy (E), materials (M) and service (S) inputs
LFS	Labour Force Survey
MLE	Maximum Likelihood Estimators
MRIO	Multi-Regional Input-Output
NUTS	The classification for European regions
OECD	Organisation for Economic Co-operation and Development
OPEC	Organization of the Petroleum Exporting Countries
PBL	Netherlands Environmental Assessment Agency
PFC	Perfluorocarbons

PRIMES	Price-Induced Market Equilibrium System
RLDC	Residual Load-Duration Curves
RMC	Raw Material Consumption
RME	Raw Material Equivalent units
STAN	OECD STructural ANalysis database
THERMIE	Demonstration counterpart to JOULE
TMR	Total Material Requirement
UN	United Nations
VAT	Value Added Tax
VOC	Volatile Organic Compounds
VRE	Variable Renewable Energy
WIOD	World Input-Output Database

Units of measurement

m	Million
bn	Billion (thousand million, as French milliard)
mtc	Million tonnes of carbon
pa	Per annum
pb	Per barrel of oil equivalent
pp	Percentage point
toe	Tonnes of oil equivalent
nes	Not elsewhere specified

1 Introduction

1.1 Introduction to E3ME

Where the model came from

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 (see Chapter 2). 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 (see Chapter 8).

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 capability

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 more recent addition of technology-focused FTT models (see Section 5.1) in key energy-using sectors further enhances the range of policies that the model can address.

Recent examples of the sorts of policies assessed in E3ME include:

- various taxation policies, including energy and carbon pricing
- climate regulations such as energy efficiency mandates
- labour market reforms and gender equality measures
- support for key technologies, such as electric vehicles

The main outputs from the model include:

- impacts on employment, unemployment, and incomes
- standard macroeconomic indicators like GDP, prices, investment, and trade
- sectoral rates of production and value added
- energy consumption, emissions, and material use

E3ME is now recognised as the most advanced model of its kind globally and has been used for numerous high-profile policy assessments. Examples include:

- an analysis of economic, social, and environmental impacts of Covid-19 recovery plans, both globally and in selected countries
- contributions to the International Renewable Energy Agency (IRENA)'s socioeconomic impact assessment of the global and regional energy transition
- an assessment of an expansion of the EU ETS to transport and buildings
- an evaluation of the economic, transition, and physical risk impacts associated with climate scenarios for financial institutions
- an assessment of the economic and labour market effects of the EU's long-term strategy for climate policy
- contribution to the EU's Impact Assessment of its 2030 environmental targets and 'Clean Energy Package'
- the 2018 New Climate Economy report

Further examples of model applications are provided in Chapter 11 and are available on the model website, www.e3me.com.

1.2 The model's basic theory

The Cambridge (UK) tradition

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).

Chapter 3 discusses the theory that underlies E3ME in more detail. The key principles of the model are:

- Agents make decisions under conditions of fundamental uncertainty; at any time, they do not know the full range of options available to them.
- Agent behaviour is subject to many real-world influences and cannot be considered as fully 'rational'. Much agent behaviour is in fact social in nature.
- Markets are subject to frictions in both the short- and long-runs; prices do not automatically balance supply and demand.
- There is usually spare capacity in the economy, including, for example, unemployed workers.
- Money is an evolved system of credit, and the quantity of money is never fixed.

- Stocks and flows in the physical and financial worlds are monitored, with important differences in how they feed back to the wider economic and energy system.

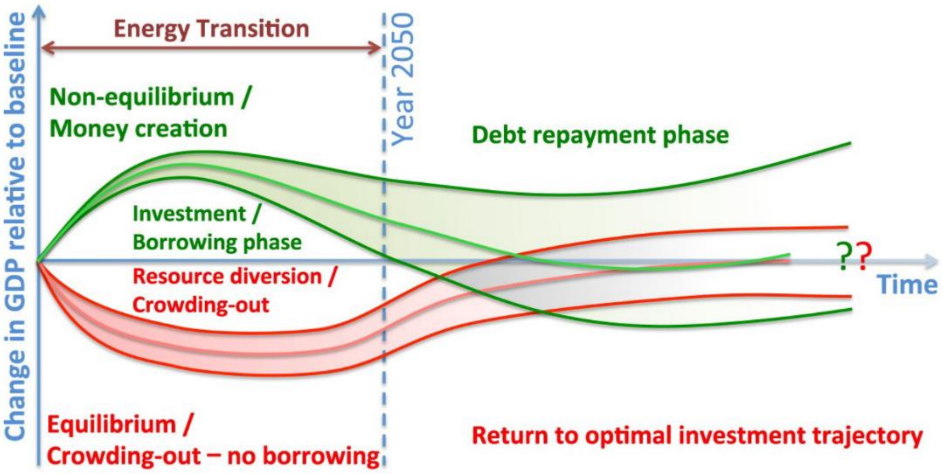
All models represent a simplification of reality and, inevitably, when building a detailed model of the economy it is necessary to make simplifying assumptions. The aim of E3ME is to cover all the necessary parts of the system, in as much detail as possible, given the available data and constraints on computing power.

Why does any of this matter?

The choice of simplifications, usually referred to as assumptions, matters a lot in macroeconomic modelling. The lay reader may wonder why there is a need to list a set of obvious principles above. Unfortunately, these principles are often not reflected in other models that are based on equilibrium principles derived from neoclassical economic theory.

Worse, the assumptions based on neoclassical economic theory can lead the model to predict the exact opposite results of an empirical model like E3ME. This finding is common in assessment of climate policy. For example, Figure 1.1 below shows a possible trajectory for GDP in a low-carbon transition (compared to a baseline case) modelled in E3ME, represented in green, compared to the effects of the same policies in an equilibrium-based model, represented in red. This effect is discussed again in Section 3.2.

Figure 1.1: Equilibrium and non-equilibrium approaches



Source: Mercure et al (2019).

Unsurprisingly, these differences in outcomes frequently catch the attention of policy makers, and results from the E3ME model are often compared to other models that are based on equilibrium assumptions. Section 3.2 discusses these comparisons in further detail and shows that the differences in results relate to the assumptions that are required to get the equilibrium-based model to solve.

Increasingly, the world is waking up to the fact that more realistic macroeconomic models are needed to address the multiple problems that humanity is facing.

Why is E3ME called a macro-econometric model

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.

As we discuss in Section 3.1, 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.

Do we need complexity as well?

Cambridge Econometrics aims to provide 'Clarity from Complexity' and modelling tools like E3ME are intended to aid this purpose. The world is undoubtedly a complex place.

Complexity also has a specific meaning that has come to be wrapped up with the concept of systems analysis (Scrieciu et al, 2021). Meadows (2008, p2) describes a system as 'A set of things… interconnected in such a way that they produce their own pattern of behaviour over time'. Such emergent properties are also core to complexity theory, for example, described in Weaver (1948).

The idea of Complex Adaptive Systems (CAS) extends the thinking to include a time dimension, with the complex system evolving over time. There is no doubt whatsoever that the economy is a Complex Adaptive System. The school of Complexity Economics (Arthur, 1999; 2015; Kirman, 2018), which has grown to accommodate Evolutionary Economics (Nelson and Winter, 1982; Nelson, 2018), insists that the economy should be viewed this way.

Unfortunately, including complexity in an empirical model is not easy and it is not compatible with a macro-econometric approach. Most models that use a complexity approach are conceptual, rather than being used for empirical analysis (see distinction in Romanowska et al, 2021, p236). Complexity authors acknowledge that unless it is necessary to address the complexity, a macro-econometric approach may be more appropriate (Thurner et al, 2018; Boulton et al, 2015).

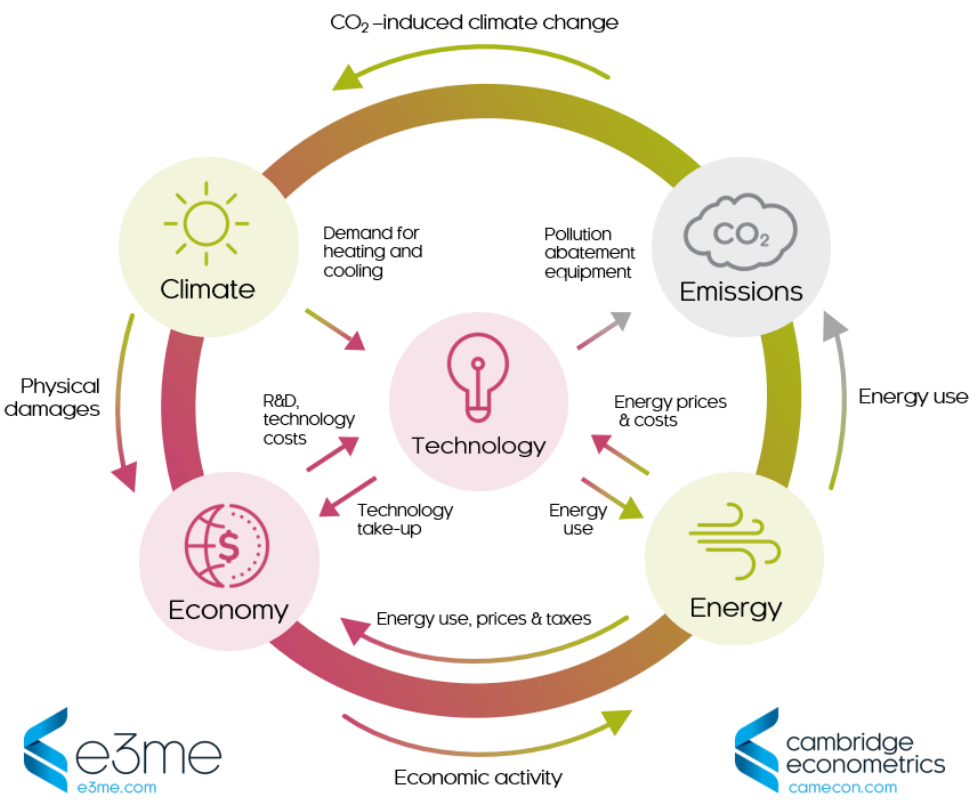
To have an operational model we must therefore carefully select where we introduce the non-linear dynamics of complexity to the model. At present the focus is on the development of technology, especially in the use of energy (see Section 5.2). Over time, however, it is anticipated that complexity-based approaches will gradually replace many of the econometric equations in the model.

1.3 Basic model structure and data

Figure 1.2 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 figure also shows the importance of technology in our modelling. Technology enters the model in several different ways (see Section 4.6) but is critical to understanding the dynamics of the various transitions in the coming decades. Technology indicators link to all the other modules in the model.

Figure 1.2: Linkages in E3ME



Economic structure

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.

Chapter 4 provides further description of E3ME's accounting structure. Detailed econometric specifications of the E3ME equations are given in Chapter 7.

Model dimensions

The main dimensions of E3ME (Version 9) are:

- 71 countries – all major world economies, the EU28 and candidate countries, plus other countries' economies grouped

- 44 (70 in Europe) industry sectors, based on standard international classifications
- 28 (43 in Europe) categories of household expenditure
- 25 different users of 12 different fuel types
- 24 power generation technologies, 25 car types, 13 residential heating technologies, and 26 steel production technologies
- 14 types of air-borne emission (where data are available) including the six GHG's monitored under the Kyoto Protocol

Data inputs

E3ME's historical database covers the period 1970-2019 (with estimates for Covid-19 impacts and recovery for 2021) and the model projects forward annually to 2050 (2100 is also possible). The main data sources for European countries are Eurostat and the IEA, supplemented by the OECD's STAN database and other sources where appropriate. For regions outside Europe, additional sources for data include the UN, OECD, World Bank, IMF, ILO, and national statistics. Gaps in the data are estimated using customised software algorithms.

Chapter 6 describes in further detail E3ME's data inputs.

1.4 Introduction to this manual

This manual provides a technical description of Version 9.0 of the E3ME model. A full set of equations is provided in Chapter 7. The other chapters in the manual describe the model's basic structure and theory, data, and software.

The manual is intended for users of model results who require further technical information. There is a separate user guide that discusses the practicalities of running the model. There is further non-technical documentation available at the model website www.e3me.com. The website also provides information about recent updates and applications of the model.

2 A Brief History of E3ME

2.1 E3ME's history

E3ME was originally intended to meet the expressed need of researchers and policy makers for a quantitative framework for analysing the impacts of Energy-Environment-Economy (E3) policies. The model was designed to address the short- and medium-term economic effects as well as, more broadly, the long-term effects of such policies.

The initial development phase

The first version of the E3ME model was built by an international European team under a succession of contracts in the JOULE/THERMIE and EC research programmes. The projects 'Completion and Extension of E3ME' and 'Applications of E3ME', were completed in 1999. The 2001 contract, 'Sectoral Economic Analysis and Forecasts' generated an update of the E3ME industry output, product, and investment classifications to bring the model into compliance with the European System of Accounts, ESA 95. This led to a significant disaggregation of the service sector which has been maintained ever since.

The 2003 contract, Tipmac, led to a full development of the E3ME transport module to include detailed country models for several modes of passenger and freight transport, and Seamate (2003/04) resulted in the improvement of the E3ME technology indices. The COMETR (2005-07), Matisse (2005-08), and Cedefop (2007-2010) projects allowed the expansion of E3ME to cover 33 European countries, including the (then) twelve EU accession countries and four candidate countries, and added the materials module.

Expansion to meet client demands

E3ME has been used to feed into direct policy assessments since 2006, which is broadly the time that the model became a tool suitable for use on a consultancy basis. Much of the subsequent development of the model has reflected the needs of Cambridge Econometrics' clients, for example in the ever-expanding disaggregation of countries in the model.

Two things happened in 2009 that changed the context of much of E3ME's analysis. The first was the realisation of the global financial crisis that began in 2008. The second was the Copenhagen climate summit. Both of these events demonstrated the importance of global connections, and the need for global coverage within a macroeconomic model. E3ME was subsequently expanded from a European to a global model and replaced the previous E3MG model that was being used at the University of Cambridge, with version 6 of the model being launched in 2013. This model version was later made consistent with the updated ESA10 national accounting framework.

Understanding technology transitions

In this period, the sorts of questions being asked in E3ME advanced from carbon/energy taxes to full decarbonisation scenarios. Moving away from marginal effects, a better treatment of technology development and uptake was required. In 2012 the first example of such a treatment (FTT:Power, see Section 5.2, Mercure, 2012 and Mercure et al, 2014) was incorporated into E3ME. The FTT approach has since been expanded to cover several other sectors of the economy and plays a critical role in determining E3ME's results in decarbonisation scenarios. As noted in Section 1.2, the FTT models also introduced non-linear, complexity-based relationships to E3ME and we expect further developments in this direction in future.

The current model

Path dependency is a key feature of E3ME simulations and the development of the model itself has been highly path dependent. Many of the improvements to the model were originally made for individual projects but have since been incorporated into the master model. They are therefore used in all subsequent applications of the model. Interactions between these various improvements are important, especially in the non-linear parts of the model.

A substantial amount of effort is put into maintaining the model, particularly into keeping the time-series database up to date. On average, the model's database has been updated once every two years so that the model remains relevant for current policy analysis. Each time the historical database is revised, new econometric equations must be estimated, and the baseline projections must also be updated.

2.2 The different versions of E3ME

Table 2.1 summarises the main changes to the model from the completion of the first version in 1999.

Table 2.1: E3ME model versions

Version	Date	Description
1.0	1999	• The first version of the E3ME model was built by an international European team under a succession of contracts in the JOULE/THERMIE and EC research programs
2.0	2001	• E3ME classifications updated to be consistent with the European System of Accounts, ESA 95
3.0	2003	• E3ME technology indices improved
4.0	2008	• Expanded to include the twelve accession countries • 29 European regions in total
5.0	2010	• Expanded to include 4 candidate countries (Iceland, Croatia, Turkey, and Macedonia) • 33 European regions in total
5.5	2011	• Several econometric equation sets revised
6.0	2013	• First E3ME Global version • 48 regions (33 Europe and 15 major economies)
6.1	2017	• 59 regions (33 Europe and 26 major economies) • Introduced FTT technology sub-model for power sector • Introduced global natural resource database
6.5	2018	• Additional 2 regions (Kazakhstan and Malaysia) • 61 regions (33 Europe and 28 major economies) • Changed trade treatment from pooled to bilateral
7.0	2019	• Introduced FTT sub-models for road transport, steel, and household heating

		• Incorporated feedbacks to human health from pollution, and economic productivity from climate change • New treatment of innovation
8.0	2021	• Additional 10 new African regions • Model's internal memory space expanded • Code parallelised to facilitate faster solution • Cloud-based version operational
9.0	**2022**	• **Expanded to include Pakistan** • **Incorporated full financial balances for major economies** • **Improved treatment of income inequality by decile in EU Member States** • **Added occupational breakdown of employment in EU Member States**

3 The Theory Underpinning E3ME

3.1 Introduction and underlying theory

The E3ME model has very much been built in the Cambridge (UK) tradition of macroeconomics. The history of Cambridge Econometrics itself may be traced back through the company's founder, Terry Barker, to Richard Stone and John Maynard Keynes.

The post-Keynesian school

The empirical approach to understanding the economy naturally leads the model to post-Keynesian economics. In the *General Theory* (Keynes, 1936), Keynes built a version of macroeconomics that was descriptive rather than normative, meaning that it describes how people *actually* behave rather than how they *should* behave (p34).

Post-Keynesian economics develops the original ideas of Keynes, for example, expanding its understanding of the financial sector. Many of its fundamental ideas were developed by economists at Cambridge, notably Joan Robinson. The term 'post-Keynesian' was first used in its current form in 1973 by Jan Kregel (Kregel, 1973) and expanded on in Eichner and Kregel (1975). Recent descriptions are provided in King (2015) and Lavoie (2014).

There have been many different interpretations of Keynes' work over the years. Many have deviated far from Keynes' original ideas, including the current New Keynesian school from which Dynamic Stochastic General Equilibrium (DSGE) models have been derived. These models represent an attempt to reconcile Keynes' thinking with neoclassical theory but end up with something that is still highly reliant on the assumptions of neoclassical theory that Keynes disputed.

In their early discussion of post-Keynesian economics, Eichner and Kregel (1975) focus on four key components:

- The dynamic and path-dependent nature of the economy
- The importance of distributional, as well as aggregate, outcomes
- Money and the financial system
- A microeconomic base to complement macro-level outcomes.

It is notable that DSGE and Computable General Equilibrium (CGE) models could only claim to address the fourth point (and even then, only with absurd assumptions; King, 2012). This fourth point remains problematic for post-Keynesian approaches too, as discussed below. The other three are core to the design of E3ME.

The starting point: Fundamental uncertainty

Post-Keynesian economics itself has evolved since the 1970s. Our interpretation of Keynes' work starts with his earlier *Treatise on Probability* (Keynes, 1921). It incorporates the thinking of the economist Hyman Minsky, who wrote an exceptionally clear analytical work on Keynes (Minsky, 1975) but is now best known for his work on financial stability (Minsky, 1986).

The critical insight of Keynes' earlier work is the concept of *fundamental uncertainty*. Under conditions of fundamental uncertainty, agents (e.g., individuals or companies) not only do not know what will happen in the near term, they also do not know what *might* happen (Skidelsky, 2010, p89-93). In recent times, this has been described as the existence of 'unknown unknowns' to complement the 'known unknowns'. The distinction is important because it means that it is not possible to build a probability distribution, as it would, by definition, include gaps and the probabilities could not sum to one.

Although the concept of uncertainty is implicit in much of Keynes *General Theory*, Minsky argues that it is essential to consider uncertainty to understand the key messages. He states that 'Keynes without uncertainty is something like Hamlet without the Prince' (Minsky, 1986, p55). It is notable that Keynes' only rebuttal to criticism of the General Theory was to make this same point (Keynes, 1937).

How uncertainty determines human behaviour

In a world with fundamental uncertainty, it is not possible to optimise decision making, because the probability distribution required to do so does not exist. Assumptions about 'rational' behaviour that are core to CGE models are therefore incompatible.

Keynes' great insight was to show that uncertainty could lead to a deficiency in effective demand, leading to involuntary unemployment. The basic logic is that households put aside a share of their income in case of future emergencies. The income that is saved is not spent and does not lead to the production of goods and the jobs associated with that production (see discussion of money below). In this way, even if human behaviour is otherwise fully rational and markets operate without frictions, involuntary unemployment is a likely outcome.

This approach differentiates post-Keynesian economics (and E3ME) from New Keynesian economics and DSGE models, which typically assume that involuntary unemployment can only result from market frictions.

The case against rational behaviour was already being made in the 19th century (Veblen, 1899) and is supported by most of the field of behavioural economics (e.g., Kahneman, 2012). There is extensive literature on market frictions (e.g., Diamond, 1982; DeGennaro and Robotti, 2007).

As well as capturing the effects of market frictions, E3ME's empirical approach means that neoclassical assumptions about the behaviour of firms and individuals are not imposed. In E3ME, it is not assumed that firms are operating in perfectly competitive markets. It is also not assumed that firms or consumers have perfect information when making decisions, or that they only take account of monetary factors when making those decisions. These features reflecting how firms and households behave in the real world are picked up in the historical data that are used to estimate E3ME's sectoral econometric equations.

Whilst E3ME relaxes many of the restrictive assumptions imposed in a standard CGE modelling approach, there is an underlying assumption that behavioural responses do not change over time unless this is specifically integrated in the design of a particular scenario. This assumption has been criticised by various authors, including Keynes (1939) and Lucas (1976). This assumption of fixed behavioural coefficients must always be considered in analysis which uses macroeconomic models. However, as former Bank of England Chief Economist Andy Haldane has pointed out, the criticism can equally be applied to the parameters in CGE and DSGE models (Haldane and Turrell, 2018).

To address the criticism of fixed behavioural parameters, many of the econometric equation sets in E3ME have been replaced with a complexity-based approach to better reflect real-world behaviour, as described below. This complexity-based approach in E3ME is predominantly used for modelling energy demand and investment, where disruptive change from new technologies is most evident.

Effective demand and economic capacity

As described above, the behavioural response to fundamental uncertainty means that the level of spending in the economy may not be sufficient to maintain full employment. The actual level of production is therefore determined by aggregate demand rather than aggregate supply. Non-rational behaviour and market frictions only place more emphasis on demand.

It is not just labour markets where there may be excess capacity. Data collected by the US and European statistical agencies show that factories typically keep 20-30% of their production capacity available (Federal Reserve, 2021; Eurostat, 2021). We thus get to another important feature of the E3ME model and post-Keynesian economics more generally: the assumption that there is usually spare capacity in the economy.

Whereas neoclassical economists tend to depict a shortage of demand as a ‘special case’, Keynes flipped the argument to suggest that full capacity utilisation is a special case that is rarely reached. In E3ME scenarios, the baseline case will almost always have spare capacity; when model scenarios show higher production than in the baseline, they are often drawing on this available capacity (although capacity may be increased too). There is therefore only limited ‘crowding out’ of other activities, something which is standard in CGE-based analyses. This issue is discussed in-depth in Mercure et al (2019) and European Commission (2017).

This is not to say that there are no capacity constraints in E3ME, however. The working age population places an upper bound on labour capacity and the ‘normal’ output equations discussed in Section 7.3.15 estimate industrial capacity. These capacity variables have price feedbacks, but with the impacts estimated using econometric equations rather than assuming movement towards an equilibrium value.

Understanding the financial system

One of the most important contributions of post-Keynesian economics to economic understanding is its interpretation of money and the financial system (Lavoie, 2020). It is also an area where post-Keynesian thought has developed from the original ideas of Keynes (who changed his views over his lifetime; see Werner, 2014; 2016).

Although E3ME is not designed to address the sorts of dynamics identified in Minsky (1986), the ‘endogenous’ money supply is a critical feature of the model. We hinted at this earlier in the discussion about potential shortages of effective demand if money is saved. In a CGE model, this would not matter because the underlying ‘loanable funds’ theory would mean that banks simply lend this money out to someone else. However, such a fixed money supply lies a long way from the credit-based money system that we use today (McLeay et al, 2014; Werner, 2014; 2016) and have done throughout most of history (Graeber, 2014; Galbraith, 1975).

In E3ME, the causation used in CGE models is reversed. Money is created when a loan is advanced to a company (or individual). This company spends the money boosting aggregate demand. Some of the money may be saved at this stage and some will be re-spent, creating multiplier effects. Eventually, however, all the money is saved. Thus, while the identity that savings and investment are equal (at global level) is respected, investment is not constrained by the available savings.

The level of investment is thus a key determinant of growth, as Keynes made clear. Keynes described the level of investment as being determined by ‘animal spirits’, which could be interpreted as the level of confidence by both the borrower and lender that any new loans will be repaid.

This point is critical in the analysis of climate policy, which often involves a large amount of upfront investment. In CGE models it is assumed that investment in low-carbon technology will displace investment in other sectors because there is a shortage of money. This is not the case in the real world, and yet it is a core determining factor in CGE models’ results.

The importance of including an endogenous money supply in models of climate policies is discussed in Pollitt and Mercure (2018). Further comparison with CGE models is provided in European Commission (2017) and Mercure et al (2019).

Putting all this in a model

The challenge of representing all this in a model need not be considerable. Although E3ME is a large and highly disaggregated tool, the basic economic structure of the model is almost identical to Michal Kalecki’s original depiction in the 1950s (Kalecki, 1954).

Kalecki is much less well-known than Keynes, but first published his basic model before the *General Theory* was published. Unlike Keynes, Kalecki was also an enthusiastic user of econometrics to parameterise his models, despite the limited computing power available in the mid-20th century.

All users of the E3ME model owe a debt to Kalecki for laying out the basic system so clearly.

Weaknesses in the post-Keynesian approach

Two important criticisms can be made of the post-Keynesian approach. The first is that by focusing only on macro and sectoral-level flows, the approach misses out important micro-level interactions and phenomena. The second is that the demand-driven approach cannot answer questions about what determines long-run economic development. The approach in E3ME is to integrate insights from complexity economics. In this way, we find that the two issues are quite closely linked.

Micro-foundations and complexity

Historically there has been a strong divide between micro and macro level analysis that has only been bridged by imposing strong assumptions about agent homogeneity and rational behaviour. The lack of ‘micro-foundations’ in the E3ME approach is one of the main criticisms of E3ME put forward by neoclassical economists. The criticism that E3ME does not have strong micro-foundations is technically correct but is weak as the micro-foundations utilised by CGE and DSGE models are founded on the assumptions noted above. King (2012) provides a good overview of the issue.

Many post-Keynesian economists dispute the need to include micro-foundations at all in a macro model (Chick, 2016). However, this approach can lead to inconsistent assumptions and a lack of transparency (Schoder, 2017).

More recent evolutionary and complexity-based theory provide a much more solid basis to link between micro and macro. Complexity economics focuses on the interactions between different agents, how they determine macro-level behaviour, and how the system changes over time. Beinhocker (2007) provides a highly accessible introduction to the field. Complexity economics is closely related to systems theory (Scrieciu et al, 2021).

Complexity arises when agents are heterogeneous and, especially when they interact directly rather than through a centralised system. The assumptions that underpin a standard CGE model are essentially enforced to remove the complexity from the system. The macro-econometric approach in E3ME accepts the existence of complexity but assumes it is rather static, missing the evolutionary part (see discussion about parameterising behaviour above).

Complexity economics is usually associated with Agent-Based Modelling. There have been some early attempts to link to a model like E3ME (although at a much smaller scale, see Dosi et al, 2010), but there remain substantial challenges in scaling up this approach, as the EURACE model has shown.

As discussed below, it is possible to integrate aspects of complexity without using an agent-based approach. At present, this is being applied for technology development in energy-using sectors, but it is anticipated that other parts of E3ME will be adapted in future.

Technology development

Darwin's great insight was to see that evolution comes from heterogeneity in populations. If we think about technology development as an evolutionary process (Anderson, 1972; Arthur, 2010), it is not a large step to see that a lack of micro representation impedes our understanding of technological progress.

Post-Keynesian economists have struggled with accounting for technological development and economic growth. With one notable exception (Keynes, 1930), Keynes himself rarely considered the issue and Kalecki's basic model is also based on fixed coefficients. Post-Keynesian models of economic growth have typically focused on capital accumulation rather than technology development (Harrod, 1939; Domar, 1946; Goodwin, 1967), which has occasionally been noted by the authors (Domar, 1944).

The model built in Kaldor (1957) illustrates another issue; while it focuses on technology, it comes from a supply-driven perspective. Reconciling technology-driven growth in potential supply with a model where output is determined by the level of effective demand has proved difficult and has led to an unwarranted focus on export-led growth (King, 2015, Ch6).

The Italian economist Luigi Pasinetti (1981, Ch 4-5) provides the most complete representation of technology. He is one of the few post-Keynesian economists to recognise that growth results not just from productivity improvements (often referred to as process innovation) but also from new products (product innovation).

E3ME incorporates both types of innovation in its econometric equations, bringing the model closer to Pasinetti's ideas and, prior to that, the ideas laid out by Schumpeter (1934). The two-way causality between the economy and technology development is a critical feature of the model, leading to a strong path dependency in outcomes, as opposed to treating technology as exogenous.

The evolutionary nature of technological development has been recognised explicitly in the modelling of energy technologies in the FTT sub-models, which assume diverse populations (see Section 5.1). 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. The FTT models share many properties with Agent-Based Models.

Natural constraints: drawing from ecological economics

Keynes wrote very little about the environment, in part because (wartime excepted) there was little pressure on natural resources when he was alive. Post-Keynesian economics has not really developed a treatment of the natural environment.

The two main schools of thought when considering the environment are Environmental Economics and Ecological Economics. Environmental economics is an extension of neoclassical economics that focuses on 'getting the prices right' to optimise overall welfare. Its underlying assumptions, in particular its rejection of uncertainty, make it incompatible with both the E3ME approach and the world that we live in.

Ecological Economics (Spash and Asara, 2018; Daly, 2019) provides much more useful insight. Like post-Keynesian economics, Ecological Economics places the economy within wider society. The difference is that Ecological Economics places society within the finite boundaries of the natural world. The natural environment provides the context for all human activity rather than being viewed as a set of market failures that must be corrected.

This structure has led to a long debate about whether there are upper limits to the size of the economy (e.g., Meadows et al, 1972; Georgescu-Roegen, 1971; Jackson, 2017; Hickel, 2020). To assess such a question requires an understanding on the limits to resource usage. In some ways, however, the question is irrelevant; it is clear that existing resource use is causing substantial environmental destruction and must be reduced.

At present E3ME only includes physical supplies of energy resources but there is ongoing work to include supply constraints on other physical resources. Results from the model are presented in physical units (e.g., tonnes of oil equivalent energy used, or tonnes of CO_2 emitted) rather than converted to monetary units.

3.2 Summary of the differences to CGE models

As discussed in the previous section, E3ME is often compared to other macroeconomic models. The Computable General Equilibrium (CGE) model remains the standard tool for long-term macroeconomic and energy-environment-economy (E3) analysis. Dynamic Stochastic General Equilibrium (DSGE) models add a short-term component but usually at the expense of sectoral detail.

The use of CGE models is widespread across the world; notable examples include GTAP (Hertel, 1999), the Monash model (Dixon and Rimmer, 2002) and GEM-E3 (Capros et al, 2012). Many of these models are based on the GTAP database that is maintained by Purdue University in the US.

In terms of basic structure, purpose, and coverage, there are many similarities between E3ME and comparable CGE models. Each is a computer-based economic model that considers E3 interactions at the global level, broken down into sectors and world regions. In addition, the regional and sectoral disaggregations are broadly similar. Both modelling approaches are based on a consistent national accounting framework and make use of similar national accounts data.

Key differences

However, beneath the surface there are substantial differences in modelling approach, and it is important to be aware of this when interpreting model results. The differences can be traced back directly to the underlying theory discussed in the previous section.

The most important difference relates to the treatment of optimisation, which follows from how the modeller views fundamental uncertainty (see previous section). A combination of perfect knowledge and rational behaviour mean that the CGE model can ignore economic demand beyond using it as a factor to set prices. If it is also assumed that markets clear, as originally described by Walras as a process of 'tâtonnement' in the 19th century (Walras, 1954), then the whole system may be solved using optimisation principles.

In contrast, econometric models like E3ME interrogate historical datasets to try to determine behavioural factors on an empirical basis and do not assume optimal behaviour. The model is demand-driven, with the assumption that supply adjusts to meet demand (subject to constraints), but at a level that is likely to be below maximum capacity.

It is this question of capacity that drives most of the differences between the two modelling approaches. If all available capacity is used to begin with, any additional demand must displace (or 'crowd out') other activity. Deviating from the optimal path in a CGE model thus leads to economic costs. In contrast, creating additional demand in E3ME allows for an expansion of total activity, for example, by drawing on previously unemployed resources. Data from the US (Federal Reserve, 2021) and Europe (Eurostat, 2021) provide strong support for the E3ME approach.

Jansen and Klaassen (2000) and Bosetti et al (2009) describe some of the differences between modelling approaches in the context of environmental tax reform. European Commission (2017) provides a discussion of the importance of capacity constraints in the two approaches. Mercure et al (2019) focuses on how the two approaches treat finance, technology, and economic development.

3.3 Summary of E3ME's key strengths

The key strengths of E3ME can be summarised as:

- Its global coverage, while still allowing for analysis at the national level for large economies (70 regions total).
- The detailed sectoral disaggregation in the model's classifications, allowing for the analysis of similarly detailed scenarios.
- The close integration of the economy, energy systems, and the environment, with two-way linkages between the economy and energy system.
- The econometric approach, which provides a strong empirical basis for the model and means that it is not reliant on some of the restrictive assumptions common to CGE models.
- The econometric specification of the model, making it suitable for short and medium-term assessment, as well as longer-term trends.

3.4 Limitations to E3ME

As with all modelling approaches, E3ME is a simplification of reality and is based on a series of assumptions. Compared to other macroeconomic modelling approaches, the assumptions are relatively non-restrictive because most relationships are determined by the historical data in the model database. This does, however, present its own limitations, of which the model user must be aware:

- The quality of the data used in the modelling is very important. Substantial resources are put into maintaining the E3ME database and filling out gaps in the data (see Section 6.2). However, particularly in developing countries, there is some uncertainty in results due to the data used.
- Econometric approaches may also be criticised for using the past to explain future trends (see discussion of behaviour in Section 3.1). In cases where there is large-scale policy change, the 'Lucas Critique' (which suggests that behaviour might change) is also applicable. There is no solution to this criticism using any modelling approach (as no one can predict the future) but we must always be aware of the uncertainty in the model results.

The other main limitation to the E3ME approach relates to the dimensions of the model. In general, it is very difficult to go into a level of detail beyond that offered by the model classifications. This means that sub-national analysis can be difficult (although possible, see description in Section 4.9) and that detailed sub-sectoral analysis is also challenging. Similarly, although usually less relevant, attempting to assess impacts on a monthly or quarterly basis is not possible.

4 E3ME's Economic Module

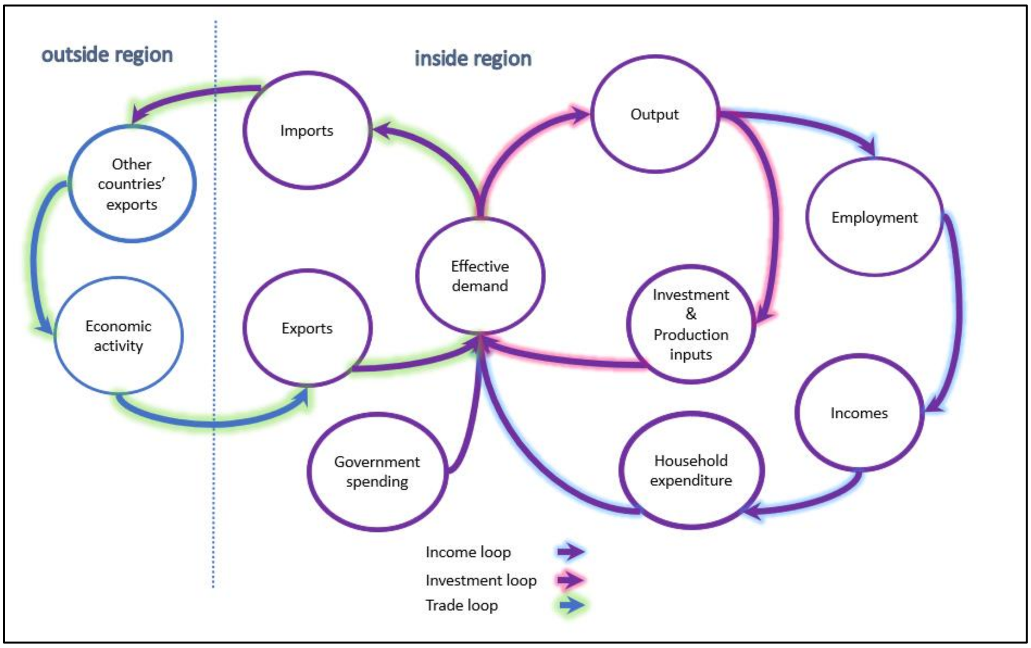
4.1 National Accounts and basic economic structure

E3ME's economic module builds on the original framework designed by Michal Kalecki (1954, see Section 3.1) and described in Barker and Peterson (1988). Figure 4.1 shows how E3ME's economic module is solved for each region, illustrating the main flows in the model. Most of the economic variables shown in the chart are solved at the sectoral level. The whole system is solved simultaneously for all sectors and all regions, although single-country solutions are also possible.

One of the core results from the model is the level of output, which is the total level of production within a sector. The measure is equivalent to the turnover of a company. Production may occur to meet the demands of other companies ('intermediate demand'), for households or government to consume, or as part of investment.

The production itself requires inputs from other sectors as well as inputs from labour and may be subject to taxes. Anything left is the operating surplus that is taken as profit. Gross Value Added (GVA) is the sum of the labour inputs, profit, and production taxes.

Figure 4.1: E3ME basic economic structure



The input-output (IO) tables determine the relationships between the sectors in each region and is another critical data input to the model. Combined with the trade relationships in the model, E3ME may be described as having a Multi-Regional Input-Output (MRIO) core.

The loops of interdependency

The model includes a mixture of accounting identities and behavioural relationships. These combine to produce several positively reinforcing loops in the model, meaning that initial increases may be amplified. These can also be seen as versions of the Keynesian multipliers that were first formalised in Cambridge in 1931 (Khan, 1931).

As noted above, output (and therefore employment) is determined by the levels of effective demand, unless there are constraints on available supply. Figure 4.1 shows three loops (or circuits) of economic interdependence, which are described below. In addition, there is an interdependency between the sectors that is not shown in the figure.

- The income loop: If a sector increases output, it may also increase employment, leading to higher incomes and additional consumer spending. This in turn feeds back into the economy, as given by a Type II multiplier.
- The investment loop: When firms increase output (and expect higher levels of future output) they must also increase production capacity by investing. This creates demand in sectors that produce investment goods (e.g., construction, engineering) and their supply chains.
- The trade loop: Some of the increases in demand described above will be met by imported goods and services. This leads to higher demand and production levels in other countries. As a result, there is also a loop between countries.
- Interdependency between sectors: If one sector increases output it will buy more inputs from its suppliers who will in turn purchase from their own suppliers. This is similar to a Type I multiplier.

4.2 Calculation of each component of demand

Consumer demand

Consumer demand is commonly referred to as household consumption/spending. Estimating household consumption is a two-stage process. Total household consumption by region is derived from functions estimated from time-series data. These equations relate consumption to regional personal disposable income, a measure of wealth for the personal sector, inflation, and interest rates. Share equations for each of the detailed consumption categories are then estimated. In the model solution, disaggregated consumption is always scaled to be consistent with the total.

Investment demand

Investment demand (measured as Gross Fixed Capital Formation) is determined through econometric equations estimated on time-series data. Expectations of future output are a key determinant of investment, but investment is also affected by relative prices and interest rates.

Unfortunately, due to data limitations, investment is not disaggregated by asset in E3ME. Stockbuilding is treated as exogenous in the model.

Intermediate demand

Intermediate demand (the sum of demand from other production sectors) is determined by the input-output relationships in the model. When one sector increases its production, it requires more inputs to do so, increasing demand in the sectors in its supply chain. Input-output coefficients for energy and material demand may vary in response to price changes, but other input-output coefficients are fixed.

Trade

Trade in E3ME makes use of the time-series data for bilateral trade that are available from Comtrade and the OECD. The approach has four stages:

- For each country, total imports are estimated using equations based on time-series national accounts data. Import volumes are determined primarily by domestic activity rates and relative prices.
- Separate bilateral equations for import shares are then estimated for each destination region, sector, and origin region.
- Bilateral imports are then scaled so that they sum to the total estimated at the first stage.
- Finally, export volumes are determined by inverting the flows of imports.

The fossil fuel sectors trade commoditised products and so the bilateral trade specification (which assumes differentiated production) is not appropriate. Cost-supply curves are instead used to determine the source of fuel supply (see Section 5.7).

Government demand

Government consumption is given by assumption, split into the main different components of spending. It is therefore exogenous in the simulations and does not change unless explicitly requested by the modeller.

The full accounting balances and econometric specifications, including the theory behind key relationships, are given in Chapter 7.

4.3 Treatment of supply and capacity constraints

Total output by product, in gross terms, is determined by summing intermediate demand and the components of final demand (described above) and subtracting the share that is met by imports. This gives a measure of effective demand for domestic production.

In E3ME, it is assumed that domestic supply adjusts to match the level of effective demand (see Figure 4.2 for how this is implemented within the National Accounts structure). This is consistent with the underlying theory that there is usually spare capacity available (see Section 3.1). This approach has the same effect as using an input-output system to produce its own multipliers, and it is indeed possible for E3ME to produce its own estimates of multipliers.

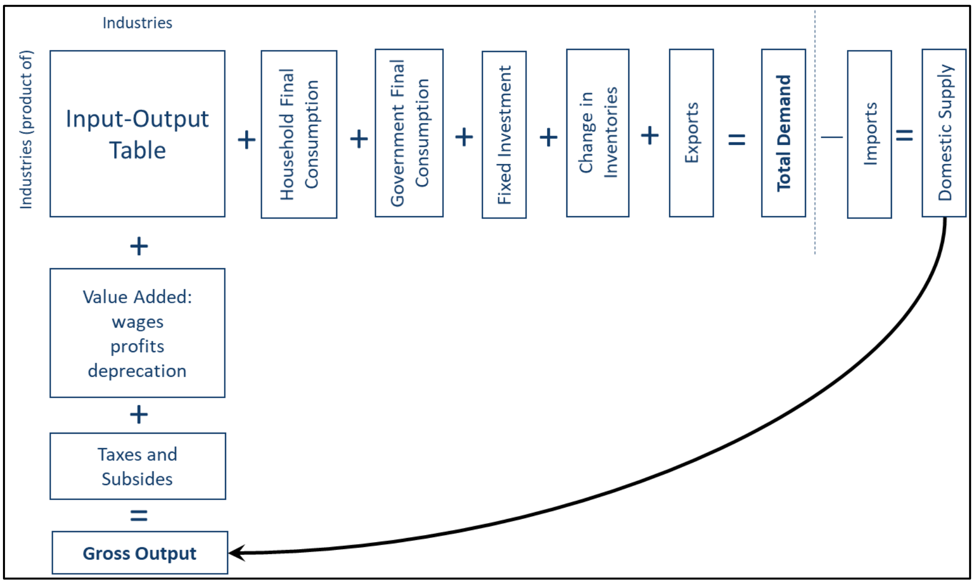
However, in contrast to simple input-output tools, E3ME includes restrictions on how much can be produced in the economy. Notably, there is a hard constraint on the potential labour supply in the model (see Section 7.3.12). Once the level of employment starts to get close to full employment (i.e., unemployment falls towards zero), wage rates increase, and jobs may be displaced from other sectors. If higher wage rates feed through to product prices, a cost-push inflationary spiral is possible. At this stage the model results become highly uncertain, reflecting the level of instability and fragility that we would see in a booming economy.

More generally, economists sometimes refer to the ‘output gap’ as the difference between actual and potential output. The output gap is non-observable, so E3ME includes implicit estimates at sectoral level. The measures are estimated econometrically and feed into pricing and investment decisions (see Section 7.3.15). If actual output increases faster than expected, both prices and investment will increase.

It is important to note that the measures of potential output are themselves endogenous, depending on a combination of expectations of future production and investment/technology accumulation.

There is no fixed limit on the size of the money supply or available finance (see Section 4.5).

Figure 4.2: Determination of supply and demand



4.4 Treatment of Prices

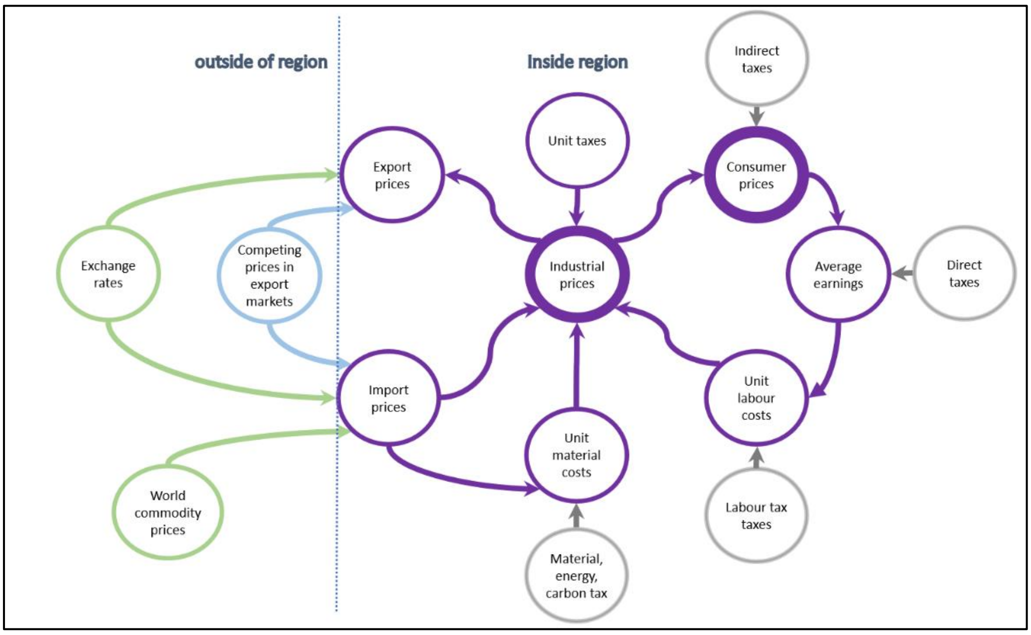
For each real variable in E3ME there is an associated price, which influences the level of effective demand. For example, each category of household expenditure has a price variable attached to it, which influences consumption patterns within the model.

Aside from wages, there are three econometric sets of price equations in the model (see Chapter 7):

- domestic production prices
- import prices
- export prices

These prices are influenced by unit costs (derived by summing labour costs, material costs, and taxes), as well as competing prices and technology. Each one is estimated at the sectoral level for each region in the model.

Figure 4.3: Price determination in E3ME



Consumer price inflation

One of the key price variables in the model is the price of domestic consumption. It is also determined initially by sector, by taking a weighted average of domestic and import prices, subtracting off the export component. This price is then used to determine the prices for final consumption goods; for example, if the car industry increases prices, this will be reflected in the price consumers pay for cars.

Aggregate regional deflators, including the Consumer Price Index, are derived by taking the average of prices across all products and sectors.

4.5 The financial sector

The financial sector plays a critical role in the modern economy, and this is reflected in E3ME. Treatment of the financial sector is one of the key features of the model that differentiate it from competing approaches (Pollitt and Mercure, 2018).

An endogenous money supply

The most important characteristic of the model's treatment of finance is its 'endogenous' money supply. As described in Section 3.1, the model follows post-Keynesian theory and uses a credit-based understanding of money that is recognised by the Bank of England (McLeay et al, 2014), empirically validated (Werner, 2014; 2016), and supported by anthropological evidence (Graeber, 2014).

When a bank advances a loan, it creates purchasing power for the borrower, while simultaneously creating an asset for itself. It does not need to reduce the volume of its lending to other firms or other sectors of the economy and there is no 'crowding out' effect. The total supply of money is increased.

The only limit on the supply of money is the willingness of banks to lend and businesses to borrow. This willingness may be influenced by expected rates of future growth in the economy and the rate of interest (see equation specification in Section 7.3.5), although the estimated model parameters suggest that the rate of interest typically only has a minor impact on investment decisions.

Investment and savings

The model maintains the identity that investment and savings should balance (at global level). However, the direction of causality is reversed from a standard CGE model. First, the money is created by the financial sector from where it may be used for investment. Saving happens at the end of the chain, potentially after several layers of economic transactions.

Money and inflation

An increase in the money supply may lead to higher inflation. However, the link between money creation and inflation is an indirect one, coming through the real economy. Prices will increase only if the additional demand moves the economy towards capacity constraints (see Section 4.3). There is no assumption that an increase in the volume of money will be cancelled out through inflation in either the short- or long-term (i.e., there is no assumption about the 'neutrality' of money).

Representation within the model

Historically, much of the financial system has been represented implicitly within the E3ME model. However, from version 8 onwards, sectoral financial balances are incorporated so that debt levels can be tracked across the projection period.

There remain substantial challenges in providing a full representation of the financial system, for example, on how to treat international financial flows, including FDI and repatriation of profits. This, therefore, remains an area for future model development.

At present there is no estimation of asset prices within E3ME. The model is, however, linked to other tools that carry out such calculations.

Interest rates

Early versions of E3ME adopted a 'horizontalist' approach to money (Moore, 1988), meaning that interest rates were fixed as exogenous. This is still one possible model specification. An alternative approach is to adopt a 'Taylor Rule', in which central bank behaviour is mimicked and interest rates respond to changes in consumer prices.

It is important to note that, even under this alternative approach, interest rates respond to developments in the real economy, rather than financial variables.

Exchange rates

Modelling exchange rates is difficult because relative rates tend to reflect investors' expectations rather than current economic activity rates. Some endogenous representation has been attempted in E3ME, although it is unclear that there is much overall difference to a fully exogenous approach. This remains an area for potential future development if further financial variables are added.

4.6 The role of technology

Why endogenous technology is important

Traditionally, the debate about technology in models has been whether it should be treated as exogenous or endogenous. Under a neoclassical production function, technological progress has often been represented as exogenous (e.g., via a time trend) or as a residual. Both methods have their drawbacks. The neoclassical approach is somewhat circular in its logic, i.e., to know a firm's production possibilities one needs to model technological progress, but in modelling technological progress one is already making an assumption about the production process. The time trend approach is also unappealing given its theoretical background.

In any case, the solar revolution has proven beyond doubt that the direction and rate of technological change is determined by what is going on in the wider economy, i.e., it is endogenous to the system. A relatively modest set of initial policies drove down solar costs, leading to higher uptake and further massive cost reductions. An endogenous representation of technology is therefore required in any macroeconomic model with claims to be a good representation of reality.

From theory to model

However, technology still remains difficult to model. As noted in Section 3.1, post-Keynesian economics has struggled to integrate technological development and long-term economic growth, and there remains an important gap between Keynesian and Schumpeterian approaches.

The two standard ways of representing technology in an economic framework are:

- The bottom-up approach – a list of technologies is included in the model and selected according to price and other characteristics.
- The top-down approach – technologies are implicit and represented as, for example, indices of progress leading along an explicit or implicit pathway.

Both approaches have shortcomings. By design, the bottom-up approach excludes potential future technologies, whereas the top-down approach largely ignores the potential transformational effects of new technologies. Ultimately, without knowing the future, any representation of technology will be partial.

Complexity-based approaches (e.g., Arthur, 2010) or evolutionary methods based on Nelson and Winter (1982) offer a way forward and are more consistent with fundamental uncertainty. However, they are not easy to fit into a modelling framework with fixed dimensions like E3ME.

Representation in E3ME

Despite these difficulties, technology is very much at the heart of E3ME and is fully integrated in the model. There are three ways that technology is represented in the model:

- For key energy-using technologies, a bottom-up approach called FTT is applied. This is described in Chapter 5.
- For other sectors, a top-down index-based approach is applied at sectoral level. This is described below.

- For specific technologies that are not covered in FTT, scenarios may be designed to represent the characteristics of those technologies and different rates of exogenous take-up are tested.

Product and process innovation

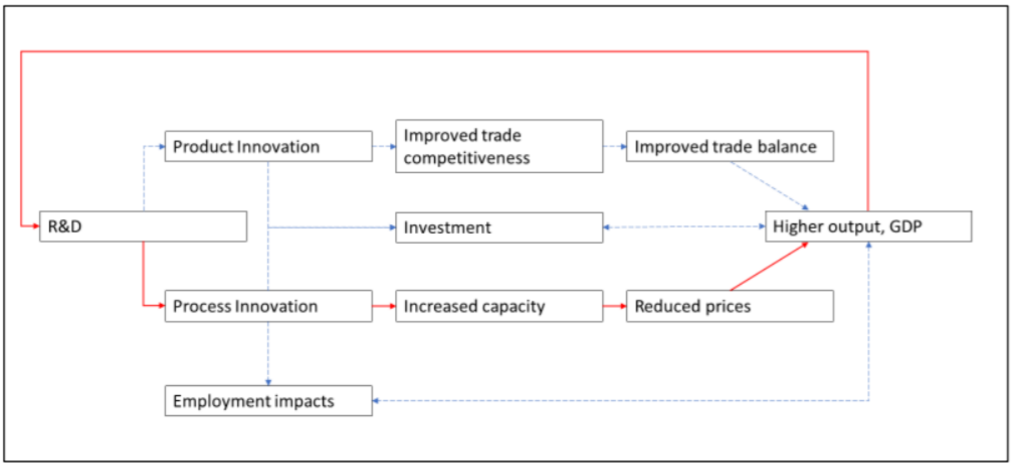
Figure 4.4 shows the main paths of innovation in E3ME. The figure is taken from modelling that was carried out for the UK government (BEIS, 2020). The subject of that report was the UK's R&D targets, but innovation may also be linked to investment.

The red line in the figure shows the path of process innovation (producing the same things but more efficiently). This approach is broadly consistent with mainstream theories of endogenous growth (e.g., Romer, 1990) and is well covered in the post-Keynesian literature (see Lavoie, 2014, p428). R&D and the expansion of knowledge improves efficiency, reduces prices, and drives growth as well as further R&D.

The treatment of product innovation (producing new things) is less standard. Product innovation improves quality and drives non-price competitiveness. This will change trade patterns and incentivise further investment and R&D in countries that capture larger market shares.

Both types of innovation will likely boost investment to some degree. Their relationships with employment are more complex; process innovation is likely to reduce employment, but higher rates of production will increase the demand for labour.

Figure 4.4: Innovation in E3ME's economic module



Specification

Technological change is irreversible[1] and is determined by the accumulation of stocks of knowledge and capital. The idea of a knowledge stock is non-controversial and is used as the basis for advances in technology across many different fields (e.g., Beinhocker, 2007). The idea of a capital stock has been controversial, especially within post-Keynesian economics (Cohen and Harcourt, 2003) but the representation in E3ME is disaggregated by sector

[1] Although some depreciation is possible, and a depreciation rate of 10% is applied to the stock variables in E3ME.

(and region), with no movement of capital between sectors. This approach addresses some of the earlier criticisms of the use of capital stock as a measure.

Recent work on innovation has emphasised the importance of knowledge spillovers in determining technological advances (Hidalgo and Hausman, 2009; Mealy and Coyle, 2021). R&D spillovers are included in the model, based on patent data. Spillovers may occur both across sectors and between regions. They are treated as 'virtual R&D', i.e., as if the sector itself was carrying out the R&D, but without any cost attached.

4.7 Labour market, skills, and income

Treatment of the labour market is another area that distinguishes E3ME from other macroeconomic models. E3ME includes econometric equation sets for employment (as a headcount), average working hours, wage rates, and participation rates. The first three of these equations are disaggregated by economic sector while participation rates are disaggregated by gender and five-year age band.

The labour force is determined by multiplying labour market participation rates by population. Unemployment (both voluntary and involuntary) is determined by taking the difference between the labour force and employment.

Labour market interactions

There are important interactions between the labour market equations. They are summarised below:

- Employment = F (Economic output, Wage rates, Working hours, …)
- Wage rages = F (Labour productivity, Unemployment, …)
- Working hours = F (Economic output in relation to capacity, …)
- Participation rates = F (Economic output, Wage rates, Working hours, …)
- Labour supply = Participation rate * Population
- Unemployment = Labour supply – Employment

The full specification for the econometric equations is given in Chapter 7.

Analysis of skills

E3ME includes measures of skills demand which are derived from the model results for sectoral employment, an off-model estimation of the occupation, and qualification trends. It does not include a measure of skills supply. In the literature, skills are proxied through occupations following ILO's definition of the four skills levels (ILO, 2012). Demand for skills is measured through occupational shares within sectors and qualification shares within occupations.

The occupational and qualification modelling is based on Cedefop (2012) methodology (Cedefop 2012). The occupational/qualification forecasts are based on either fixed-share coefficients (in the case of few observations) or linear/ logistic trend-extrapolated coefficients.

Nevertheless, it is important to be aware of the limitation in skills treatment within the main model structure. If a modelled scenario shows an increase in employment, it is implicitly assumed that workers with the necessary skills are available. For studying large changes in employment, a supplementary bottom-up analysis is required to test the feasibility of the model results.

Incomes

Due to limitations in the available time-series data, E3ME adopts a representative household for each region in its core calculations. Household income is determined as:

- Income = Wages – Taxes + Benefits + Other income

The taxes currently distinguished are standard income taxes and employees' social security payments (employers' social security payments are not included in wages). A single benefit rate is used for each region.

'Other income' includes factors such as dividend payments, property rent, and remittances. At present, it is not possible to derive data for these financial flows, so they are either estimated, fixed, or held constant in relation to wages.

Household income, once converted to real terms, is an important component in the model's consumption equations, with a one-to-one relationship assumed in the long-run (see full equation in Chapter 7).

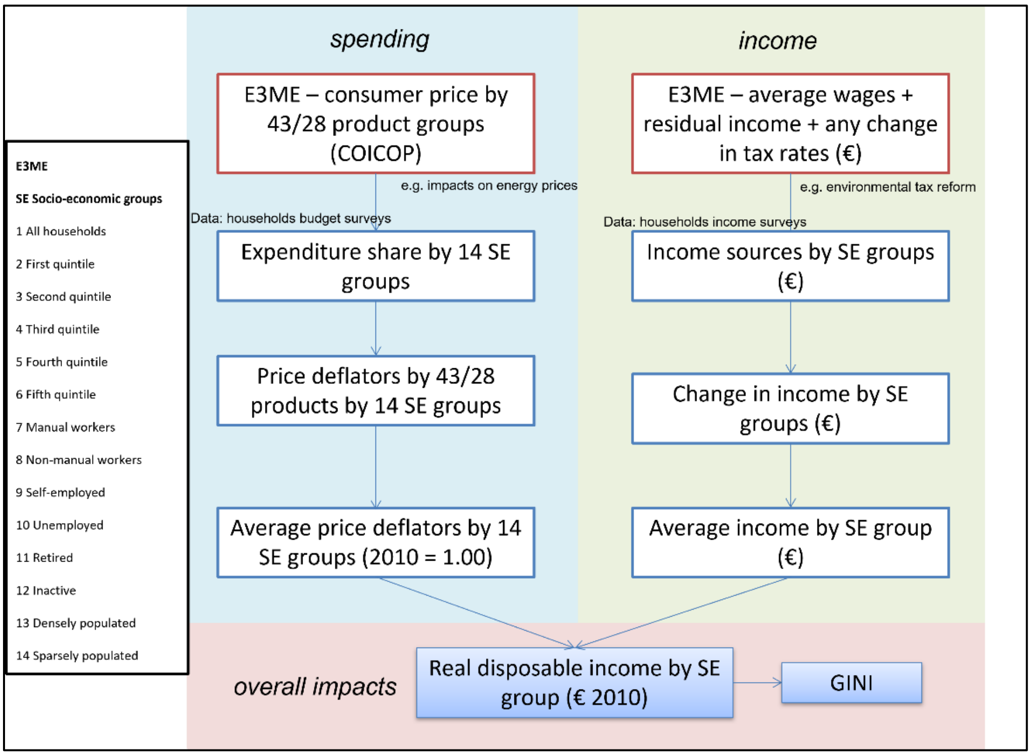
4.8 Income distribution

it is important to recognise the limitations of a macro-sectoral model when considering questions about inequality and income distribution. For a detailed analysis of income distribution, a microsimulation model, such as Euromod (Sutherland et al, 1999; 2013) is required.

Nevertheless, an approximation of distributional effects may be possible with E3ME. As noted above, data limitations mean that a representative household is used in the econometric equations, but a supplementary analysis offers some disaggregation of household types. Unfortunately, this approach means that no feedback to the other model equations is currently possible, unless specified exogenously by the model user as part of a scenario.

Figure 4.5 summarises the approach. It is important to note that the approach depends on data on expenditure patterns being available for each household type. Generally, the data are available for OECD countries and the World Bank provides more aggregated estimates for many developing countries.

Figure 4.5: E3ME's treatment of income distribution



Income The approach is based on two components. The first of these is the income component: for each social group, the shares of their income from wages, benefits, and other income (minus their tax deductions) are scaled in line with the aggregate model results for wages and benefits, etc. For example, a scenario that includes increases in benefit rates would show positive results for low-income groups who rely more on benefits.

Spending The second part links household expenditure survey data to the model results for consumer prices. This is mainly used to assess the effects of higher energy prices, as in many countries low-income households use a larger share of their incomes for space heating. A rise in energy costs would therefore reduce their real incomes disproportionately.

Gini coefficients The results for distributional income have been extended to provide an expenditure-based version of the Gini coefficient (by interpolating the income quintiles). While the available data mean that it is not possible to create a Gini coefficient based on changes in income, we can assess the real expenditure effects to give an equivalent measure. This would give results in the following form: "This policy affects the real spending power of all income groups; its distributional impacts are equivalent to a change in the Gini coefficient of X.X%."

Limitations There are many limitations to this approach, reflecting the available data. For example:

- It is not possible to estimate different responses to higher costs (e.g., for energy) among the groups. For example, it is often suggested that high-income households have access to finance to pay for energy efficient equipment, which could be reflected by a higher price elasticity.

- It is not possible to consider how changes in wage rates affect particular social groups. For example, there is no linkage between sectoral employment and the social groups, and it is not possible to address differences in wages within sectors.
- The approach cannot address heterogeneity within the groups. For example, model results suggest that higher costs for motor fuels often affect low-income households less, as they are less likely to own a car. But low-income households that do have cars will still be affected.

In summary, the results should be considered carefully in the context of the scenarios modelled and at times perhaps viewed with caution. Nevertheless, the approach can give at least an indication of the type of distributional effects expected, possibly suggesting grounds for further analysis with a dedicated microsimulation tool.

4.9 Further regional disaggregation of results

With certain assumptions, regional E3ME results may be disaggregated to more granular spatial resolution in various applications. For example, results for the ASEAN region can be disaggregated to country level. For European regions, further disaggregation to sub-national level is possible.

This approach is not intended to replace dedicated models but has the advantage of giving indicative results that are consistent with global scenarios.

Country level

The underlying assumption in the country-level disaggregation is that the basic trends within a regional grouping of countries are consistent. For the variables of interest external data are obtained for all countries which form the E3ME aggregate (e.g., in the case of the Central Africa OPEC region this means Angola, Equatorial Guinea, Gabon, and the Republic of the Congo). As usual, international datasets are preferred (see Section 6.1), with proxies used to fill missing values. Shares of activity within the aggregate region are estimated and used to obtain weighted results of the regional impacts. From these, country-level impact magnitudes are derived.

It is important to note that this is a static disaggregation method, with the underlying assumption that the relative importance of each country within the aggregate region remains unchanged. This method also assumes that within the aggregate E3ME region the impacts in relative (percentage) terms are equal across each country.

Per capita adjustment

To account for different population growth rates between countries, a further adjustment is made. The method keeps constant the relative per-capita GDP across each country (e.g., a country that currently has a GDP double that of the aggregate region will stay that way). The projected values are calculated in the following way:

$$y_{FC} = \frac{z_{CC}}{z_{CA}} * \frac{p_{FC}}{p_{FA}} * y_{FA}$$

where y is the variable of interest, z is the per capita version of y, and p is the population. In the first index F stands for forecast, and C is the current (historical) value. In the second index C is the country and A is the aggregate.

In words: the projected country-level variable is formed by multiplying the projected E3ME aggregate level variable with two ratios:

- the ratio of the current per capita country level and E3ME aggregate level variable
- the ratio of the projected population at country level and the E3ME aggregate level

These two ratios correct the projected variable value with the different population growths of the countries.

Sub-national regions (NUTS)

Within Europe, sub-national extrapolation of results is also possible, to both the NUTS-2 and NUTS-3 level. Results for employment and GVA can be derived, subject to available data. The method, based on the one presented in Mayor et al (2007), combines historical data to determine regional competitiveness. Auto-Regressive Integrated Moving Average (ARIMA) modelling is used to project competitiveness factors forwards and E3ME scenario results for national level impacts.

Shift-share model

First, the shift-share model defines growth rates at three separate levels based on historical data:

- Total growth rate at the national level
- Sectoral growth rate at the national level
- Sectoral growth rate at the regional level

A dynamic shift-share approach is used to calculate the components for every period and for every variable of interest. Then the results are aggregated over the full historical period.

ARIMA forecasting of the competitive component

Then, to generate a forecast of the competitiveness factor (sectoral growth rate at the regional level), obtained through the shift-share model, ARIMA modelling is used. The ARIMA models are based on the idea that data can be thought of as the realisation of a stochastic process. The goal is to find a simple model that captures the essential characteristics of the stochastic process (i.e., to achieve pattern replication rather than pattern explanation). As such, the only pieces of systematic information used in time-series modelling are the past behaviour of that series and the deterministic components (such as constants, dummy variables, time trends, etc.)

These models are estimated through Maximum Likelihood Estimators (MLE) and are characterised by three main parameters:

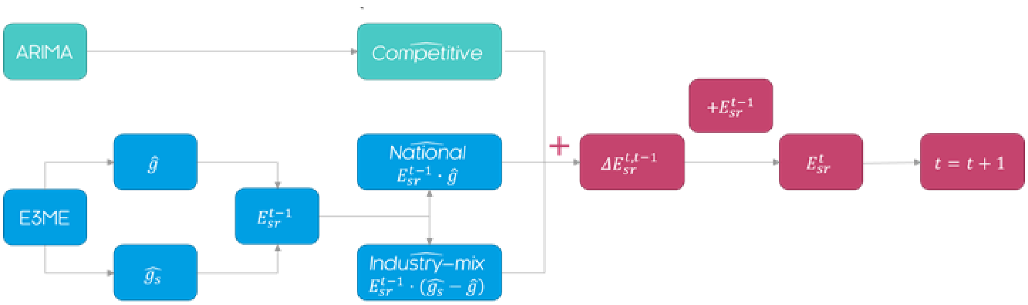
- p: the order of the autoregressive (AR) part of the model
- d: the degree of first differencing required to achieve stationarity
- q: the order of the moving average (MA) part of the model

ARIMA models can be augmented with further explanatory variables (provided forecasts are available for these additional / extra variables), forming ARIMAX models. A time-series with the competitive effect of the economic variables is obtained using the dynamic shift-share and regional population projections, and a separate ARIMAX(p, d, q) model is specified for each sector of each region within each country.

Reverse dynamic shift-share

Finally, the ARIMA(X) forecasts are integrated with E3ME results. The following recursive process is applied for each time period of the forecast horizon. This process could be seen as a ‘reverse dynamic shift-share’: as forecasts of the three shift-share components are combined to give expected change in the variable year-by-year and eventually to give the final predictions of the variable levels. Figure 4. summarises the main steps.

Figure 4.6: Approach to deriving sub-national results



5 E3ME's Energy and Environmental Modules

5.1 Introduction

Energy demand data in E3ME cover the use of 12 different fuels by 23 fuel users. The representation of energy demand in E3ME incorporates elements of both top-down and bottom-up modelling approaches. Whilst economic activity has been an important driver of energy demand throughout history, the relationship between economic activity and energy demand is becoming more complex as new technologies are developed and the efficiency of processes are improved. We have already started to see a decoupling of energy demand and economic activity in advanced economies, and it is likely that this trend will continue as efforts are ramped up to decarbonise the global economy. To best represent the complex effects of technological change on energy demand within E3ME, we have replaced top-down econometric equations with bottom-up models of technology take-up where data are available.

This chapter describes the bottom-up technology-detailed models of energy demand, as well as the broader econometric approach that is used for modelling energy demand in those sectors where technology-specific data are unavailable.

The FTT models

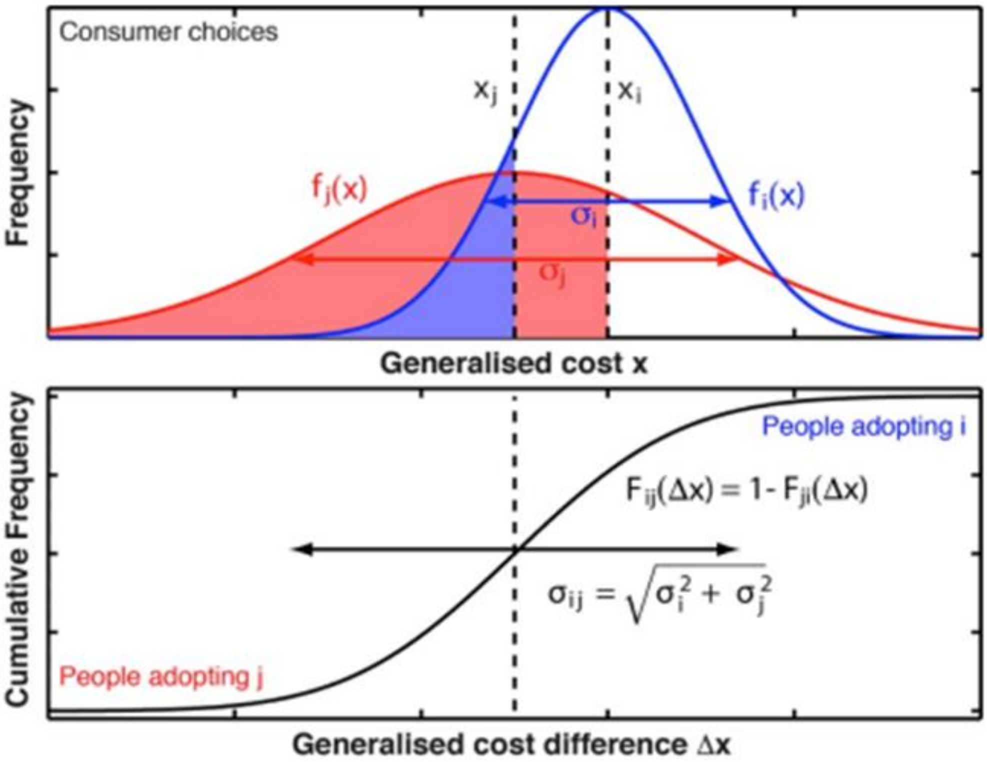
For key energy-using sectors, E3ME incorporates a set of evolutionary models called Future Technology Transformations (FTT). These tools simulate technological decision making. Investments, end-use prices, and energy consumption are fed back to the economy module and the rest of the energy module from the technological choices.

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.

Figure 5.1 represents the distribution of consumer preferences regarding investment in two alternative technologies (as shown in the top panel). This determines cumulative take-up for those technologies (as shown in the bottom panel). FTT considers the expected variation in both agent preferences and the technology costs when calculating rates of technology take-up. The relative preference of agents for technology *j* over technology *I* is denoted with the matrix $F_{ij}(x)$, a fraction between 0 and 1. This leads to shares of technologies being transferred between technological categories as agents gradually replace the stock.

Figure 5.1 Schematic representation of pair-wise comparison of technological options by heterogenous agents with varying preferences in FTT.



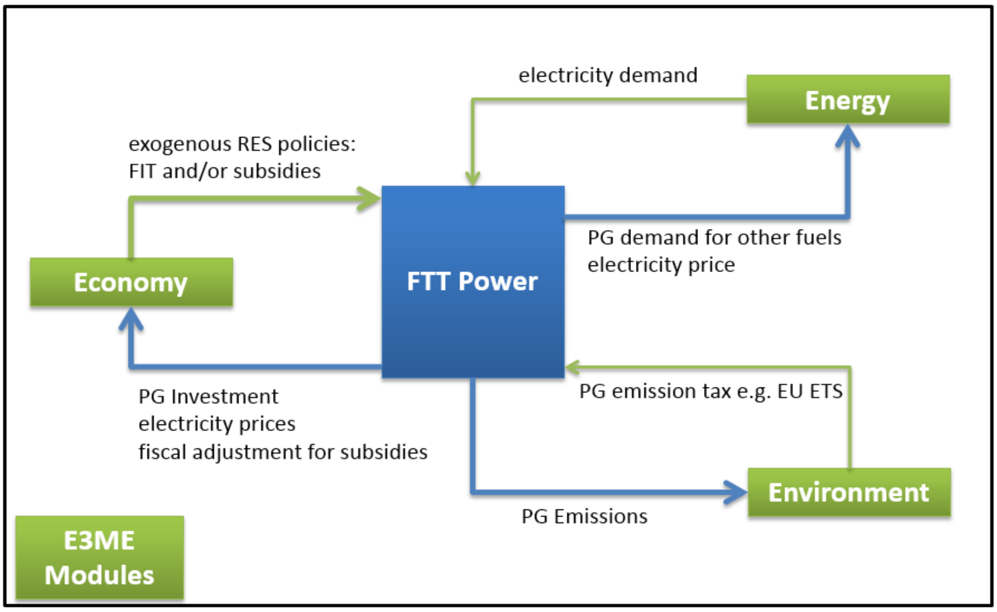
5.2 FTT:Power

The original FTT model covered the power sector. It is described in Mercure and Salas (2012) but has since been developed further, notably in the treatment of dispatch (see below). FTT:Power covers 24 technologies that compete for market shares. The model considers the perspectives of investors and dispatchers. Investor decisions follow from the replicator dynamics described in Section 5.1 and are motived by cost minimisation. Dispatchers allow technologies based on merit order and seek to maintain grid stability. The choices that investors make have consequences for the dispatchers and vice versa.

Depending on the type of technology, systemic constraints play a role in the diffusion. The uptake of variable renewable energy (VRE) sources, such as solar PV and wind power, will require intermittent capacity or storage capacity. To estimate these effects, FTT:Power incorporates residual load-duration curves (RLDCs) developed by (Ueckerdt, et al. 2017). These curves are parameterised using the share of energy generated by wind and solar PV and determine the load that all other non-VRE technologies must supply. The RLDC reports back the load factors for non-VRE technologies, the amount of electricity that is curtailed and the amount of short-term storage that is needed given the current mix of technologies. Separated from the RLDC, long-term storage is based on the installed capacity of power generation technologies and how often the capacity runs.

As shown in Figure 5.2, FTT:Power's main feedbacks to the rest of E3ME are investment requirements, electricity prices, energy use, and emissions. In addition, jobs in the power sector are calculated in a bottom-up fashion by applying technology-specific employment coefficients.

Figure 5.2 Feedback from FTT:Power to E3ME modules



The integration of FTT:Power allows for simulation of a much wider range of policies, including feed-in-tariffs, subsidies on capital investment, energy tax/subsidies, carbon pricing, government procurement programs, and phase-out regulations.

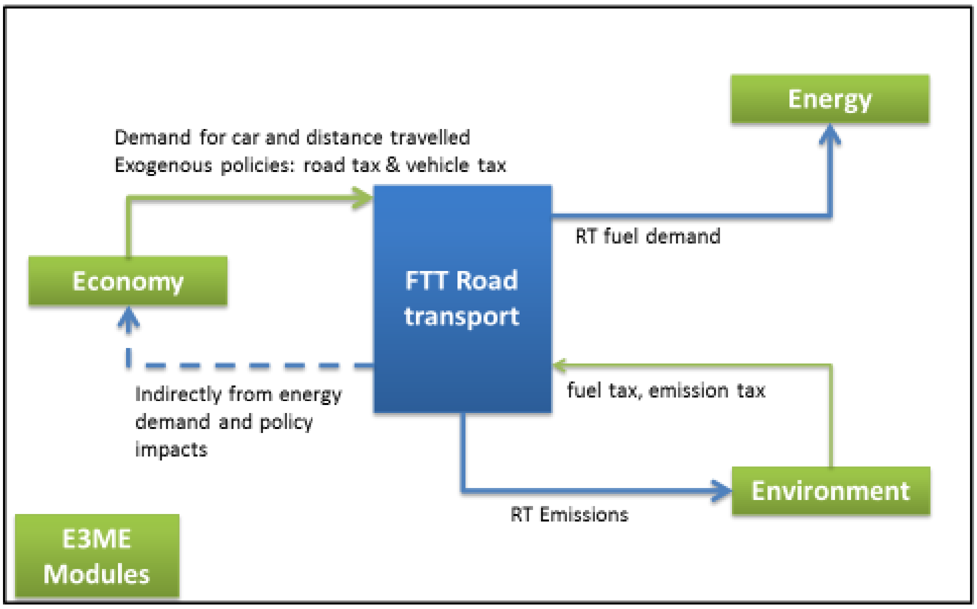
5.3 FTT:RoadTransport

With road transport contributing a large share of global emissions and fuel use, having a reliable description of consumer decisions on vehicle purchases and use is essential (Mercure et al, 2018). The standard approach of optimisation disregards consumer preferences and therefore sits far from the observed reality. Many consumers buy the most expensive car they can, rather than the cheapest.

FTT:RoadTransport covers 25 different vehicle types consisting of different power trains and engine sizes. Decision making regarding these preferences, along with sub-optimal behaviour, is captured in FTT:RoadTransport (Mercure and Lam, 2015). Using the levelised cost of transport, all vehicle types are compared on a pair-wise basis. To account for regional consumer preferences, an adjustment factor has been introduced which captures intangible costs.

Based on the vehicle fleet composition and use, consumer expenditures on vehicle purchases and transport-related fuel expenditure are fed back to E3ME, as shown in Figure 5.3.

Figure 5.3 Feedback from FTT:RoadTransport to E3ME modules



FTT:RoadTransport allows for simulation of a wide range of real-world policies, including road taxes, vehicle taxes, carbon-related fuel taxes/subsidies, fuel standards, subsidies on upfront purchase prices, phase-outs, and government procurement programs.

5.4 FTT:Heat

FTT:Heat (Knobloch et al, 2018; 2021) simulates households' choices for heating technologies. The model is driven by useful energy demand for residential heating, which is assumed exogenously. A household's useful energy demand for heating is assumed to be independent of the heating technology used, but determined by characteristics such as climatic conditions, building characteristics, household size, household income, and individual preferences for room and water temperatures.

FTT:Heat covers 13 heating technologies that compete to deliver the useful energy demand for heat. Final energy demand is derived from the useful energy demand delivered by heating technologies and the respective conversion losses. Consumers invest in capacity, but FTT:Heat does not capture behavioural aspects that may change how the heating technologies are used. To a degree, behaviour is captured by the total residential useful energy demand. Usage of heating technologies is, however, affected by climate zones, which serves as an indicator for capacity factors.

Based on the technology mix, consumer expenditure on heating equipment and fuel expenditure are fed back to E3ME.

Possible policies that can be assessed in FTT:Heat include upfront subsidies, energy taxes/subsidies, phase-outs, and government procurement programs.

5.5 FTT:Steel

As the fourth member of the FTT family, FTT:Steel captures technological diffusion within the iron and steel sector. The steelmaking process is subdivided into four stages: 1) Pre-processing of raw materials (e.g., coke production from coal, agglomerating of iron ore with limestone); 2) Ironmaking (the chemical reduction of iron ore to metallic iron); 3) Steelmaking (further refinement of iron by e.g. reducing the carbon content); and 4) Finishing (e.g. rolling of crude steel to produce steel sheets).

FTT:Steel covers 26 steelmaking pathways which include several components of the stages described above, with the exception of steel scrap recycling (which bypasses the pre-processing and ironmaking stages). All pathways can include steel scrap in the steelmaking process which would proportionally displace the need for the two preceding stages.

Given constraints and input prices, the 26 pathways compete for market shares, while the levels are determined by domestic steel production which is driven by E3ME's overall demand for production in the basic metals sector.

The availability of steel scrap is a constraint for diffusion of the recycling pathway as it is likely that steel demand will outweigh scrap supply (Pauliuk, et al. 2013). Given the dynamics of scrap availability and the potential for each process to use scrap (to a degree), a lifecycle inventory approach is followed to determine the inputs required to produce 1 kton of crude steel through each pathway at any stage of the simulation.

Based on the technology mix and scrap availability, FTT:Steel reports back investment needs, energy and material demand, steel prices, and employment in the iron and steel sector.

The policies covered by FTT:Steel include public capital investment, energy and material taxes/subsidies, carbon pricing, carbon border adjustment mechanisms, government procurement programmes, and phase-out regulations.

5.6 Other final demand

In those sectors where there are insufficient data available to construct a bottom-up model of energy-using technologies, energy demand is instead modelled using a top-down econometric approach. In these cases, the demand for energy is modelled as a function of economic activity and relative energy prices.

5.7 Global energy supply

Global energy prices are determined by available supplies and the cost of extracting these supplies. A survey of renewable resources was carried out by Mercure and Salas (2012). This database provides cost-supply curves covering 90 countries and can be re-aggregated to various configurations of regions following the development of E3ME.

The database also includes a review of non-renewable fossil and nuclear fuels. These however are not used as cost-supply curves since such curves would need to change as consumption progresses. Instead, a dynamic model of resource consumption was introduced, which tracks how a cost-distribution of resources is gradually depleted. This is parameterised by the current rate of reserves to resources ratios for these fuels and determines a dynamic marginal cost (Mercure and Salas, 2013).

At present the model baseline assumes that ratios of extraction to reserves remain constant. However, these parameters may be adjusted to test scenarios for different market strategies, for example, of OPEC responses to declining global oil demand (see e.g., Mercure et al, 2018b).

It is anticipated that future versions of E3ME will develop the energy supply module further to incorporate transportation costs and a more comprehensive treatment of the refining sector.

5.8 Emissions

The emissions module calculates air pollution generated from the end-use of different fuels and from primary use of fuels in the energy industries themselves, particularly electricity generation. The current emissions included are:

- carbon dioxide (CO_2)
- sulphur dioxide (SO_2)
- nitrogen oxides (NOx)
- carbon monoxide (CO)
- methane (CH_4)
- larger particulates (PM_{10})
- volatile organic compounds (VOC)
- chlorofluorocarbons (CFCs)
- nitrous oxide (N_2O)
- hydrofluorocarbons (HFC)
- perfluorocarbons (PFC)
- sulphur hexafluoride (SF_6)

These last four, together with CO_2 and CH_4, constitute the six greenhouse gases monitored under the Kyoto Protocol.

CO_2 emissions

Data for CO_2 emissions from energy consumption are available for each of the energy users in the model. Coefficients (tonnes of carbon in CO_2 emitted per toe) are implicitly derived using historical data (and sometimes also baseline projections). This forms the relationship between energy consumption and emissions.

Process CO_2 emissions, such as those from the chemicals and cement sectors, are also included explicitly in the modelling, but are linked to production from those sectors rather than to energy consumption.

Other emissions

The treatment of other emissions is less detailed, and results are not usually disaggregated by sector. In addition, it should be noted that many of the impacts of the other emissions (e.g., PM_{10}) are localised and cannot be captured by a model that operates at national level.

The general approach is to link these emissions to a small set of sources that fit into the model variables, such as consumption of a particular fuel or output of a particular economic sector. Linear coefficients are then formed to link these activity sources to emission levels.

While this ensures that the model results match published totals, and gives an indication of possible outcomes from policy, it is not intended to replace more specialised tools. For example, E3ME would not be an appropriate tool to assess policies to reduce methane in the agricultural sector because it does not include the necessary detail; a dedicated (partial) agricultural model would instead be required.

5.9 Material demand

It is still the case that very few macroeconomic models currently include physical measures of material consumption, although environmentally extended input-output analysis is much more common. The advantage that E3ME offers over the input-output approach is its dynamic nature. Rates of material intensity are allowed to change in response to price and other economic factors, rather than following a fixed input-output structure. This means that, as well as explaining the past, E3ME can be used to project forwards material consumption and to test scenarios of policies aimed to reduce material consumption.

Material types

E3ME estimates material consumption in each region of the model. At present the following material types are modelled:

- Food
- Feed
- Forestry
- Construction minerals
- Industrial minerals
- Ferrous ores
- Non-ferrous ores

These categories match the aggregate categories that feature in most of the standard datasets (e.g., Eurostat). In future they could be expanded further for specific analysis, for example, to assess production possibilities for materials where shortages may be possible in future.

Material variables

E3ME principally uses Domestic Material Input (DMI) as its measure of material consumption, although exports (X) can be separated to get Domestic Material Consumption (DMC), and imports (M) removed to get Domestic Extraction (DE).

The basic model structure does not include rucksack measures or estimates of unused materials, but Total Material Requirement (TMR) is estimated using a coefficient method, fixing the ratio of TMR to DMI.

Imports and exports in Raw Material Equivalent units (RME) are included in the model to derive Raw Material Consumption (RMC).

Basic structure

The basic structure of the material demand equations is similar to that of the equations for aggregate energy demand (see Section 5.1 and Section 7.3.16). Material consumption (DMI per unit of output) is a function of economic activity, material prices and measures of technology. There is also a term in the equation to account for the changing share of imports in consumption, due to the relatively different weights of imports and domestic extraction.

5.10 Feedbacks to the economy

The preceding sections have summarised some of the economic feedbacks from the energy and materials modules to the economy. The idea is that the same transactions appear in the energy data and in the economic data, albeit in different units. For example, the iron and steel sector's purchases of coal appear as:

- coal consumption by ferrous metals in the IEA energy balances (as time-series), measured in tonnes of oil equivalent
- an input-output flow between the two sectors in the National Accounts (for the base year), measured in millions of euros or dollars

Energy feedback

The feedbacks from the energy and materials modules assume a one-to-one relationship between these two measures once price changes are taken into account.

I-O feedback

This approach relies on consistency between the economic and physical data sets. Theoretically the energy balances multiplied by the fuel costs (excluding taxes) should match against the flows in the input-output table, excluding distribution costs. However, this is often not the case (for example, due to differences in definition) and the mismatch in data can lead to apparently non-important uses of fuel having large economic consequences.

The team at Cambridge Econometrics therefore works to ensure consistency in the data sets wherever it is reasonably possible. Adjustments are sometimes made to the base-year input-output tables to ensure accuracy in the modelling.

Consumer spending feedback

There are also feedbacks from the energy module to household final demand. Consumer expenditure on energy in the national accounts is equivalent to the energy balances for household purchases in the same way that an input-output flow provides an economic representation of industry purchases of energy. In E3ME, the approach is to set the economic variables so that they maintain consistency with physical energy flows. The same issues about consistency of data described above apply here.

Energy prices, taxes, and subsidies

International energy prices are determined by the supply curves described in Section 5.7. These prices may be modified by taxes or subsidies but are otherwise not changed in the energy module. The net-revenues from any taxes or subsidies are added to the government's balance and may be used for revenue recycling purposes (i.e., offsetting other taxes). The exception is electricity prices, which are set in the FTT:Power model. The prices determined in FTT:Power (by a weighted average of levelised generation costs) are fed back to the industry prices for the electricity supply sector.

Investment

The FTT models also provide measures of investment, which are fed back to the economy module through specific equations. Particularly in the power sector, these investments can be large and are one of the main drivers of results in decarbonisation scenarios.

Feedbacks from the materials module

The feedbacks from the material module to the economy are similar to those from the energy module. It is assumed that all material consumption meets intermediate demands (i.e., materials are used as part of the production process and not bought by households directly). A relatively small number of sectors produce the materials: agriculture and fishing produce food and feed; the forestry sector produces forestry; and other mining produces all mineral categories. The feedback is through adjustments to economic input-output coefficients, as described above.

Emission damage costs

Using estimated (ExternE) damage coefficients, E3ME may also estimate ancillary costs/benefits relating to a change in associated emissions e.g., PM_{10}, SO_2, or NOx within European countries.

The approach is to parameterise the results from the EcoSenseLE (Light Edition) model that is available online by running a set of queries with a unit increase in emissions. Characteristics relating to pollution source (e.g., urban/rural, height of release) are attributed to each sector.

The results can be used to give marginal costs/benefits relating to impacts on human health, crops, and buildings. The advantage of integrating this into E3ME is that the assessment can be combined with the macroeconomic analysis. In future it would also be interesting to look at some of these outcomes in more detail. For example, instead of taking basic costs (in millions of euros), it would be possible to explicitly include changes in labour productivity and costs to national health systems (see Pollitt and Gardiner, 2016, for a discussion of how to do this).

This treatment could also be expanded to cover non-European countries, subject to damage coefficients being available.

6 Data Inputs to E3ME

6.1 Data sources

Any model is only as good as the data it uses and E3ME is no exception. In fact, for macro-econometric models like E3ME, the data determine the model's behavioural parameters, adding to their importance. As a result, much time and care are spent maintaining and updating the data.

Time-series economic data

For time-series data, the main dimensions considered when maintaining and updating are:

- indicator
- country/region
- sector
- time period (annually from 1970)

In addition, indicators that are expressed in monetary units have constant and current price versions.

The raw data are gathered from the sources described below and stored on the T databank. The model uses only official sources and international sources are preferred (both for purposes of comparability and practical reasons). It is often necessary to combine data sets to fill out gaps in the data and to estimate remaining missing values (see Section 6.2).

The data must be consistent across countries and in the same units. For monetary data, the euro is used. The data are updated as and when new figures become available, with comprehensive updates carried out at least once every two years. For European countries, data sources are used following this ranking:

1. The Eurostat national accounts branch is the primary source for European countries and provides a consistent data source across countries. The OECD's STAN data set also provides some sectoral disaggregation.
2. Data from the AMECO database are used to provide macroeconomic figures and to check totals in the Eurostat data.
3. When Eurostat data are not available or need to be improved, other internationally available sources such as the IMF are consulted.
4. Once these international data sources have been exhausted, national statistical agencies and other data sources are used to update the remaining missing series and gaps in the data.

For non-European countries, the data are typically more limited, particularly for countries outside the OECD. Where possible, the UN National Accounts and OECD's STAN database are used as the primary data sources. The Asian Development Bank also provides some information for Asian countries. Otherwise, the database relies on national sources. Table 6.1 gives a summary of the data sources for each economic variable used in E3ME's global model.

Energy and Emission data

Historical energy use data are sourced from the IEA energy balances. These data are converted into the E3ME fuel types and fuel user classifications. A baseline set of projections for energy demand is then created based on published projections, for example, from the PRIMES model in the EU, or the IEA's global World Energy Outlook publication (see Section 6.2 for further details).

Historical emissions data are sourced from Eurostat (CO_2 data for European regions only), PBL (HFCs, PFCs and SF_6 for all regions), and EDGAR (all other emissions and regions covered in E3ME). These data are converted to the E3ME 'emissions sources' classification and are stored under separate variables for each pollutant. The CO_2 data are further converted to the E3ME 'fuel users' classification, under separate variables for emissions from energy use and from industrial processes. In a small number of cases, this conversion into E3ME classifications requires splitting aggregate categories in the source data using proxy variables, such as energy use.

Bilateral trade

With the expansion of new regions in Version 8.0, E3ME's bilateral trade data have been improved and updated. The dimensions of the database remain the same as the previous version:

- Time (year since 1990)
- Origin
- Sector
- Destination

The primary data source for manufacturing sectors is Comtrade. Data for services were taken from the OECD for all member countries over the period 1995-2018 and expanded to include trade with non-OECD countries. Trade data from the World Trade Organization are also used to help filling the missing gaps between the data series. Some remaining values have been estimated based on data that are available nationally and using share estimates. These data could be further improved upon in the future.

Data with limited geographical coverage

For a number of variables in the model, the database currently only covers a subset of the economies represented in E3ME. These include:

- Income by decile (for EU Member States)
- Occupational structure (for EU Member States)
- Financial balances (for major economies)

Table 6.1: Data sources in E3ME

Sources	Variables
UN World Population Prospects	Population
ILO modelled estimates	Labour force, employment, employees
OECD LFS	Labour force, unemployment
World Bank	GDP, labour cost
UN National Accounts	Gross output, gross value added, gross fixed capital formation, imports, exports, consumer spending, government spending
OECD STAN database	Gross output, gross value added, gross fixed capital formation
OECD National Accounts	Gross output, gross value added, consumer spending, government spending
Asian Development Bank (ADB) Input-Output	Gross output, gross value added, consumer spending, government spending, imports, exports
WIOD database	Gross output, gross value added, labour cost
Eora National-Input-Output tables	Gross output, gross value added, gross fixed capital formation, government spending, consumer spending, labour costs
UAE National Accounts	Gross output, gross value added, gross fixed capital formation, government spending, consumer spending, labour costs
IEA Energy Balances	Energy demand
Eurostat, EDGAR, PBL[2]	Emissions

6.2 Data processing and treatment

General rule

The team at CE has developed a software package to fill in gaps in any of the E3ME time-series. It uses growth rates and shares between sectors and variables to estimate missing data points, both in cases of interpolation and extrapolation. Some time-series (e.g., energy prices, see below) have specific rules for filling gaps in the data, but the general procedures are described here.

The most straightforward case is when the growth rates of a variable are known, allowing the level to be estimated from these growth rates, as long as the initial level is known. Sharing is used when time-series data for an aggregation of sectors are available, but the individual time-series is not. In

[2] Olivier and Peters (2020).

this case, the sectoral time-series can be calculated by sharing the total, using either actual or estimated shares.

In the case of extrapolation, it is often the case that aggregate data for several sectors are used when the sectoral disaggregation at the E3ME level is not available. For example, government expenditure is a good proxy for the total growth in education, health, and defence when the latter are unavailable. A special procedure has been put in place to estimate growth in more disaggregated sectors so that the sum matches the known total, while the individual sectoral growth follows the characteristics of each sector. Interpolation is used when no external source is available to estimate the path of change during an interval which is bookended by available data. Under different assumptions, time-series projections are created for each country and each aggregated variable: consumption, employment, GDP, trade, and investment.

Energy price data

Raw data for energy prices are collected from the IEA Energy Statistics publications as total prices in $/toe (i.e., including taxes) by country and by fuel since 1978 and taxes per unit of fuel since 1978. The IEA provides incomplete, delivered price (with and without tax) time-series for distillate (light) oil, electricity, natural gas, steam coal, and coke. The raw data have three types of missing data: "not applicable", "not available" and "confidential", which are all treated as missing when read in. CE fills these using these assumptions:

- If data are missing for all years, the tax is assumed to be zero
- If data are missing at the end of the series, then taxes stay constant at the final year the data are available
- If data are missing at the beginning of the series, then taxes rise at 5% per year up to the first year of observation
- Negative values are assumed to be errors (i.e., CE assumes no subsidies -these data are treated as missing)

Missing years are appended over 1970-77 to the total price data. Underlying price data are formed as total price data minus taxes. These data will therefore have missing values over 1970-77 and at every point where total price data are missing. The data are then organised into arrays corresponding to the E3ME classifications and converted to euros.

7 E3ME's Equations

Much like other economic models, E3ME consists of a combination of accounting balances and behavioural relationships. This chapter sets out the specifications of key equation sets in the model. Section 7.1 describes the key economic identities within the model while Section 7.2 explains the estimation approach while Section 7.3 describes the specification of the econometric equations that define behavioural relationships within the model.

7.1 E3ME's accounting identities

Accounting identities are central to E3ME's modelling approach and ensure that consistency is maintained across indicators. This section describes the most important economic identities used within the model: GDP, gross output, and income.

7.1.1 GDP

GDP provides a measure of net production at the whole-economy level. It is calculated as the sum of final consumption by households, firms (investment), government, and net trade. GDP is an output from the model and is not used internally within the model, since key feedbacks are all modelled at the industry sector level.

Table 7.1: GDP identity

GDP identity:

RGDP = RSC + RSK + RSG + RSX - RSM

Definitions:

RGDP	is a matrix of GDP for 71 regions, m euro at 2010 prices
RSC	is a matrix of total consumer expenditure for 71 regions, m euro at 2010 prices
RSK	is a matrix of total investment (GFCF) for 71 regions, m euro at 2010 prices
RSG	is a matrix of total final government expenditure for 71 regions, m euro at 2010 prices
RSX	is a matrix of total exports for 71 regions, m euro at 2010 prices
RSM	is a matrix of total imports for 71 regions, m euro at 2010 prices

7.1.2 Gross output

E3ME defines gross output at a sectoral level, considering domestic consumption (both household and government), product flow and absorption, and trade. Output is equivalent to turnover as it includes intermediate inputs to production, unlike gross value added which does not include purchases from other sectors.

Table 7.2: Gross output identity

Gross output identity:

QR = QRC + QRY + QRG + QRK + QRX – QRM + QRR

Definitions:

QR	is a matrix of gross output for 70/43 industries and 71 regions, m euro at 2010 prices
QRC	is a matrix of consumer purchases for 70/43 industries and 71 regions, m euro at 2010 prices
QRY	is a matrix of products absorbed by industries for 70/43 ind. and 71 reg., m euro at 2010 prices
QRG	is a matrix of government purchases for 70/43 industries and 71 regions, m euro at 2010 prices
QRK	is a matrix of product flows to fixed investment for 70/43 ind. and 71 reg., m euro at 2010 prices
QRX	is a matrix of exports for 70/43 industries and 71 regions, m euro at 2010 prices
QRM	is a matrix of imports for 70/43 industries and 71 regions, m euro at 2010 prices
QRR	model residuals for QR

7.1.3 Income

Income in E3ME relates consumption to personal disposable income and is disaggregated both regionally and across sectors. It provides a measure of wealth in the personal sector, as well as inflation and interest rates. It takes into account deductions for tax and social contributions as well as additions for wage and benefit payments.

Table 7.3: Income identity

Income identity:

RGDI = RRI – RDTX – REES + RWS + RBEN

Definitions:

RGDI	is a matrix of gross disposable income for 70/43 ind. and 71 reg., m euro at current prices
RRI	is a matrix of residual income for 70/43 ind. and 71 reg., m euro at current prices
RDTX	is a matrix of income tax deductions for 70/43 ind. and 71 reg., m euro at current prices
REES	is a matrix of employee social contributions for 70/43 ind. and 71 reg., m euro at current prices
RWS	is a matrix of wages for 70/43 ind. and 71 reg., m euro at current prices
RBEN	is a matrix of benefit payments for 70/43 ind. and 71 reg., m euro at current prices

7.2 E3ME's Econometric approach

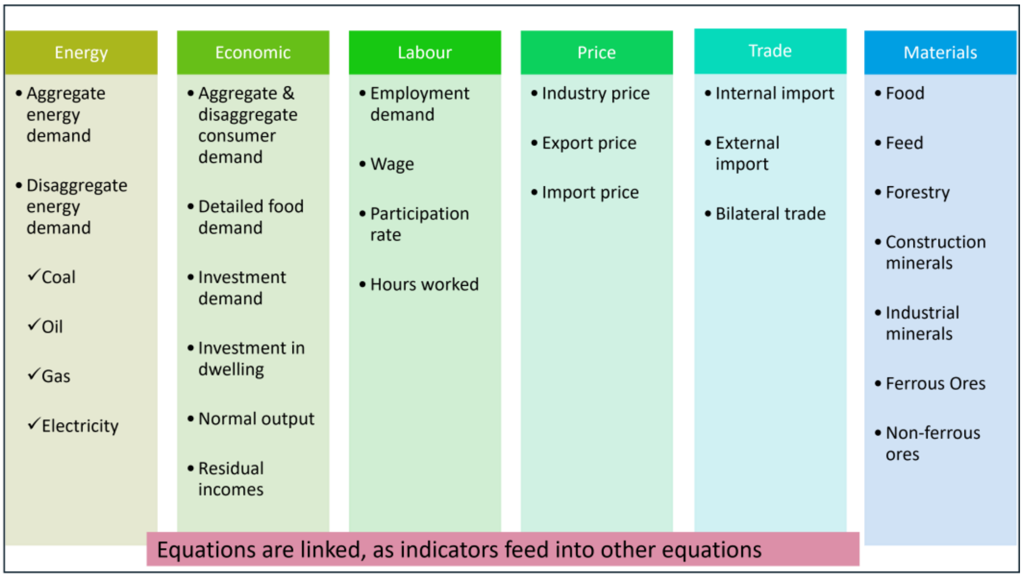
E3ME takes an econometric approach to its modelling, using historical time-series data as the basis for its equation parameters. This approach is used to predict key economic indicators, understand their behaviour over time, and understand how they might react when their key drivers change.

The equations themselves are derived from economic theory. In addition to adding robustness to the modelling, this theoretical underpinning provides an indication of the shape and magnitude of the results, which helps with the overall accuracy of the modelling. The internal forecast created from these econometric equations is calibrated against official external data sources in order to maintain consistency and applicability.

E3ME's modelling follows the two-stage error correction framework introduced by Engle and Granger (1987), comprising of a long-term and short-term element. The long-term element is a cointegration model, which identifies the long-run trends in the economy. The short-term element is an Error Correction Model (ECM) which deals with adjustments around the trends identified by the cointegration element, handling shocks to the system. The two elements work in tandem to ensure that indicators have a stable long-term co-movement (i.e., a common stochastic trend), and that they respond to any shocks by returning to the long-term trend. The combination of these two elements makes E3ME suitable for both long- and short-term analysis.

E3ME's econometric approach is highly data-driven, relying on a large quantity of detailed time-series data. Wherever possible, E3ME uses datasets beginning in 1970, with the highest degree of disaggregation available (often by sector, consumer product, fuel, or fuel user, depending on the dataset). As such, the econometric approach is used primarily in the energy and economy sections of the model, where the data quality is best, although it is still used heavily in other sections. Figure 7.1 below outlines the key model equations which are estimated using econometrics.

Figure 7.1: Key equations modelled with econometrics



When the high data threshold is not met (e.g., if the time-series is not long enough or the data are poor quality), E3ME uses shrinkage, an estimation technique used in the heterogeneous panel data literature, to estimate elasticities. Shrinkage restricts the parameters of the data-poor country to the mean elasticities of countries or country groups with higher quality data. This provides long-run elasticities for data-poor economies and maintains the assumption that, in the long-term, behavioural parameters remain similar in different economies. Shrinkage is used until the time-series data are long enough.

Even when the datasets are long enough, econometric estimation does not always produce elasticities which correspond to economic intuition. Parameter bounds are applied on the elasticities to ensure that they are economically sensible and create a robust forecast.

In cases where, despite the econometric testing and economic sense checks, a given equation is still problematic, the model can revert to using non-econometric alternative specifications. For instance, individual sectors can be set to follow country-level trends, or those of other sectors and variables, and in extreme cases, can be calculated exogenously, without the use of econometrics.

7.3 E3ME's Econometric equations

Given the overall size of the model, it is perhaps surprising that there are less than 40 variables which are estimated through econometric relationships. However, these variables are, in most cases, disaggregated in two dimensions (e.g., 70 sectors and 71 regions). As such, this version of E3ME includes more than 60,000 estimated equations, excluding bilateral trade. In addition, IDIOM allows up to ten alternative functional forms to explain each disaggregated category.

Non-standard equation sets

There are several equation sets that have been developed but are not included in the standard model version:

- The transport equations are not operational in the current version of E3ME but are maintained within the model structure to facilitate possible future linkages with transport models.
- The econometric equations for biofuel demand are not operational due to a lack of data on biofuel prices. Analysis has been carried out previously for Sweden, but the standard model treatment uses a simpler shift-share approach.
- Since the introduction of bilateral trade, the export equations are no longer used in the standard model solution (exports are now the adjusted reverse sum of bilateral imports). However, the structure is maintained for applications that consider a country/region in isolation.
- E3ME has a set of food demand equations developed in project work which are not operational in the current version of E3ME but are maintained within the model structure to facilitate future linkages with agriculture and land use models.
- Currently the equation developed to capture R&D investment demand for EU countries is not used in the standard model solution but follows a simpler non-econometric dynamic.

7.3.1 Summary specification of equations

Table 7. provides an overview of the estimated equations. Table 7. summarises the variables used and the units of measurement for the dependent variable. A full list of model variables is available on request.

Bilateral trade

The equation sets used for bilateral trade have an additional dimension as they include equations defined by both origin and destination (as well as by sector). Their structure is, therefore, somewhat different to (and less complex than) the other model equation sets (see Section 7.3.6).

Dummy variables

The use of dummy variables in E3ME is restricted by the limited degrees of freedom offered by the time-series data, but there are two important cases where dummy variables are added to all the equation sets. These are:

- A dummy variable for German reunification. For Germany this variable has value zero up to 1990 and value 1 from 1991 onwards. For other countries it is always zero (time-series for CEE countries only begin in 1995).
- The financial crisis in 2009 provoked many non-linear reactions. To reduce bias in our parameter estimates, a dummy variable for 2009 (zero before 2009, one from 2009 onwards) is included in all the equation sets. Note that the shock only enters to the short-run model (in differenced form).

To avoid excessive repetition, the dummy variables are not included in the formal definitions provided in the rest of this chapter, but they are an important part of the model estimation and solution.

Technology indices

For European countries there are two technology indices, one of which is based on ICT investment (YKNO) and one of which is based on other investment (YCAP). This distinction is based on the EU KLEMS database that covers the EU and other OECD countries. At present only the EU data are used (although this may be expanded further in future model versions) so other countries do not have both terms. For non-EU countries the relevant indicator is YRKE which includes all investment spending and R&D where data are available. The other term in the equation is fixed at zero.

The technology indices are discussed in more detail in Section 4.6.

Table 7.4: Stochastic Functions in E3ME

1	BFR0	Aggregate energy demand
2	BFRC	Coal demand
3	BFRO	Heavy oil demand
4	BFRG	Natural gas demand
5	BFRE	Electricity demand
6	BRSC	Aggregate consumption
7	BCR	Disaggregate consumption
8	BKR	Industrial investment
9	BQEM	External imports
10	BQIM	Internal imports
11	BYRH	Hours worked
12	BYRE	Industrial employment
13	BPYH	Industrial prices
14	BPQX	Export prices
15	BPQM	Import prices
16	BYRW	Industrial average earnings
17	BLRP	Labour participation rate
18	BRRI	Residual income
19	BRDW	Investment in Dwellings
20	BYRN	Normal output
21	BMU1	Demand for food
22	BMU2	Demand for feed
23	BMU3	Demand for wood
24	BMU4	Demand for construction minerals
25	BMU5	Demand for industrial minerals
26	BMU6	Demand for ferrous ores
27	BMU7	Demand for non-ferrous ores
	BITRADE	Bilateral trade

Table 7.5: Summary of the standard equation sets in E3ME version 7.0

EQ set	Endog. var	V1	V2	V3	V4	V5	V6	V7	V8	V9	Units
1	FR0	FRY	PREN	FRTD	ZRDM	ZRDT[1]	FRK				th toe
2-5	FR(fuel)	FR0	PFRF	FRTD	ZRDM	ZRDT[1]	FRK				th toe
6	RSC	RRPD	RRLR	CDEP	ODEP	RVD	RUNR*	RPSC*			m € 2010 prices
7	CR	RRPD	PRCR	RRLR	RPSC	CDEP	ODEP	SHAR*			consumption ratio
8	KR	YR	PKR/PYR	YRWC	PQMA(3, 5)[2]	YRDS	RRLR	RCRR*	YYN*		m € 2010 prices
9	QEM	QRDI	PQRM	PYH	EX	YKNO	YCAP	SVIM	YYN*		m € 2010 prices
10	QIM	QRDI	PQRM	PYH	EX	YKNO	YCAP	SVIM	YYN*		m € 2010 prices
11	YRH	YRNH	YRKC*YRKS[3]	YRKN	YYN						hours per week
12	YRE	YR	YRWC	YRH	YKNO	YCAP					thousands
13	PYH	YRUC	PQRM	YKNO	YCAP	YYN*					index 2010=1
14	PQRX	PQRY	PQWE	EX	YRULT	YKNO	YCAP				index 2010=1
15	PQRM	PQRF	PQWE	EX	YRUL	YKNO	YCAP				index 2010=1
16	YRW	LYWE	LYRXE	LYRP	RUNR	RBNR	APSC	REIW*	YYN*		th € per year
17	LRP	RSQ	RWSR	LRUN	RBNR[3]	RSER	RHRS	LRQU			rate [0,1]
18	RRI	RWS	RPSY	VRYM	RLR						m €
19	RDW	RRPD	RRLR	CDEP	ODEP	RUNR	RPSC*				m € 2010 prices
20	YRN	YR5	YKNO+YCAP	RUNR							m € 2010 prices
21-27	MU	MURY	PMAT	KR	YRD	MUM					th tonnes
BiTrade	BIQRM	PQRX	YRKE								m € 2010 prices

Notes: All equations also include dummy variables for German unification and the 2009 financial crisis.
Variables marked with * only enter to the short-run model.
1 R&D on transport equipment is included in as an additional explanatory variable only for the oil equations.
2 The model has a dual classification system. For the first 33 regions PQMA(5) is used, for the rest PQMA(3).
3 Age groups 50+ use pensions instead (RPNR).

Conventions adopted for the notation

The names of variables and parameter sets closely follow the conventions for Fortran names, i.e., they are groups of capital letters and numbers beginning with a letter.

Nearly all the variables and parameters are defined over the regional dimension. In order to reduce the complexity of the notation this regional dimension is omitted in the tables below. Therefore, all variables and parameters should be assumed to vary over the regions of E3ME unless otherwise stated.

Individual elements of vectors, rows, columns, or elements of matrices are denoted by replacing the dot by the appropriate number in the classification, e.g., YR(5,.) is gross output of the oil and gas industry (in each region) which is the fifth industry in the European sectoral classification[3].

The full syntax is given below.

+ - * and /	denote addition, subtraction, multiplication, and division of scalars and of individual elements of vectors and matrices.
( )	are grouping brackets.
[ ]	enclose comments.
(.)	as a postscript on a name indicates that it is a vector with the dot denoting all the elements.
(.,.)	as a postscript on a name indicates that it is a matrix.
(.,.)'	denotes that the matrix is transposed.
(-1), (-2) etc.	as applied to a variable or a group of variables as a postscript denote a one, two etc. period lag.
LN(V)	is the natural logarithm of variable V.
DLN(V)	is the change in LN(V).
ECT	is the lagged error term from the long-run cointegrating equation that gets used in the dynamic equation.

[3] The appropriate sector is used for each region, so in this case it would be sector 3 for non-European regions.

7.3.2 Aggregate energy demand

The equation specification is given in Table 7.3. The original equation is based on work by Barker et al (1995) and Hunt and Manning (1989). The work by Serletis (1992), and Bentzen and Engsted (1993) has also helped in forming the specification for the cointegrating equation.

Overall structure

Since there are substitutable inputs between fuels, total energy demand in relation to the output of energy-using industries is likely to be more stable than that of the individual components. Nevertheless, total energy demand is subject to considerable variation which reflects both technical progress in conservation and changes in the cost of energy relative to other inputs. The aggregate energy equation considers the total energy used (summation of all twelve carriers) in thousand tonnes of oil equivalent (th toe) by each energy user. The energy demand is dependent on the economic 'activity' for that user (converted from the 70/43 economic sectors). This is expressed as gross economic output for most sectors, although household energy demand is expressed as a function of total consumers' expenditure. A restriction is imposed so that higher activity does not result in higher energy use (all other factors being equal).

The average price used in the equations weights the prices of individual energy carriers by their share of consumption by each user. Due to data limitations, the current energy demand equations do not allow for asymmetrical effects (i.e., rising energy prices leading to reductions in fuel demand, but falling prices not leading to an increase). Such asymmetrical price effects in aggregate energy demand equations have been the subject of other research (Gately, 1993; Walker and Wirl, 1993; Grubb, 1995, 2014).

The behaviour relies on the fact that energy is used via capital stock with a long lifetime, and that technical change is progressive and not generally reversed. These factors mean that when energy prices rise and energy savings are introduced, the savings are not reversed when the energy prices fall again. Therefore, energy demand responds to rises in real prices but not falls. This will be revisited in future.

Price elasticities

Long-run price elasticities are taken from the literature rather than estimated using the time-series data. The long-run price elasticity for road fuel is imposed at -0.7 for all regions, following the research on long-run demand (Franzen and Sterner, 1995; Johansson and Schipper, 1997, p. 289). CE's internal research, using cross-sectional analysis of the E3ME dataset has confirmed this result. Elasticities for other sectors are around -0.2.

Technology and capital stock

The measures of R&D expenditure and investment capture the effect of new ways to decrease energy demand (energy saving technical progress) and the elimination of inefficient technologies, such as replacing the older, more inefficient uses of energy. The variables FRK and FRTD are determined by converting the economic data for investment and R&D into the energy-using categories. Research and development expenditure in the engineering sectors (for machinery) and the vehicles sectors (for the world) take into account spill over effects from international companies.

The power sector

The power generation sector is solved using the bottom-up FTT model (see Section 5.2) rather than the estimated equations. The top-down approach offered by the econometric equations is not appropriate for this sector because:

- there are a small number of large plants, meaning that estimated parameters give a poor performance
- the econometric approach is not well suited to the development of new renewable technologies due to its reliance on historical data

Bunker fuels

No econometric estimation is conducted in the current model version for maritime and aviation bunker fuel demand for either total or disaggregate fuel demand. Demand for bunker fuels is driven by different factors than demand for other fuel users (e.g., global trade volume and prices). An econometric specification is currently under development for them.

Table 7.6: Aggregate Energy Demand Equations

Co-integrating long-term equation:			
LN(FR0(.))			[total energy used by energy user]
	=	BFR0(.,10)	
	+	BFR0(,.11) * LN(FRY(.))	[activity measure]
	+	BFR0(.,12) * LN(PREN(.))	[average price ratio]
	+	BFR0(.,13) * LN(FRTD(.))	[R&D by energy user]
	+	BFR0(.,14) * LN(ZRDM)	[global R&D in machinery]
	+	BFR0(.,15) * LN(ZRDT)	[global R&D in transport]
	+	BFR0(.,16) * LN(FRK(.))	[investment by energy user]
	+	error term	
Dynamic equation:			
DLN(FR0(.))			[total energy used by energy user]
	=	BFR0(.,1)	
	+	BFR0(.,2) * DLN(FRY(.))	[activity measure]
	+	BFR0(.,3) * DLN(PREN(.))	[average price ratio]
	+	BFR0(.,4) * DLN(FRTD(.))	[R&D by energy user]
	+	BFR0(.,5) * DLN(ZRDM)	[global R&D in machinery]
	+	BFR0(.,6) * DLN(ZRDT)	[global R&D in transport]
	+	BFR0(.,7) * DLN(FRK(.))	[investment by energy user]
	+	BFR0(.,8) * DLN(FR0(-1))	[lagged change in energy use]
	+	BFR0(.,9) * ECT	[error correction term: lagged long-run residual]
Identity:			
PREN	=	PFR0(.) / PRYR	[relative price ratio]
Restrictions:			
BFR0(.,3 .,4 .,5 .,6 .,7 .,12 .,13 .,14 .,15 .,16) <= 0			['right sign']
BFR0(.,2 .,11) >= 0			['right sign']
0 > BFR0(.,9) > -1			['good error correction mechanism']
Definitions:			
BFR0	is a matrix of parameters		
FR0	is a matrix of total energy used by 25 energy users for 71 regions, th toe		
PREN	is a matrix of relative energy price ratios for 25 energy users and 71 regions		
PFR0	is a matrix of average energy prices for 25 energy users and 71 regions, euro/toe		
PRYR	is a matrix of average producer prices in the economy as a whole (2010 = 1.0, local currency)		
FRY	is a matrix of activity for 25 energy users and 71 regions, m euro at 2010 prices		

FRTD	is a matrix of R&D by 25 energy users for 71 regions, m euro at 2010 prices
ZRDM	is global R&D in machinery, m euro at 2010 prices
ZRDT	is global R&D in transport, m euro at 2010 prices
FRK	is a matrix of investment by 25 energy users for 71 regions, m euro at 2010 prices

7.3.3 Disaggregate energy demand for coal, heavy fuel oil, gas, and electricity

The specification is shown in Table 7.7.

The equations for disaggregated energy demand have been specified for four energy carriers[4]: coal, heavy fuel oil, natural gas, and electricity. The carriers have the characteristic that they are highly substitutable inputs to the process of heat generation in many industries. The specification of the equations follows similar patterns as the aggregate energy demand equations (see Section 7.3.2). The equations contain the same R&D and investment variables with the same restrictions imposed, although the measure of transport R&D, ZRDT, is only used in the oil equation. Instead of using a measure of economic activity, the sector's total energy consumption is used.

The price term is a ratio of the energy carrier price to that of the aggregate energy price. The relative fuel prices have changed dramatically over the period of historical data, particularly towards the start and end of the time-series, but the other independent variables match those used for the aggregate equation (see Table 7.4). Again, the power generation sector is solved using the FTT submodel and does not use the estimated equation.

Table 7.7: The disaggregate energy demand equations

Equations used for F = coal (C), Heavy Fuel Oil (O), Natural Gas (G), Electricity (E).			
Co-integrating long-term equation:			
LN(FRF(.))			[fuel used by energy user]
	=	BFRF(.,10)	
	+	BFRF(.,11) * LN(FR0(.))	[total energy used by energy user]
	+	BFRF(.,12) * LN(PFRP(.))	[price ratio]
	+	BFRF(.,13) * LN(FRTD(.))	[R&D by energy user]
	+	BFRF(.,14) * LN(ZRDM)	[global R&D in machinery]
	+	BFRF(.,15) * LN(ZRDT)	[global R&D in transport]
	+	BFRF(.,16) * LN(FRK(.))	[investment by energy user]
	+	error term	
Dynamic equation:			
DLN(FRF(.))			[fuel used by energy user]
	=	BFRF(.,1)	
	+	BFRF(.,2) * DLN(FR0(.))	[total energy used by energy user]
	+	BFRF(.,3) * DLN(PFRP(.))	[price ratio]
	+	BFRF(.,4) * DLN(FRTD(.))	[R&D by energy user]
	+	BFRF(.,5) * DLN(ZRDM)	[global R&D in machinery]
	+	BFRF(.,6) * DLN(ZRDT)	[global R&D in transport]

[4] These are also referred to as 'fuels' for brevity.

	+	BFRF(.,7) * DLN(FRK(.))	[investment by energy user]
	+	BFRF(.,8) * DLN(FRF(-1))	[lagged change in energy use]
	+	BFRF(.,9) * ECT	[error correction term: lagged long-run residual]

Identity:

PFRP = PFRF(.)/PFR0(.) [price ratio]

Restrictions:

BFRF(.,3 .,4 .,5 .,6 .,7 .,12.,13 .,14 .,15 .,16) <= 0	['right sign']
BFRF(.,2 .,11) >= 0	['right sign']
0 > BFRF(.,9) > -1	['good error correction mechanism']

Definitions:

BFRF	is a matrix of parameters
FRF	is a matrix of fuel used by 25 energy users for 71 regions, th toe
FR0	is a matrix of total energy used by 25 energy users for 71 regions, th toe
PFRP	is a matrix of relative price ratios for energy carrier F, by 25 energy users for 71 regions
PFRF	is a matrix of prices for energy carrier F, by 25 energy users for 71 regions, $/toe
PFR0	is a matrix of average energy prices for 25 energy users and 71 regions, $/toe
FRTD	is a matrix of R&D by 25 energy users for 71 regions, m euro at 2010 prices
ZRDM	is R&D in machinery by the EU, m euro at 2010 prices
ZRDT	is R&D in transport by the EU, m euro at 2010 prices (oil equation only)
FRK	is a matrix of investment by 25 energy users for 71 regions, m euro at 2010 prices

7.3.4 Household consumption

Aggregate household consumption

The equation specification is given in Table 7.. It should be noted that the dependent variable and terms for income and wealth are converted into per capita measures, although this is excluded from the table for conciseness. As consumption accounts for around 50% of final demand the equation is a key feature of the model.

Most studies have followed those of Davidson et al (1978) which have examined the dynamic links between consumption, income, and wealth in an error correction model. In more recent studies, attention has focused more upon the role of wealth (housing wealth in particular) and financial liberalisation (Barrell and Davis, 2007; Kerdrain, 2011).

The specification of the equation is similar to that used in the previous HERMES model, which generalises the permanent income and the lifecycle theories in an error correction model. Indeed, the long-run elasticity of consumption in relation to income has been set equal to one to ensure the lifecycle theory is fulfilled. These equations relate total consumption to regional personal disposable income, a measure of wealth for the personal sector, inflation, and interest rates. Variables covering child and old-age dependency rates are also included in an attempt to capture any change in consumption patterns caused by an ageing population. The unemployment rate is used as a proxy for the degree of uncertainty in the economy and has been found to have significant effects on short-term consumption levels.

Due to a lack of available data on household wealth, cumulative investment in dwellings was used as a proxy for the housing stock and there is no proxy for financial wealth. However, in line with other findings, E3ME's equations show only a modest link between household wealth and spending (very few studies find an elasticity greater than 0.1, and 0.02-0.03 is not uncommon).

Disaggregate consumption

The specification is shown in

Table 7.. Both the long-term and dynamic equations have a similar specification to the aggregate consumption equations but include the relative prices of each consumption category.

Table 7.8: The Aggregate Consumption Equations

Co-integrating long-term equation:			
LN(RSC)			[real consumers' expenditure]
	=	BRSC(11)	
	+	BRSC(12) * LN(RRPD)	[real gross disposable income]
	+	BRSC(13) * LN(RRLR)	[real long-run rate of interest]
	+	BRSC(14) * LN(CDEP)	[child dependency ratio]
	+	BRSC(15) * LN(ODEP)	[old age pensioner dependency ratio]
	+	BRSC(16) * LN(RVD)	[household wealth]
	+	error term	
Dynamic equation:			
DLN(RSC)			[real consumers' expenditure]
	=	BRSC(1)	
	+	BRSC(2) * DLN(RRPD)	[real gross disposable income]
	+	BRSC(3) * DLN(RRLR)	[real long-run rate of interest]
	+	BRSC(4) * DLN(CDEP)	[child dependency ratio]
	+	BRSC(5) * DLN(ODEP)	[old age pensioner dependency ratio]
	+	BRSC(6) * DLN(RVD)	[household wealth]
	+	BRSC(7) * LN(RUNR)	[unemployment rate]
	+	BRSC(8) * DLN(RPSC)	[consumer price inflation]
	+	BRSC(9) * DLN(RSC(-1))	[lagged change in consumers' expenditure]
	+	BRSC(10) * ECT	[error correction term: lagged long-run residual]
Identities:			
RRLR	=	1 + (RLR–DLN(PRSC))/100	[real long-run rate of interest]
RRPD	=	(RGDI*EX/PRSC)	[real gross disposable income]
CDEP, ODEP	=	CPOP/RPOP, OPOP/RPOP	[dependency ratios]
Restrictions:			
BRSC(12) = 1			['life cycle hypothesis']
BRSC(2, 6, 16) >= 0			['right sign']
BRSC(3, 7, 8, 13) <= 0			['right sign']
0 > BRSC(10) > -1			['good error correction mechanism']
Definitions			
BRSC	is a matrix of parameters		
RSC	is a vector of total consumers' expenditure for 71 regions, m euro at 2010 prices		
RRPD	is a matrix of real disposable income for 71 regions, m euro at current prices		
RRLR	is a matrix of real long-run rate of interest for 71 regions		
RGDI	is a matrix of gross disposable income for 71 regions, m euro at current prices		

RLR	is a matrix of long-run nominal interest rates for 71 regions
EX	is a vector of exchange rates, local currency per euro, 2010=1.0
RPOP	is a vector of regional population for 71 regions, in thousands of persons
CDEP	is a vector of child dependency ratios for 71 regions, ratio
ODEP	is a vector of old age dependency ratios for 71 regions, ratio
CPOP	is a vector of child population for 71 regions, in thousands of persons
OPOP	is a vector of old-age population for 71 regions, in thousands of persons
RUNR	is a vector of unemployment rates for 71 regions, as a percentage of the labour force
PRSC	is a vector of consumer price deflator for 71 regions, 2010=1.0
RPSC	is a vector of consumer price inflation for 71 regions, rate
RVD	is the cumulative sum of investment in dwellings for 71 regions, m euro at 2010 prices

Table 7.9: The Disaggregate Consumption Equations

Co-integrating long-term equation:			
LN(SHAR(.))			[consumers' budget share, logistic form]
	=	BCR(.,10)	
	+	BCR(.,11) * LN(RRPD)	[real gross disposable income]
	+	BCR(.,12) * LN(PRCR(.))	[relative price of consumption]
	+	BCR(.,13) * LN(RRLR)	[real long-run rate of interest]
	+	BCR(.,14) * LN(RPSC)	[consumer price inflation]
	+	BCR(.,15) * LN(CDEP)	[child dependency ratio]
	+	BCR(.,16) * LN(ODEP)	[old age pensioner dependency ratio]
	+	error term	
Dynamic equation:			
DLN(SHAR(.))			[consumers' budget share, logistic form]
	=	BCR(.,1)	
	+	BCR(.,2) * DLN(RRPD)	[real gross disposable income]
	+	BCR(.,3) * DLN(PRCR(.))	[relative price of consumption]
	+	BCR(.,4) * DLN(RRLR)	[real long-run rate of interest]
	+	BCR(.,5) * DLN(RPSC)	[consumer price inflation]
	+	BCR(.,6) * DLN(CDEP)	[child dependency ratio]
	+	BCR(.,7) * DLN(ODEP)	[old age pensioner dependency ratio]
	+	BCR(.,8) * DLN(SHAR)(-1)	[lagged change in consumers' budget share]
	+	BCR(.,9) * ECT	[error correction term: lagged long-run residual]
Identities:			
SHAR	=	(VCR(.)/VCRT) / (1-(VCR(.)/VCRT))	[consumers' budget share, logistic form]
RRPD	=	(RGDI*EX/RPSC)/RPOP	[real gross disposable income]
PRCR	=	VCR(.)/CR(.)/PRSC	[real price of consumption]
RRLR	=	1+(RLR-DLN(PRSC))/100	[real long-run rate of interest]
CDEP	=	CPOP/RPOP	[child dependency ratio]
ODEP	=	OPOP/RPOP	[OAP dependency ratio]
Restriction:			
BCR(2, 11) >= 0			['right sign']
BCR(3, 4, 12, 13) <= 0			['right sign']
0 > BCR(9) > -1			['good error correction mechanism']

Definitions:

BCR	is a matrix of parameters
CR	is a matrix of consumers' expenditure for 43/28 commodities for 71 regions, m euro at 2010 prices
VCR	is a matrix of consumers' expenditure for 43/28 commodities for 71 regions, m euro at current prices
VCRT	is a vector of total consumers' expenditure for 71 regions, m euro at current prices
RRPD	is a matrix of real disposable income for 71 regions, m euro at current prices
RRLR	is a matrix of real long-run rate of interest for 71 regions
RGDI	is a matrix of gross disposable income for 71 regions, in m euro at current prices
RLR	is a matrix of long-run nominal interest rates for 71 regions
RPOP	is a vector of regional population for 71 regions, in thousands of persons
CDEP	is a vector of child dependency ratios for 71 regions, ratio
ODEP	is a vector of old age dependency ratios for 71 regions, ratio
CPOP	is a vector of child population for 71 regions, in thousands of persons
OPOP	is a vector of old-age population for 71 regions, in thousands of persons
PRCR	is a matrix of relative consumer prices for 43/28 commodities for 71 regions
PRSC	is a vector of consumer price inflation for 71 regions, rate
RPSC	is a vector of the real consumer price inflation for 71 regions, in percentage terms
EX	is a vector of exchange rates, local currency per euro, 2010=1.0
SHAR	is a matrix of consumers' budget shares for 43/28 commodities for 71 regions

7.3.5 Industrial investment

Investment (see Table 7.) is a very important and very volatile component of final demand, so its treatment in the model is of central importance to the model's simulation and forecasting performance. Ideally, the treatment of investment in a sectoral model such as E3ME should disaggregate by asset (e.g., vehicles, plants and machinery, and buildings) as well as by investing industry, but this has not proved possible due to data limitations.

The specification of the investment equations in E3ME has built upon earlier work published in Barker and Peterson (1987) as well as Kaldor (1957). The theory behind the choice of variables explaining the long-run path of investment is a mix between the neoclassical tradition (whereby factor demands are explained solely in terms of other factor prices) and the accelerator model (which recognises the importance of output as a determining influence). For the dynamic representation, other variables are added, including the real rate of interest and the ratio of actual to normal (expected) output. The latter was designed to capture the decision to invest for increased capacity, as opposed to solely for replacement needs.

E3ME is bound by the investment-savings national accounts identity but, unlike CGE models, the representation of capital markets in E3ME does not assume full 'crowding out'. E3ME allows for the possibility of non-optimal allocation of capital and the transfers of financial funds from existing assets (which push up prices but does not lead directly to higher rates of economic activity) to the development and construction of new assets. This means that it is possible for total gross fixed capital formation to increase, without there being necessarily an equivalent increase in savings.

Table 7.10: The Industrial Investment Equations

Co-integrating long-term equation:			
LN(KR(.))			[investment]
	=	BKR(.,12)	
	+	BKR(.,13) * LN(YR(.))	[real output]
	+	BKR(.,14) * LN(PKR(.)/PYR(.))	[relative price of investment]
	+	BKR(.,15) * LN(YRWC(.))	[real average labour cost]
	+	BKR(.,16) * LN(PQRM(3 and 5,.))	[real oil price effect]
	+	BKR(.,17) * LN(DEBT(.))	[outstanding debt / output ratio]
	+	BKR(.,18) * LN(YRDS(.))	[real R&D spending]
	+	error term	
Dynamic equation:			
DLN(KR(.))			[change in investment]
	=	BKR(.,1)	
	+	BKR(.,2) * DLN(YR(.))	[real output]
	+	BKR(.,3) * DLN(PKR(.)/PYR(.))	[relative price of investment]
	+	BKR(.,4) * DLN(YRWC(.))	[real average labour costs]
	+	BKR(.,5) * DLN(PQRM(3 and 5,.))	[real oil price effect]
	+	BKR(.,6) * DLN(DEBT(.))	[outstanding debt / output ratio]
	+	BKR(.,7) * DLN(YRDS(.))	[real R&D spending]
	+	BKR(.,8) * LN(RCRR(.))	[real commercial rate of interest]
	+	BKR(.,9) * DLN(YYN(.))	[actual/normal output]
	+	BKR(.,10) * DLN(KR)(-1)	[lagged change in investment]
	+	BKR(.,11) * ECT	[error correction term: lagged long-run residual]
Identities:			
YRWC	=	(YRLC(.) / PYR(.)) / YREE(.)	[real average labour costs]
RRLR	=	1 + (RLR – DLN(PRSC)) / 100	[real long-run rate of interest]
RCRR	=	RILR + RSPR	[real commercial rate of interest]
Restrictions:			
BKR(.,2 .,4 .,7 .,9 .,13 .,15 .,18) >= 0			['right sign']
BKR(.,3 .,6 .,8 .,14, .,17) <= 0			['right sign']
0 > BKR(.,10) > -1			['good error correction mechanism']
Definitions:			
BKR	is a matrix of parameters		
KR	is a matrix of investment expenditure for 70/43 industries and 71 regions, m euro at 2010 prices		
YR	is a matrix of gross industry output for 70/43 industries and 71 regions, m euro at 2010 prices		
PYR	is a matrix of industry output price for 70/43 industries and 71 regions, 2010=1.0, local currency		
PKR	is a matrix of industry investment price for 70/43 industries and 71 regions, 2010=1.0, local currency		
PQRM	is a matrix of import prices for 70/43 industries and 71 regions, 2010=1.0, local currency The model has a dual classification system. Oil price is captured for the first 33 regions in PQMA(5), for the rest of the regions PQMA(3) is used;		
PRSC	is a vector of consumer price deflator for 71 regions, 2010=1.0		
YRWC	is a matrix of real average labour costs 70/43 industries and 71 regions, local currency at current prices		

YRLC	is a matrix of wage costs (including social security contributions) for 70/43 industries and 71 regions, local currency at current prices
YREE	is a matrix of employees for 70/43 industries and 71 regions, in thousands of persons
DEBT	is a matrix of outstanding debt/output ratios for 70/43 industries and 71 regions
YRDS	is a matrix of import prices for 70/43 industries and 71 regions, m euro at 2010 prices
RCRR	is a vector of real commercial rate of interest rates for 71 regions
RLR	is a vector of long-run nominal interest rates for 71 regions
YYN	is a matrix of the ratio of gross output to normal output, for 70/43 industries and 71 regions
RILR	is a vector long-term nominal risk-free rate of interest for 71 regions
RSPR	is a vector of nominal commercial spreads for 71 regions

7.3.6 The trade equations

Modelling trade is an important feature in a regional model such as E3ME for two main reasons. Firstly, globalisation has meant that international trade has accounted for an increasing share of total production and is expected to increase further in the future. Secondly, exports and imports represent the linkage between countries in E3ME, so effects moving from one country to another are transmitted via this area of the model.

Previous approach

The original specification of the trade equations in E3ME was based around the proposals in Ragot (1994). It also draws on the variety hypothesis (Barker, 1977) and its incorporation in a UK multisectoral model (Barker and Peterson, 1987). Trade was treated as if it takes place through a 'pool', i.e., a transport and distribution network, with the export and import volume equations representing each country's exports into this pool and imports from it. In previous versions of E3ME trade was split into transactions within and external to the EU.

Bilateral trade

This split is maintained in the current version of the model and has been expanded to include other trade zones as well. However, the modelling approach has been revised considerably and now uses a bilateral approach, similar in method to a Two-Tier Armington model (Armington 1969). It can be summarised in the following steps:

- solve the model equations for total imports in each sector (split within and external to trading zones)
- solve the model equations for bilateral imports
- scale the bilateral trade results for consistency with the aggregate results
- derive total exports as the sum and inverse of bilateral imports

The bilateral import equations are estimated for six regional groups and 16 sectors, aggregated from the standard E3ME classifications. The resulting parameters from these equations are allocated to the E3ME regions and sectors based on the group to which they belong (e.g., Germany's bilateral trade estimated parameters will be those of Europe in the estimation). The model then solves the bilateral trade equation in the standard E3ME classification based on these assigned parameters. Table 7. shows the region and sector groups for which the bilateral trade parameters are estimated.

Table 7.11 Bilateral import equation region and sector groups

Regions	Sectors

Europe	Agriculture
US	Mining and quarrying
Rest of America	Food
China	Textiles
Rest of Asia	Wood, paper, printing, publishing
Rest of the World	Chemicals
	Non-metallic mineral products
	Basic metals
	Engineering
	Vehicles
	Other manufacturing
	Utilities, distribution, retail
	Hotels and catering
	Transport and communications
	Business services
	Other services

For each of the aggregated sectors, the equation is estimated as import by one region group towards all other region groups. The explanatory variables are the bilateral import price and a measure of technology (cumulated investment).

Aggregate import volumes

The equations for aggregate import volumes are largely unchanged from previous versions of the model. Imports are split into those within a country's trading zone (internal imports) and those from the rest of the world (external imports). In the equations, activity is modelled by sales to the domestic market. The three prices affected by this are import price, price of sales to the domestic market and the relative price of the currency, i.e., the exchange rate.

Aside from the restrictions on sign and significance, price homogeneity is imposed between the price of imports and price of sales to the domestic market. This has the effect of making the price relative, removing the long-term effect of the exchange rate variable. Technical progress measures are included to allow for the effects of innovations on trade performance. In the internal imports equations, there is an additional synthetic indicator for the development of trading zones such as the European single market.

The formal specification of the import equations is shown in Table 7.2 and Table 7.12.

Bilateral imports

The bilateral trade data are defined at the 43-sector level. The other dimensions in the data are origin (71 regions), destination (71 regions) and year (1995-2012). Initial attempts were made to carry out time-series estimation at this level of detail (i.e., 70*70*43 equations) but this proved to be infeasible due to computation time and gaps in the data.

The following adjustments were therefore made to the estimation procedure:

- the regions were aggregated to five global areas (Europe, US, China, North America, and Rest of World)

- the 43 sectors were aggregated to 19
- only a levels-based estimation was carried out

The equation specification allows the bilateral import share to be determined by export prices and technology in the exporting region. As the time-series grow in length, additional explanatory factors will be added to the equation to deal with factors like scale effects. The functional form will also be revisited.

The equations are estimated at the aggregate level and the parameters are then applied to each of the more disaggregated sectors. The number of regions included in the estimation will be gradually expanded as the data are cleaned and further improved. Although the sectoral aggregation may seem quite severe, it has only limited impact on the results because the sectors aggregated are principally non-traded ones (e.g., utilities, distribution/retail, and public services) or thinly traded service sectors.

Export volumes

Given the results for bilateral imports, the model results for exports (both bilaterally and as a region's total) are relatively simplistic to derive; trade flows are reversed and aggregated to give regional totals.

It is important to note that there is a further scaling 'calibration' exercise to ensure that model outputs are consistent with historical figures for regional exports. This scaling takes into account the discrepancy between the sums of global imports and exports.

Table 7.2: The Internal Import Volume Equations

The equations for QIM: internal import volume and QEM: external import volume have the same structure and are both represented by this table and described as QM equation.

Co-integrating long-term equation:			
LN(QM(.))			[internal import volume]
	=	BQM(.,12)	
	+	BQM(.,13) * LN(QRDI(.))	[home sales]
	+	BQM(.,14) * LN(PQRM(.))	[import price]
	+	BQM(.,15) * LN(PYH(.))	[price home sales by home producers]
	+	BQM(.,16) * LN(EX)	[exchange rate]
	+	BQM(.,17) * LN(YKNO(.))	[stock of knowledge]
	+	BQM(.,18) * LN(YCAP(.))	[stock of capital]
	+	BQM(.,19) * SVIM	[proxy for internal market programme, [=0 for external trade]
	+	error term	
Dynamic equation:			
DLN(QM(.))			[change in internal import volume]
	=	BQM(.,1)	
	+	BQM(.,2) * DLN(QRDI(.))	[home sales]
	+	BQM(.,3) * DLN(PQRM(.))	[import price]
	+	BQM(.,4) * DLN(PYH(.))	[price home sales by home producers]
	+	BQM(.,5) * DLN(EX)	[exchange rate]
	+	BQM(.,6) * DLN(YKNO(.))	[stock of knowledge]
	+	BQM(.,7) * DLN(YCAP(.))	[stock of capital]

	+	BQM(.,8) * DSVIM	[proxy for internal market programme, [=0 for external trade]
	+	BQM(.,9) * DLN(YYN(.))	[actual/normal output]
	+	BIM(.,10) * DLN(QM)(-1)	[lagged change in import volume]
	+	BQM(.,11) * ECT	[error correction term: lagged long-run residual]

Identity:

QRDI	=	QR(.) + QRM(.)	[home sales]
PYH	=	(VQR(.) - VQRX(.)) / (QR(.) - QRX(.))	[price home sales by home producers]

Restrictions:

BQM(.,14) + BQM(.,15) = 0	[price homogeneity]
BQM(.,16) = BQM(.,14) + BQM(.,15)	[price and exchange rate symmetry]
BQM(.,2 .,4 .,13 .,15) >= 0	['right sign']
BQM(.,3 .,5 .,6 .,7 .,14 .,16 .,17 .,18) <= 0	['right sign']
0 > BQM(.,11) > -1	['good error correction mechanism']

Definitions:

BQM	is a matrix of parameters for equation QIM or QEM
QIM	is a matrix of internal imports for 70/43 industries and 71 regions, m euro at 2010 prices
QEM	is a matrix of external imports for 70/43 industries and 71 regions, m euro at 2010 prices
PQRM	is a matrix of import prices for 70/43 industries and 71 regions, 2010=1.0, local currency
EX	is a vector of exchange rates, local currency per euro, 2010=1.0
QR	is a matrix of gross output for 70/43 industries and 71 regions, m euro at 2010 prices
QRM	is a matrix of imports for 70/43 industries and 71 regions, m euro at 2010 prices
QRX	is a matrix of exports for 70/43 industries and 71 regions, m euro at 2010 prices
YKNO	is a matrix of the knowledge stock for 70/43 industries and 71 regions, m euro at 2010 prices
YCAP	is a matrix of the capital stock for 70/43 industries and 71 regions, m euro at 2010 prices
YRKS	is a matrix of skills for 70/43 industries and 71 regions
SVIM	is an indicator of progress in the trade bloc
YYN	is a matrix of the ratio of gross output to normal output, for 70/43 industries and 71 regions
V-	indicates a current price version of the variable

7.3.7 Average working hours

A measure of hours worked (see Table 7.3) in each industry is needed because employment is modelled in the number of employees, rather than in person-hours. From this, one would expect the related coefficient in the employment equation to be negative; if people are, on average, working longer hours, then this should have an adverse effect on job opportunities, and vice versa. The effect of identifying an hours-worked variable will even out when it comes to analysing productivity effects, but in countries with relatively flexible labour markets, such as the UK, it is a good idea to try and model the effects explicitly.

The chosen model follows the methodology of Neal and Wilson (1987). The relationship at its simplest level can be explained by the identity:

$$yh_t = ynh_t + \beta 1 yoh_t + \beta 2 ysh_t$$

where:

yh_t = average hours per person per week

ynh_t = normal hours per person per week

yoh_t = overtime hours per person per week

ysh_t = short-time hours per person per week

$\beta 1, \beta 2$ = proportion of people on overtime and short-time, respectively

The main issue is then to develop a theory that expresses the demand for hours worked in terms of the RHS variables, or proxies for them. Using the firm's cost-minimisation framework:

$$\min_{v}(wv) s.t. f(v) = q$$

where:

q = output

$f(v)$ = a production function defined over a vector of v inputs

w = input prices

The level of 'optimal hours' (yh^*) can be derived as a function of factor prices, but it is only under very restrictive assumptions that optimal hours are equal to normal hours worked, which is usually taken to mean the level of utilisation that minimises the hourly wage rate.

Specification in E3ME

There is clearly some relation between the two concepts, however. The procedure adopted is of a general relationship:

$$yh_t^* = h^*(const, ynh_t, T_t)$$

where:

$h^*(.)$ has a log-linear specification

T_t = technological progress

The discrepancy between desired actual hours and optimal hours is assumed to arise mainly from short-run output adjustments. With a fixed capital stock, any deviation of output from its forecast level will be met largely through adjustment in hours worked, i.e., either by overtime or short-time working, while employment levels are adjusted by the firm. Thus, we have:

$$yh_t^d = h^d(\frac{q^e}{qt}, yh^{*t}, n_t)$$

which gives desired actual hours as a function of output forecast errors, optimal hours, and employment, n_t.

To form an equation for actual hours worked, the hours worked identity and disaggregate consumption equation are combined to substitute out for yh^*. However, to avoid a feedback loop with the employment equations in the model solution, employment is left out of the final specification. This gives the general model form:

$$yh_t = h\left(ynh_t, \frac{q^e}{q_t}, T_t\right)$$

This general form can, on finding a cointegrating relationship between the above variables, be represented by an error correction mechanism, the first stage of which is the levels regression and the second stage of which is the dynamic regression.

Table 7.3: The Industrial Hours-Worked Equations

Co-integrating long-term equation:			
LN(YRH(.))			[average hours worked]
	=	BYRH(.,8)	
	+	BYRH(.,9) * LN(YRNH(.))	[normal hours worked]
	+	BYRH(.,10) * LN(YKNO(.))	[stock of knowledge]
	+	BYRH(.,11) * LN(YCAP(.))	[stock of capital]
	+	error term	
Dynamic equation:			
DLN(YRH(.))			[change in average hours worked]
	=	BYRH(.,1)	
	+	BYRH(.,2) * DLN(YRNH(.))	[normal hours worked]
	+	BYRH(.,3) * DLN(YKNO(.))	[stock of knowledge]
	+	BYRH(.,4) * DLN(YCAP(.))	[stock of capital]
	+	BYRH(.,5) * LN(YYN(.))	[actual/normal output]
	+	BYRH(.,6) * DLN(YRH)(-1)	[lagged change in average hours worked]
	+	BYRH(.,7) * ECT	[error correction term: lagged long-run residual]
Restrictions:			
BYRH(.,2 .,9) = 1			[normal hours homogeneity]
BYRH(.,3 .,4 .,10 .,11) <= 0			['right sign']
BYRH(.,5) >= 0			['right sign']
0 > BYRH(.,7) > -1			['good error correction mechanism']

Definitions:

BYRH	is a matrix of parameters
YRH	is a matrix of average hours worked per week for 70/43 industries and 71 regions
YKNO	is a matrix of the knowledge stock for 70/43 industries and 71 regions, m euro at 2010 prices
YCAP	is a matrix of the capital stock for 70/43 industries and 71 regions, m euro at 2010 prices
YRNH	is a matrix of normal hours worked per week for 70/43 industries and 71 regions
YYN	is a matrix of the ratio of gross output to normal output, for 70/43 industries and 71 regions

7.3.8 Industrial employment

The chosen model follows the work of Lee, Pesaran, and Pierse (1990) but also incorporates insights from the work on growth theory developed by Scott (1989). A detailed methodological description with empirical results is contained in E3ME working papers no. 28 (Gardiner, 1994) and no. 43 (later Barker and Gardiner, 1996). This includes a formal representation of the theoretical optimisation problem for firms to minimise costs for a given level of output.

In the econometric representation in E3ME, employment is determined as a function of real output, real wage costs, hours-worked, the oil import price (used as a proxy for energy prices) and the measures of technological progress. This is shown in Table 7.4.

Over the forecast period the oil import price effect has been set to zero, as sometimes large oil price shocks are modelled. However, the equation specification does still allow for switching from energy to labour in response to higher prices. Industry prices are formed from sectoral unit costs and included in the wage term; higher energy prices within each sector therefore have a similar effect to reducing wage rates.

Table 7.4: The Industrial Employment Equations

Co-integrating long-term equation:			
LN(YRE(.))			[total employment]
	=	BYRE(.,9)	
	+	BYRE(.,10) * LN(YR(.))	[real output]
	+	BYRE(.,11) * LN(YRWC (.))	[real average labour costs]
	+	BYRE(.,12) * LN(YRH(.))	[hours worked]
	+	BYRE(.,13) * LN(YKNO(.))	[stock of knowledge]
	+	BYRE(.,14) * LN(YCAP(.))	[stock of capital]
	+	error term	
Dynamic equation:			
DLN(YRE(.))			[change in total employment]
	=	BYRE(,.1)	
	+	BYRE(,.2) * DLN(YR(.))	[real output]
	+	BYRE(,.3) * DLN(LYLC(.))	[real wage costs]
	+	BYRE(,.4) * DLN(YRH(.))	[hours worked]
	+	BYRE(,.5) * DLN(PQRM(5,.))	[real oil price]
	+	BYRE(,.) * DLN(YKNO(.))	[stock of knowledge]
	+	BYRE(,.6) * DLN(YCAP(.))	[stock of capital]
	+	BYRE(,.7) * DLN(YRE)(-1)	[lagged change in employment]
	+	BYRE(,.8) * ECT	[error correction term: lagged long-run residual]
Identity:			
YRWC	=	(YRLC(.)/PYR(.)) / YREE(.)	[real average labour costs]
Restrictions:			
BYRE(.,2 .,10) >= 0			['right sign']
BYRE(.,3 .,4 .,11 .,12) <= 0			['right sign']
0 > BYRE(.,9) > -1			['good error correction mechanism']
Definitions:			
BYRE	is a matrix of parameters		
YRE	is a matrix of total employment for 70/43 industries and 71 regions, in thousands of persons		
YR	is a matrix of gross industry output for 70/43 industries and 71 regions, m euro at 2010 prices		
YRH	is a matrix of average hours worked per week for 70/43 industries and 71 regions		
YRLC	is a matrix of employer labour costs (wages plus imputed social security contributions) for 70/43 industries and 71 regions, local currency at current prices		

YKNO	is a matrix of the knowledge stock for 70/43 industries and 71 regions, m euro at 2010 prices
YCAP	is a matrix of the capital stock for 70/43 industries and 71 regions, m euro at 2010 prices
PYR	is a matrix of industry output prices for 70/43 industries and 71 regions, 2010=1.0, local currency
YREE	is a matrix of wage and salary earners for 71 regions, in thousands of persons

7.3.9 Domestic industry prices

The following model of industry price formation (see Table 7.5) was developed from Lee (1988), having previously been derived from Layard et al (1991). The original empirical results were presented in E3ME working paper no. 43 (later Barker and Gardiner, 1996).

The basis for price setting is a measure of unit costs, which is formed by summing material, labour, and taxation costs, and dividing this by sectoral output. Material costs are estimated using input-output coefficients and the relative prices in each sector that provides inputs. Each industry is assumed to produce a homogenous product but does not necessarily operate in a fully competitive marketplace. The degree to which cost increases are passed on in final product prices is determined by the level of competition in the sector.

Although import prices are included in unit costs, depending on the import content of production, import prices are added separately in the equation to allow for the effects of international competition on domestic price formation. In the long-term relationship, homogeneity is imposed between higher domestic and import cost effects, so that their combined impact is unitary. The equations also include the technology indices, as a higher quality product may command a higher price.

An important relationship in the short-term equation is the actual/normal output ratio. If actual output increases above expected/trend levels, this can cause prices to rise due to capacity constraints. However, if capacity increases (represented in the model by an increase in normal output, see Section 7.3.15) then prices can fall, leading to higher real incomes and economic growth.

Some sectors have a specific treatment of price and do not use the estimated equations, instead using a simpler relationship:

- Commoditised sectors – domestic prices are assumed to be the same as global market prices and therefore track import prices
- The electricity sector – electricity prices are set by average levelised costs of generation
- Government sectors – these are assumed to move in line with aggregate regional consumer price inflation
- Regulated sectors – these are also assumed to move in line with aggregate inflation

Table 7.5: The Industrial Price Equations

Co-integrating long-term equation:

LN(PYH(.))			[price of home sales by home producers]
	=	BPYH(.,9)	
	+	BPYH(.,10) * LN(YRUC(.))	[unit costs]
	+	BPYH(.,11) * LN(PQRM(.))	[import price]
	+	BPYH(.,12) * LN(YKNO(.))	[stock of knowledge]
	+	BPYH(.,13) * LN(YCAP(.))	[stock of capital]
	+	error term	

Dynamic equation:

DLN(PYH(.))			[change in price of home sales by home prods.]
	=	BPYH(.,1)	
	+	BPYH(.,2) * DLN(YRUC(.))	[unit costs]
	+	BPYH(.,3) * DLN(PQRM(.))	[import price]
	+	BPYH(.,4) * DLN(YKNO(.))	[stock of knowledge]
	+	BPYH(.,5) * DLN(YCAP(.))	[stock of capital]
	+	BPYH(.,6) * DLN(YYN(.))	[actual/normal output]
	+	BPYH(.,7) * DLN(PYH)(-1)	[lagged change in price]
	+	BPYH(.,8) * ECT	[error correction term: lagged long-run residual]

Identities:

PYH	=	(VQR(.) - VQRX(.)) / (QR(.) - QRX(.))	[price of home sales by home producers]
YRUC	=	YRUM(.) + YRUL(.) + YRUT(.)	[unit costs]
YRUM	=	SUM (QYC(.) * PQRD(.)) / YR(.)	[material input unit costs]
YRUL	=	YRLC(.) / YR(.)	[unit labour costs]
YRUT	=	YRT(.) / YR(.)	[unit tax costs]
PQRD	=	(VQR(.) + VQRM(.) – VQRX(.)) / (QR(.) + QRM(.) – QRX(.))	[price of sales to the domestic market]

Restrictions:

BPYH(.,10) + BPYH(.,11) = 1	[price homogeneity]
BPYH(.,2 .,3 .,4 .,5 .,6 .,10 .,11 .,12.,13) >= 0	[‘right sign’]
0 > BPYH(.,8) > -1	[‘good error correction mechanism’]

Definitions:

BPYH	is a matrix of parameters
PYH	is a matrix of prices of home sales by home producers for 70/43 industries and 71 regions, (local currency)
YRUC	is a matrix of industrial unit costs for 70/43 industries and 71 regions, m euro at 2010 prices
YRUM	is a matrix of industrial unit material costs for 70/43 industries and 71 regions, m euro at 2010 prices
YRUL	is a matrix of industrial unit labour costs for 70/43 industries and 71 regions, m euro at 2010 prices
YRUL	is a matrix of industrial unit tax costs for 70/43 industries and 71 regions, m euro at 2010 prices
PQRM	is a matrix of import prices for 70/43 industries and 71 regions, m euro at 2010 prices
YR	is a matrix of gross industry output for 70/43 industries and 71 regions, m euro at 2010 prices
YKNO	is a matrix of the knowledge stock for 70/43 industries and 71 regions, m euro at 2010 prices
YCAP	is a matrix of the capital stock for 70/43 industries and 71 regions, m euro at 2010 prices

QR	is a matrix of gross output for 70/43 industries and 71 regions, m euro at 2010 prices
QRM	is a matrix of imports for 70/43 industries and 71 regions, m euro at 2010 prices
QRX	is a matrix of exports for 70/43 industries and 71 regions, m euro at 2010 prices
YYN	is a matrix of the ratio of gross output to normal output, for 70/43 industries and 71 regions
QYC	is an input-output coefficient matrix
YRLC	is a matrix of labour costs for 70/43 industries and 71 regions, local currency at current prices
YRT	is a matrix of net taxes for 70/43 industries and 71 regions, local currency at current prices
V-	indicates a current price version of the variable

7.3.10 Export and import prices

The export price equations and the import price equations (see Table 7. and

Table 7.6) play a large role in the response to exchange rate movements, acting as an important transmission mechanism for effects such as currency devaluation. The effects can be dissipated in a number of ways, creating inflationary pressures, leading to movements in the balance of payments, etc.

The basic model of trade prices used in E3ME assumes that each region operates in oligopolistic markets and is a small economy in relation to the total market. Certain commodities, such as crude mineral oil, have prices treated exogenously, but the majority are treated in the following manner. Following from the assumption on market structure, prices are set by producers as mark-ups on costs, i.e., unit costs of production. Aside from this, the same variables are used for both import and export prices, within a general log-log functional form.

Alongside the unit cost variable, there are three price terms included in each regression to deal with developments outside the region in question. They are an 'other region' price (created from other countries' export prices in the same manner as described in the trade volume equations), a world commodity price variable, and the exchange rate. The measures of technological progress are also included to cope with the quality effect on prices caused by increased levels of investment and R&D.

Restrictions are imposed to force price homogeneity and exchange rate symmetry on the long-term equations, again in much the same manner as for the trade volume equations.

Table 7.16 The Export Price Equations

Co-integrating long-term equation:			
LN(PQRX(.))			[export price]
	=	BPQX(.,10)	
	+	BPQX(.,11) * LN(PQRY(.))	[other regions' export prices]
	+	BPQX(.,12) * LN(PQWE(.))	[world commodity prices]
	+	BPQX(.,13) * LN(EX)	[exchange rate]
	+	BPQX(.,14) * LN(YRULT(.))	[unit labour and tax costs]
	+	BPQX(.,15) * LN(YKNO(.))	[stock of knowledge]
	+	BPQX(.,16) * LN(YCAP(.))	[stock of capital]
	+	error term	
Dynamic equation:			
DLN(PQRX(.))			[change in export prices]

	=	BPQX(.,1)	
	+	BPQX(.,2) * DLN(PQRY(.))	[other regions' export prices]
	+	BPQX(.,3) * DLN(PQWE(.))	[world commodity prices]
	+	BPQX(.,4) * DLN(EX)	[exchange rate]
	+	BPQX(.,5) * DLN(YRULT(.))	[unit labour and tax costs]
	+	BPQX(.,6) * DLN(YKNO(.))	[stock of knowledge]
	+	BPQX(.,7) * DLN(YCAP(.))	[stock of capital]
	+	BPQX(.,8) * DLN(PQRX)(-1)	[lagged change in export prices]
	+	BPQX(.,9) * ECT	[error correction term: lagged long-run residual]

Identities:

PQRY	=	SUM(QZXC(.)*VQRX(.)) / SUM(QZXC(.))*QRX(.))	[other regions' export prices]
PQWE	=	QMC(.) * PM	[world commodity price index]
YRULT	=	(YRLC(.) + YRT(.)) / QR(.)	[unit labour and tax costs]

Restrictions:

BPQX(.,11) + BPQX(.,12) = 1 - BPQX(.,14)	[price homogeneity]
BPQX(.,11) + BPQX(.,12) = BPQX(.,13)	[exchange rate symmetry]
BPQX(.,2 .,3 .,4 .,5 .,6 .,7 .,11 .,12 .,13 .,14 .,15 .,16) >=0	['right sign']
0 > BPQX(.,9) > -1	['good error correction mechanism']

Definitions:

BPQX	is a matrix of parameters
PQRX	is a matrix of export prices for 70/43 industries and 71 regions, 2010=1.0, local currency
PQRY	is a matrix of other regions' export price index (weighted by bilateral exports) for 70/43 industries and 71 regions, 2010=1.0
PQWE	is a matrix of world commodity price index for 70/43 industries and 71 regions, 2010=1.0
EX	is a vector of exchange rates, local currency per euro, 2010=1.0
QZXC	is a matrix of bilateral trade shares of industry exports by destination for 70/43 industries and 71 regions
QMC	is a converter matrix between 70/43 industry and 7 world commodity classifications
PM	is a vector of commodity prices (in euros) for 7 commodities, 2010=1.0
YKNO	is a matrix of the knowledge stock for 70/43 industries and 71 regions, m euro at 2010 prices
YCAP	is a matrix of the capital stock for 70/43 industries and 71 regions, m euro at 2010 prices
YRLC	is a matrix of employer labour costs for 70/43 industries and 71 regions, local currency at current prices
YRT	is a matrix of tax costs, for 70/43 industries and 71 regions, m euro at current prices
QR	is a matrix of industry gross output for 70/43 industries and 71 regions, m euro at 2010 prices
VQRX	is a matrix of industry exports for 70/43 industries and 71 regions, m euro at current prices
QRX	is a matrix of industry exports for 70/43 industries and 71 regions, m euro at 2010 prices

Table 7.6: The Import Price Equations

Co-integrating long-term equation:

LN(PQRM(.))			[import price]
	=	BPQM(.,10)	
	+	BPQM(.,11) * LN(PQRF(.))	[other regions' export prices]
	+	BPQM(.,12) * LN(PQWE(.))	[world commodity prices]
	+	BPQM(.,13) * LN(EX)	[exchange rate]

	+	BPQM(.,14) * LN(YRUL(.))	[unit labour costs]
	+	BPQM(.,15) * LN(YKNO(.))	[stock of knowledge]
	+	BPQM(.,16) * LN(YCAP(.))	[stock of capital]
	+	error term	

Dynamic equation:

DLN(PQRM(.))			[change in import price]
	=	BPQM(.,1)	
	+	BPQM(.,2) * DLN(PQRF(.))	[other regions' export prices]
	+	BPQM(.,3) * DLN(PQWE(.))	[world commodity prices]
	+	BPQM(.,4) * DLN(EX)	[exchange rate]
	+	BPQM(.,5) * DLN(YRUL(.))	[unit labour costs]
	+	BPQM(.,6) * DLN(YKNO(.))	[ICT technological progress]
	+	BPQM(.,7) * DLN(YCAP(.))	[stock of knowledge]
	+	BPQM(.,8) * DLN(PQRM)(-1)	[stock of capital]
	+	BPQM(.,9) * ECT	[error correction term: lagged long-run residual]

Identities:

PQRF	=	SUM(QZMC(.)) * VQRX(.)) / SUM(QZMC(.) * QRX(.))	[other regions' export prices]
PQWE	=	QMC(.) * PM	[world commodity price index]
YRUL	=	YRLC(.) * EX / QR(.)	[unit labour costs]

Restrictions:

BPQM(.,11) + BPQM(.,12) = 1 – BPQM(.,14)	[price homogeneity]
BPQM(.,11) + BPQM(.,12) = BPQM(.,13)	[exchange rate symmetry]
BPQM(.,2 .,3 .,4 .,5 .,11 .,12 .,13 .,14) >= 0	['right sign']
BPQM(.,6 .,7 .,15 .,16) <= 0	['right sign']
0 > BPQM(.,9) >- 1	['good error correction mechanism']

Definitions:

BPQM	is a matrix of parameters
PQRM	is a matrix of import prices for 70/43 industries and 71 regions, 2010=1.0, local currency
PQRF	is a matrix of other regions' export price index (weighted by bilateral imports) for 70/43 industries and 71 regions, 2010=1.0
PQWE	is a matrix of world commodity price index for 70/43 industries and 71 regions, 2010=1.0
EX	is a vector of exchange rates, local currency per euro, 2010=1.0
QZMC	is a matrix of bilateral trade shares of industry imports by origin for 70/43 industries and 71 regions
QMC	is a converter matrix between the 70/43 industry and 7 commodity classifications
PM	is a vector of commodity prices (in euros) for 7 commodities, 2010=1.0
YKNO	is a matrix of the knowledge stock for 70/43 industries and 71 regions, m euro at 2010 prices
YCAP	is a matrix of the capital stock for 70/43 industries and 71 regions, m euro at 2010 prices
YRLC	is a matrix of employer labour costs for 70/43 industries and 71 regions, local currency at current prices
QR	is a matrix of industry gross output for 70/43 industries and 71 regions, m euro at 2010 prices
VQRX	is a matrix of industry exports for 70/43 industries and 71 regions, m euro at current prices
QRX	is a matrix of industry exports for 70/43 industries and 71 regions, m euro at 2010 prices

7.3.11 Industrial average earnings

The specification is given in Table 7.7.

The starting point for the formation of the wage rates equation used in E3ME is the approach adopted by Lee and Pesaran (1993), which is general enough to accommodate differing degrees of market power on both sides of the labour market. More information and empirical results are provided in E3ME working paper no. 43 (Barker and Gardiner, 1994).

The treatment of wage determination is based on a theory of the wage-setting decisions made by a utility-maximising union, where the union derives utility (the representative of its members) from higher real consumption wages (relative to a fallback level) and from higher levels of employment (also relative to a fallback level). The fallback level is taken to be proportional to a simple average of employment levels in the last two years in the empirical work.

The wage rate is set by unions choosing wage rates to maximise utility subject to the labour-demand constraint imposed by profit-maximising firms. The form of the equation is relatively straightforward: real wages in a sector rise (with weights) if there are internal, sector-specific shocks which cause revenue per worker to rise (e.g., productivity innovations in the sector), or if employment levels are rising. Real wages are also influenced by external effects, including changes in the real wage that can be obtained in the remainder of the economy, changes in incomes received if unemployed, and changes in the unemployment rate itself.

Ignoring other terms, Lee and Pesaran (1993) impose long-run restrictions on the equations, so that the weights on the internal and external influences sum to one, the growth of real product wage rates equals that of labour productivity in the whole economy, and all taxes are paid by employees (pp 37-38). In this model, employer taxes only affect the wage rate through consumer prices, along with import prices, prices of goods and services from other industries and indirect taxes.

The empirical evidence on the wage equation (surveyed by Layard et al 1991) strongly suggests that, in the long-term, bargaining takes place over real pay, and this is imposed in all the equations presented below. However, in the dynamic equation for the change in wage rates, a response of real rates is allowed and tested by introducing the change in consumer prices. In addition, it has been assumed that long-run price homogeneity holds, so that the long-run economy-wide real product wage rates grow at the same rate as economy-wide labour productivity.

The basic model can be extended further to cover industrial wage determination by country as well as by industry, introducing wage rates in the same industry but other countries into the information set. This means that the external influences on wage bargaining in an industry are divided into those from other industries in the same country, and those from the same industry in other countries.

The specification allows for external industry and regional effects on an industry's wage rates, internal effects of productivity growth, and general economy-wide effects of the unemployment and benefit rates. The parameter on the adjusted price index is imposed at unity in all equations, implying that the explanation given is of the real consumer wage.

Table 7.7: The Industrial Average Earnings Equations

Co-integrating long-term equation:			
LN(YRW(.))			[gross nominal average earnings]
	=	BYRW(.,12)	
	+	BYRW(.,13) * LN(YRWE(.))	[external industry wage rates]
	+	BYRW(.,14) * LN(YRXE(.))	[external regional wage rates]
	+	BYRW(.,15) * LYRP	[adjusted labour productivity]
	+	BYRW(.,16) * LN(RUNR)	[unemployment rate]
	+	BYRW(.,17) * LN(RBNR)	[benefit rate]
	+	BYRW(.,18) * LAPSC	[adjusted consumer prices]
	+	error term	
Dynamic equation:			
DLN(YRW(.))			[change in gross earnings]
	=	BYRW(.,1)	
	+	BYRW(.,2) * DLN(LYRWE(.))	[external industry wage rates]
	+	BYRW(.,3) * DLN(LYRXE(.))	[external regional wage rates]
	+	BYRW(.,4) * DLYRP	[productivity]
	+	BYRW(.,5) * DLN(RUNR(.))	[unemployment rate]
	+	BYRW(.,6) * DLN(RBNR(.))	[benefit rate]
	+	BYRW(.,7) * D(LAPSC)	[change in adjusted consumer prices]
	+	BYRW(.,8) * LN(REIW)	[adjusted consumer prices]
	+	BYRW(.,9) * DLN(YYN(.))	[normal/actual output]
	+	BYRW(.,10) * DLN(YRW)(-1)	[lagged change in wage rates]
	+	BYRW(.,11) * ECT	[error correction term: lagged long-run residual]
Identities:			
LYRP	=	LYR(.)-LYRE(.)+LPYR(.)-LPRSC + LRRET + LRETR	[adjusted labour productivity]
LAPSC	=	LN(PRSC) + RRET	[log adjusted consumer price deflator]
ARET	=	RRET * RETR * RITR	[adjusted wage retention rate]
REIW	=	(1 + RTIN / 100) * SURE + RPSC * (1-SURE)	[adjusted consumer prices]
YRWE(.)	=	SUM OVER I (I = all other industries) (LN(YRW(I)) * YRLC(I) / SUM(YRLC(I)) - LAPSC)	[external industry wage rates]
YRXE(.)	=	LN(YRW(.)) * RRDD + LN(EX) - LAPSC	[external regional wage rates]
RBNR	=	RBEN / RWS	[the benefit rate]
Restrictions:			
BYRW(.,13) + BYRW(.,14) + BYRW(.,15) = 1			[price homogeneity]
BYRW(.,2 .,3 .,4 .,6 .,7 .,9 .,13 .,14 .,15 .,17 .,18) >= 0			['right sign']
BYRW(.,5 .,16) <= 0			['right sign']
0 > BYRW(.,11) > -1			['good error correction mechanism']
Definitions:			
BYRW	is a matrix of parameters		
YRW	is a matrix of nominal average earnings (contractual wage) for 70/43 industries and 71 regions, national currency per person-year		

LYRWE	is a matrix of the log of external industry real wage rates (same region) for 70/43 industries and 71 regions, in thousands of persons
LYRXE	is a matrix of the log of external regional real wage rates (same industry) for 70/43 industries and 71 regions, m euro at 2010 prices
LYRP	is a matrix of the log of adjusted labour productivities for 70/43 industries and 71 regions, m euro at 2010 prices
YRLC	is a matrix of nominal employer costs (wages and salaries plus employers' and imputed social security contributions) for 70/43 industries and 71 regions, local currency at current price
RWS	is a vector of total wages for 71 regions, local currency at current price
LYRE	is a matrix of the log of total employment for 70/43 industries and 71 regions, in thousands of persons
LYR	is a matrix of the log of gross industry output for 70/43 industries and 71 regions, m euro at 2010 prices
LPYR	is a matrix of the log of prices of gross output for 70/43 industries and 71 regions, 2010=1.0, local currency
REIW	is a vector of adjusted prices for 71 regions, local currency at current price
YYN	is a matrix of the ration of gross output to normal output, for 70/43 industries and 71 regions
PRSC	is the price deflator for total consumers' expenditure, 2010=1.0, local currency
RPSC	is a vector of consumer price inflation for 71 regions, rate
SURE	is a vector of investor confidence measure for 71 regions
RTIN	is a vector of expected consumer price inflation for 71 regions, rate
RRET	is a vector of wage retention rate for 71 regions
RETR	is a vector of 1 + employers' social security rate for 71 regions
RITR	is a vector of 1 + indirect tax rate for 71 regions
RUNR	is the standardised unemployment rate
RBNR	is a vector of the social benefit to wage ratio paid to households, m euro at current prices for 71 regions
RBEN	is a vector of the social benefit paid to households, m euro at current prices for 71 regions
RRDD	is a normalized distance indicator matrix for 71 regions with zeros down the leading diagonal and rows summing to one
EX	is a vector of exchange rates, local currency per euro, 2010=1.0

7.3.12 Labour participation rate

The theoretical model for labour force participation rates (see Table 7.8) stems from a paper by Briscoe and Wilson (1992). The standard analysis of participation in the labour force is based around the idea of a reservation wage, such that if the market wage is greater than an individual's reservation wage, they will actively seek employment, and vice versa. It should be noted that this type of model assumes an excess demand for labour.

The reservation wage is normally described via a group of personal characteristics such as non-wage income, educational level, age, etc. Many of these personal traits are inherently unobservable, such as the value of leisure, and the reservation wage can thus be written as:

$$W^* = w^*(X^*, o^*)$$

where:

W^* is the reservation wage

X^* is a vector of observed characteristics

o^* is a variable of unobserved characteristics

Workers choose to participate in the labour force if $W > W^*$,where W is the market wage. Combined with the factors determining the market wage, the decision to participate can then be represented by:

$P = p(W, X^*, o^*)$

where:

P is the participation rate

In time-series studies, much of the personal background data usually used in cross-section studies are unavailable, so any model is necessarily limited to variables describing human wealth (in the narrowest of senses) and market wage determination. The original variables that were available for inclusion were the market wage rate, a measure of market activity (output), a proxy for non-labour income, and some measure of the tightness of the labour market, such as the unemployment rate. Pollitt and Chewpreecha (2008) later expanded on this after an empirical assessment found that average working hours and qualifications had significant impacts on participation. The same study found that defining unemployment by demographic group (using LFS data) and including a measure of pension income for older age groups improved performance.

The basic model, capturing variables in both the cointegrating and dynamic regressions, can therefore be written as:

$P = f(W, GDP, RUNR, RYH, RBEN, RQU, RSER)$

where:

W is the real market wage

GDP is real output

RUNR is the unemployment rate in each population group

RYH is average hours worked

RBEN is a measure of social benefit or pensions

RQU is the qualifications mix

RSER is a measure of economic structure, i.e., manufacturing versus services

The participation rate is estimated separately for male and females in five-year age bands to capture the different factors behind activity in the labour force between different population groups. Data limitations, however, mean that few of the explanatory variables (e.g., wages) are gender specific. The equation is estimated in logistic form, which means that the dependent variable is subject to the transformation

$L\_i = \ln{[p\_i/(1 - p\_i\ )]}.$

This is because the participation rate, p_i, is constrained within the [0,1] interval, something which the shape of the resulting logistic transformation ensures.

Table 7.8: The Participation Rate Equations

Co-integrating long-term equation:		
LN(LRP/(1-LRP))		[participation rate, logistic form]
=	BLRP(.,11)	
+	BLRP(.,12) * LN(RSQ)	[industry output]
+	BLRP(.,13) * LN(RWSR)	[real retained wage rates]
+	BLRP(.,14) * LN(LRUN(.))	[unemployment rate by group]
+	BLRP(.,15) * LN(RBPR)	[benefit or pension rate]
+	BLRP(.,16) * LN(RSER)	[economic structure]
+	BLRP(.,17) * LN(RYH)	[average hours worked]
+	BLRP(.,18) * LN(LRQU)	[qualification mix]
+	error term	
Dynamic equation:		
DLN(LRP/(1-LRP))		[participation rate, logistic form]
=	BLRP(.,1)	
+	BLRP(.,2) * DLN(RSQ)	[industry output]
+	BLRP(.,3) * DLN(RWSR)	[real retained wage rates]
+	BLRP(.,4) * DLN(LRUN(.))	[unemployment rate by group]
+	BLRP(.,5) * DLN(RBPR)	[benefit or pension rate]
+	BLRP(.,6) * DLN(RSER)	[economic structure]
+	BLRP(.,7) * DLN(RYH)	[average hours worked]
+	BLRP(.,8) * DLN(LRQU)	[qualifications mix]
+	BLRP(.,9) * DLN(LRP/(1-LRP))(-1)	[lagged change in participation rate]
+	BLRP(.,10) * ECT	[error correction term: lagged long-run residual]
Identities:		
RWSR =	EX*(RWS) / (PRSC*REEM)	[real retained wage rates]
LRP =	RLAB / RPOP	[participation rate]
RSER =	RSERV / NSERV	[economic structure]
Restrictions:		
BLRP(.,2 .,3 .,12 .,13) >= 0		['right sign']
BLRP(.,4 .,5 .,7 .,14 .,15 .,17) <= 0		['right sign']
0 > BLRP(.,10) > - 1		['good error correction mechanism']
Definitions:		
BLRP	is a matrix of parameters	
LRP	is a vector of labour force participation rate for 27 age/gender groups and 71 regions, as a proportion	
RLAB	is a matrix of labour force for 27 age/gender groups and 71 regions, in thousands of persons	
RPOP	is a matrix of population of working age for 27 age/gender groups and 71 regions, in thousands of persons	
RSQ	is a vector of total gross industry output for 71 regions, m euro at 2010 prices	
RWSR	is a vector of retention rates of real wages and salaries for 71 regions, rate	
RWS	is a vector of total nominal wages and salaries (wages and salaries excluding employers' imputed social security contributions) for 71 regions, m euro at current prices	
LRUN	is the standardized unemployment rate for 27 age/gender groups and 71 regions	
PRSC	is a vector of total consumer price deflator for 71 regions, in thousands of persons	
REEM	is a vector of total wage and salary earners for 71 regions, in thousands of persons	

RBPR	is the social benefit rate paid to households (15-49 age groups) compared to wages, or average pensions in euros pa (50+ age groups)
RSERV	is total gross output of service industries for 71 regions, m euro at 2010 prices
NSERV	is total gross output of non-service industries for 71 regions, m euro at 2010 prices
RSER	is the sectoral concentration variable for 71 regions to represent increased female participation rates
RYH	is the average hours worked per week for 71 regions
LRQU	is the (logged) qualifications mix for 27 age/gender groups for 71 regions
EX	is a vector of exchange rates, local currency per euro, 2010=1.0

7.3.13 Residual (non-wage) income

The specification is given in Table 7..

With wage rates explained by price levels and conditions in the labour market, the wage and salary payments by industry can be calculated from the industrial employment levels. These are some of the largest payments to the personal sector, but not the only ones.

To complete the income loop, a method had to be devised to cope with the difference between income from wages and salaries and gross disposable income less social security benefits. The solution was an equation that models the residual income between the two: the long-run equation relationship includes the real wage, the index of output price, GDP, and the real rate of interest as explanatory variables.

This equation set is by its nature, a temporary one, and will be replaced when a complete accounting structure for institutional payments and receipts can be established. The econometric equation is often not used, with residual income either fixed as exogenous or determined by a simpler treatment (e.g., as a fixed share of wage income).

Table 7.20: The Residual Income Equations

Co-integrating long-term equation:			
LN(RRI)			[residual income]
	=	BRRI(8)	
	+	BRRI(9) * LN(RWS)	[total wages]
	+	BRRI(10) * LN(RPSY)	[inflation]
	+	BRRI(11) * LN(VRYM)	[GDP (current prices)]
	+	BRRI(12) * LN(RLR)	[interest rates]
	+	error term	
Dynamic equation:			
DLN(RRI)			[residual income]
	=	BRRI(1)	
	+	BRRI(2) * DLN(RWS)	[total wages]
	+	BRRI(3) * DLN(RPSY)	[inflation]
	+	BRRI(4) * DLN(VRYM)	[GDP (current prices)]
	+	BRRI(5) * DLN(RLR)	[interest rates]
	+	BRRI(6) * DLN(RRI(-1))	[lagged changes in residual income]

	+	BRRI(7) * ECT	[error correction term: lagged long-run residual]
Identities:			
RRI	=	RGDI + RDTX + REES - RWS - RBEN	[residual income]
RPSY	=	Growth(PRYM)	[inflation]
Restriction:			
BLRP(.,4 .,5 .,11 .,12) >= 0			['right sign']
BLRP(.,2 .,3 .,9 .,10) <= 0			['right sign']
0 > BRRI(.,7) > -1			['good error correction mechanism']
Definitions:			
BRRI	is a matrix of parameters		
VRYM	is a vector of GDP at market prices for 71 regions, m euro at current prices		
RGDI	is a matrix of nominal gross disposable income for 71 regions, m euro at current prices		
RLR	is a matrix of long-run interest rates for 71 regions		
RWS	is a vector of nominal wages for 71 regions, m euro at current prices		
PRYM	is a vector of price for GVA for 71 regions, 2010=1.0		
EX	is a vector of exchange rates, local currency per euro, 2010=1.0		
RDTX	is a vector of total direct tax payments made by households, for 71 regions, m euro at current prices		
REES	is a vector of total of employees' NI contributions, for 71 regions, m euro at current prices		
RBEN	is a vector of social benefit paid to households, for 71 regions, m euro at current prices		

7.3.14 Investment in dwellings

Given that investment in dwellings (see Table 7.) is a big component of investment, it was felt that the industrial investment equation was inadequate in explaining the investment in dwellings and that it should be treated separately due to the different factors driving the decision-making process.

For the long-run equation the demand for housing is expected to have a positive relationship with real gross disposable income. Since most of the housing market is financed through borrowing, e.g., mortgages, the demand for housing also seems likely to be sensitive to variations in the real rate of interest. Variables covering child and old-age dependency rates are included to capture changes in investment in dwellings caused by changing demography. For the dynamic equation the unemployment rate is included, to capture the variation in the labour market, as well as the total consumer price deflator.

Table 7.21: The Investment in Dwellings Equations

Co-integrating long-term equation:			
LN(RDW)			[investment in dwellings]
	=	BRDW(10)	
	+	BRDW(11) * LN(RRPD)	[real gross disposable income]
	+	BRDW(12) * LN(RRLR)	[real long-run rate of interest]
	+	BRDW(13) * LN(CDEP)	[child dependency ratio]
	+	BRDW(14) * LN(ODEP)	[old age pensioner dependency ratio]
	+	error term	

Dynamic equation:		
DLN(RDW)		[investment in dwellings]
=	BRDW(1)	
+	BRDW(2) * DLN(RRPD)	[real gross disposable income]
+	BRDW(3) * DLN(RRLR)	[real rate of interest]
+	BRDW(4) * DLN(CDEP)	[child dependency ratio]
+	BRDW(5) * DLN(ODEP)	[old age pensioner dependency ratio]
+	BRDW(6) * DLN(RUNR)	[unemployment rate]
+	BRDW(7) * LN(RPSC)	[total consumer price inflation]
+	BRDW(8) * DLN(RDW(-1))	[lagged changes in residual income]
+	BRDW(9) * ECT	[error correction term: lagged long-run residual]

Identities:			
RRPD	=	(RGDI * EX / PRSC)	[real gross disposable income]
RRLR	=	1 + (RLR - DLN(PRSC)) / 100	[real long-run rate of interest]
CDEP	=	CPOP / RPOP	[child dependency ratio]
ODEP	=	OPOP / RPOP	[old age pensioner dependency ratio]

Restrictions:	
BRDW(.,2 .,11) >= 0	['right sign']
BRDW(.,3 .,6 .,7 .,12) <= 0	['right sign']
0 > BRDW(.,9) > -1	['good error correction mechanism']

Definitions:	
BRDW	is a matrix of parameters
RDW	is a vector of investment in dwellings, m euro at 2010 prices
RGDI	is a matrix of gross disposable income for 71 regions, m euro at current prices
RLR	is a matrix of long-run interest rates for 71 regions
EX	is a vector of exchange rates, local currency per euro, 2010=1.0
RPSC	is a vector of total consumer price inflation for 71 regions, rate
RPOP	is a vector of working-age population for 71 regions, thousands of persons
CDEP	is a vector of child dependency ratios for 71 regions, ratio
ODEP	is a vector of old age dependency ratios for 71 regions, ratio
CPOP	is a vector of child population for 71 regions, thousands of persons
OPOP	is a vector of old-age population for 71 regions, thousands of persons
RUNR	is a vector of unemployment rates for 71 regions, as a percentage of the labour force

7.3.15 Normal output equations

The specification is provided in Table 7.9.

In E3ME, normal output is a measure of production capacity in each economic sector. Normal output appears in the dynamic part of many of the other equation sets as the denominator of the ratio (output / normal output). For example, a higher level of normal output can lead to lower prices and wage demands.

The technology variables also feature in the normal output equations since accumulated investment and R&D can lead to increases in capacity. Normal output is, therefore, a key component of the representation of endogenous growth in the model. Investment leads to higher capacity, lower prices, increases in real income, higher GDP, and in turn more investment.

The fitted values of the equation below are used as a proxy for normal output.

Table 7.9: The Normal Output Equations

Co-integrating long-term equation:			
LN(YRN)			[normal industrial output]
	=	BYRN(.,7)	
	+	BYRN(.,8) * LN(YR5(.))	[real average industry output of the past 5 years]
	+	BYRN(.,9) * LN(YKNO(.) + YCAP(.)))	[stock of knowledge and capital]
	+	BYRN(.,10) * LN(RUNR)	[unemployment rate]
	+	error term	
Dynamic equation:			
DLN(YRN)			[normal industrial output]
	=	BYRN(.,1)	
	+	BYRN(.,2) * DLN(YR5(.))	[real average industry output of the past 5 years]
	+	BYRN(.,3) * DLN(YKNO(.) + YCAP(.)))	[stock of knowledge and capital]
	+	BYRN(.,4) * DLN(RUNR)	[unemployment rate]
	+	BYRN(.,5) * DLN(YRN)(-1)	[lagged change in normal industrial output]
	+	BYRN(.,6) * ECT	[error correction term: lagged long-run residual]
Restrictions:			
BYRN(.,2) = 1			[long-run homogeneity of output and normal output]
BYRN(.,3 .,4 .,8 .,9 .,10) >= 0			['right sign']
0 > BYRN(.,6) > -1			['good error correction mechanism']
Definitions:			
BYRN	is a matrix of parameters		
YRN	is a matrix of normal industrial output for 70/43 sectors and 71 regions, m euro at 2010 prices, calculated as the fitted values of the dependent variable		
YR5	is a matrix of real average industry output of the past 5 years for 70/43 industries and 71 regions, m euro at 2010 prices		
YKNO	is a matrix of the knowledge stock for 70/43 industries and 71 regions, m euro at 2010 prices		
YCAP	is a matrix of the capital stock for 70/43 industries and 71 regions, m euro at 2010 prices		
RUNR	is a vector of unemployment rates for 71 regions, measured as a percentage of the labour force		

7.3.16 Material demand equation for food, feed, forestry, construction minerals, industrial minerals, ores, and water

This section refers to the materials submodel that was developed as part of the Matisse FP5 research project (Pollitt, 2007, 2008), and more recently applied in analysis for DG Environment. The equations are included in the standard model specification and form an important part of the overall structure.

Following the framework of E3ME's fuel demand equations, material demand is modelled as a function of economic activity, material prices, and two measures of innovation (investment and R&D spending). An additional variable has been added to take into account the differences in definition between domestically extracted and imported materials; this has recently been investigated more closely with the expansion of the model to include Raw Material Consumption (RMC).

For each material an equation is estimated for the 16 user groups. However, in reality, a large proportion of these equations are not used as not all the material user groups demand all the materials. For example, construction is the only user group to demand construction minerals. Table 7.10 outlines the specification of the material demand equations, giving material 1, food, as an example.

The equation set for water demand is not currently operational due to data limitations – but can easily be activated if data became available.

Table 7.10: The Material Demand Equations

Note: MU1 refers to material 1 (Food). The equations below are applicable to materials 1-7.		
Co-integrating long-term equation:		
LN(MU1(.)/QR(.))		[material intensity]
=	BMU1(.,8)	
+	BMU1(.,9) * LN(QR(.))	[output by material users]
+	BMU1(.,10) * LN(PMAT1(.))	[price of material]
+	BMU1(.,11) * LN(KR(.)/QR(.))	[investment ratio by material users]
+	BMU1(.,12) * LN(YRD(.)(.)/QR(.)))	[R&D ratio by material users]
+	BMU1(.,13) * (MUM1(.)/MUD1(.))	[trade ratio: import/domestic consumption]
+	error term	
Dynamic equation:		
DLN(MU1(.)/QR(.))		[material intensity]
=	BMU1(.,1)	
+	BMU1(.,2) * DLN(QR(.))	[output by material users]
+	BMU1(.,3) * DLN(PMAT1(.))	[price of material]
+	BMU1(.,4) * DLN(KR(.)/QR(.))	[investment ratio by material users]
+	BMU1(.,5) * DLN(YRD(.)/QR(.))	[R&D ratio by material users]
+	BMU1(.,6) * D(MUM1(.)/MUD1(.))	[trade ratio: import/domestic consumption]
+	BMU1(.,7) * ECT	[error correction term: lagged long-run residual]
Restrictions:		
BMU1(.,2 .,9) >= 0		['right sign']
BMU1(.,3 .,4 .,5 .,9 .,10 .,11) <= 0		['right sign']
0 > BMU1(.,7) > -1		['good error correction mechanism']
Definitions:		
BMU1	is a matrix of parameters (for material 1)	
MU1	is a matrix of material use (for material 1) by material user for 16 material users and for 71 regions, 000s of tonnes	

QR	is a matrix of output of products converted here to 16 material users and 71 regions, m euros at 2010 prices
PMAT1	is the price of material 1, 2010=1.0
KR	is a matrix of investment by 16 material users and for 71 regions, m euros at 2010 prices
YRD	is a matrix of R&D by 16 material users and for 71 regions, m euros at 2010 prices
MUM1	is a matrix of imports of material 1 by 16 material users and for 71 regions, 000s of tonnes
MUD1	is a matrix of domestic extraction of material 1 by 16 material users and for 71 regions, 000s of tonnes

8 Baseline and Scenarios

8.1 E3ME baseline and calibration process

Role of the baseline

E3ME uses a scenario-based approach. The starting point is a baseline case that is usually described as a business-as-usual approach. Policies are added to form a scenario and the results from the scenario are compared to the baseline. In this way, the effects of the policies are isolated.

Results from E3ME scenarios are usually presented as (percentage) differences from the baseline, highlighting the relative changes caused by the scenarios. Even though they are rarely used in the presentation of results, it is important that the levels used in the baseline are accurate. Analysis has shown that the values used in the baseline can be very important in determining outcomes. For example, if a scenario has a fixed emission target (e.g., 40% below 1990 levels), then the baseline levels are vital in determining the amount of mitigation action that must be done in the scenario to meet the target. Alternatively, if a scenario adds a fixed amount to energy prices, then reliable baseline energy price levels are needed determine the relative (percentage) impact of that increase.

Calibration

It is important to have a baseline that does not introduce bias into the scenario results. A common requirement of E3ME analysis is that the baseline is consistent with forecasts used in other analysis, such as the ‘PRIMES’ projections produced by DG Energy in the European Commission.

The ‘calibration’ process in E3ME is vastly different to the calibration used in CGE models. In a CGE model, the calibration process determines some or all the model’s parameters. In E3ME, calibration is a scaling process. It can be thought of as equivalent to CGE calibration but with only the equations’ intercepts being set. All other parameters are determined by the econometric equations. This means that E3ME’s results, as differences from the baseline, are only minorly impacted by calibration, whereas in a CGE model calibration will determine these differences.

Calibration method

The first stage in matching E3ME’s projections to a published forecast is to process these figures into E3ME’s format. This means that the various dimensions of the model must be matched, including:

- Geographical coverage (i.e., each country in the model)
- Annual time periods
- Sectoral coverage (including fuels and fuel users)
- National Accounts entries

Once the data from the external forecast are processed, E3ME is solved to match those numbers. The results are referred to as the ‘calibrated projections’. The calibrated projections are compared to and then replaced with the figures from the published values. The differences between the two are stored and saved as ‘residuals’.[5]

[5] The meaning of residuals here is different to the definition used in econometric estimation.

Endogenous baseline and scenarios

The final stage is the 'endogenous solution' in which the model equations are solved and the residuals are added on to these results. In theory, the outcome should be the same as for the calibrated forecast, although in practice there can be calibration errors, so it is not always an exact match.

Unlike the calibrated baseline, where the model results need to match official vales, inputs to the endogenous baseline may be changed in order to produce a different outcome. This creates a baseline set of projections that matches published values but which can also be used for comparison with scenarios.

Operational example

Consider an example for the aggregate consumption equation. If, in the first year of the projections, E3ME predicts a value of €100bn but the published forecast suggests €101bn then the calibrated projections will estimate a residual of 1.01 (i.e., 101/100).

If we then test a scenario in which consumption increases by 2% in this year, the model results will be €100bn (endogenous baseline) and €102bn (scenario). These will be adjusted (multiplied) by the residual to become €101bn and €103.02bn.

When these results are presented as percentage difference from the baseline, the figure that is reported is still 2% (103.02/101), so the calibration does not directly affect the conclusions from the model results.

When are results influenced by calibration?

In this example there is no impact from the calibration exercise on the results relative to baseline. This is typically true for any log-linear relationship within the model structure, as the calibration factors are cancelled out when calculating differences from base.

However, there are relationships in the model that are not log-linear, most commonly simple linear factors. These include the national accounting identities for GDP and for (gross) output, and the calculation for unemployment (as labour supply minus demand). For example, if the calibration results in higher trade ratios in a certain country, then the effects that trade impacts have on GDP will increase in the scenarios.

It is, therefore, important that the baseline provides a reasonable representation of reality, otherwise it is possible to introduce bias into the model results.

8.2 E3ME policy inputs

As an economy-energy-environment (E3) model, E3ME allows for policy inputs in each of those three domains. The policy inputs available in E3ME can equally be categorised into three broad types: regulations, price-based measures, and spending measures. Table 8.1 shows some examples of policy inputs across both dimensions.

Table 8.1: E3ME policies by category

	Economy	Energy	Environment
Regulation	-	Phase-out of coal power plants	Emissions quota

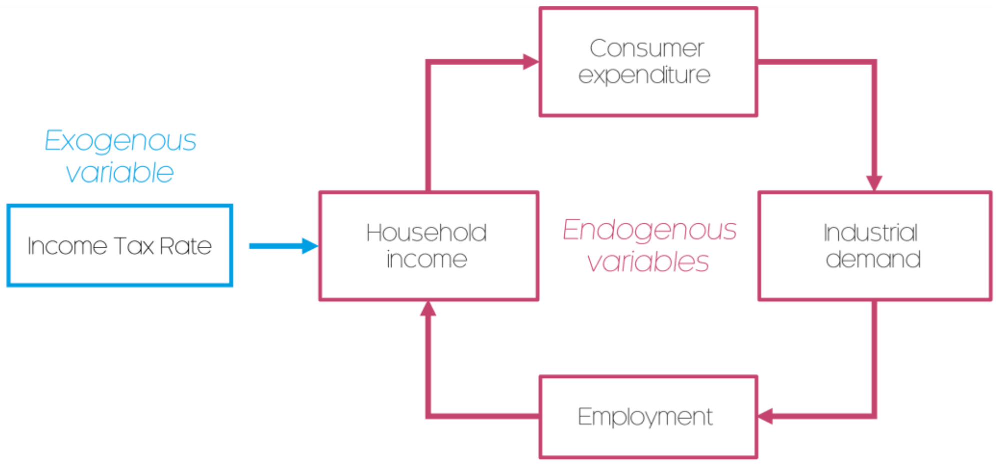
Pricing measure	Value-added tax	Fuel tax	Carbon tax
Spending	Lump sum payments to households	Investment in energy efficiency measures	Investment in carbon removal technology

However, these distinctions are not always so clear cut. E3ME modelling can demonstrate how the impacts of policy inputs cut across domains due to the interactions between the economic, energy, and environmental systems. To give a simple example, increased spending is likely to drive up both energy consumption and carbon emissions.

Furthermore, modelling a single policy in E3ME can often require multiple inputs of different types. For example, energy efficiency investments include both a spending component and a corresponding assumption of reduced energy demand.

These policy inputs are examples of 'exogenous' inputs to the model, variables whose values are defined externally to the model. Exogenous variables affect the values of other variables, but are themselves unaffected by model dynamics. By contrast, the value of an 'endogenous' variable both affects and is affected by model dynamics, as shown in Figure 8.1. This approach represents the economy from the perspective of the policymaker, who has full control over policy levers.

Figure 8.1: Exogenous and endogenous variables



Investment

Investment inputs can be assigned to the public or private sector but are most often used in E3ME to represent government investment in fixed assets as part of an environmental policy package.[6] A typical example of this is energy efficiency investment, which requires upfront investment to generate future energy savings.

[6] Note that "investment" in this context refers to gross fixed capital formation, i.e., expenditure on inputs which are used in economic production for more than one year. This can include spending on new industrial plants, infrastructure, tree planting, and R&D, among other things. In the case of government investment, it excludes *final* government expenditure on items such as education, health, and welfare payments.

Importantly, E3ME does not include the same constraints to aggregate investment levels as are found in many CGE models (see sections 3.2 and 4.5). In accordance with the endogenous theory of money, it is not assumed in E3ME that investment is constrained by savings, and therefore lower consumer expenditure is not a precondition of higher investment. Furthermore, it is not typically assumed that additional public investment will 'crowd out' private investment, as it may catalyse the employment of spare economic capacity. As a result, it is possible in E3ME for additional investment to boost aggregate demand and GDP, whereas in many CGE models theoretical constraints rule this out as a possibility.

Energy demand

Exogenous changes to energy demand can be specified for each region, fuel, and fuel user in the model. There are many reasons that these assumptions may be introduced into a modelling scenario, but the most common use cases are for investments affecting energy use (such as energy efficiency measures), or for regulatory measures mandating changes in energy use (such as biofuel blending mandates). Regulatory measures are an especially important tool in deep decarbonisation scenarios in which there may be few alternatives to address the 'last mile' of hard-to-abate sectors.

Carbon prices and fuel taxes

Carbon pricing is a core energy and environmental policy in E3ME. It can represent either carbon taxes or emissions trading schemes (ETS), although in practice both are usually modelled in the same way in E3ME – as a flat tax rate paid per unit of CO_2 emitted. Unlike most other policy inputs, carbon pricing is included in the E3ME baseline, with a common European carbon price replicating the EU ETS system.[7]

In E3ME, carbon prices are applied only to CO_2 emissions from energy use. E3ME allows for the specification of a single carbon price per region. There is no option to set different prices for different sectors and fuels, but it is possible to set exemptions for certain fuels and sectors. A typical example of these exemptions is for energy use in road transport and household heating, as it is conventionally assumed to be too politically controversial and administratively complicated to apply a carbon price to household energy use. Instead, taxes on these sectors are usually structured as different kinds of fuel taxes, which also feature as an important policy input in E3ME.

Technology-specific policies (FTT)

The sector-specific FTT models incorporated into E3ME (see chapter 5) each have a set of policy inputs associated with them. These policies can all be targeted at the level of a particular technology within a sector, affecting the adoption rate of that technology relative to its competitors. While each FTT model has its own distinct set of policy inputs, the input types listed below are generic policy inputs common to all FTT models in E3ME.

Phase-out regulation

Technology phase-out regulations are represented in FTT through maximum capacity constraints.[8] These constraints prevent new sales of technologies once the technology is above a defined capacity limit. However, they do not

[7] Carbon prices are defined in nominal terms in E3ME, which greatly simplifies the modelling of unified regional carbon prices across multiple countries, which each have their own inflation rates.

[8] The capacity constraints are defined in absolute terms, as opposed to market shares. In FTT:Power, for example, capacity constraints are defined in MW. As well as policy constraints, capacity constraints are also used in E3ME to represent physical constraints, such as the potential of hydroelectric power, which is constrained by the availability of rivers in a particular region.

enforce premature scrapping of legacy technologies before the end of their lifetimes. As a result, even if the capacity limit for a technology is set at zero, its market share may not reach zero for many years, until legacy technologies have reached the end of their lifetimes.

Investment subsidy

Technology adoption can also be influenced by pricing incentives affecting the investment cost of a particular technology. In E3ME/FTT, the technology investment subsidy is defined as a proportion of the investment cost covered by government. These subsidies reduce the levelised cost of the technology from the perspective of investors.

Strategic investment

It is possible for governments to directly intervene in technology markets through strategic procurement. In FTT, this is modelled as exogenously defined technology capacities. The scaling dynamics in FTT mean that these policies are especially effective in the early stages of the diffusion curve, as a small initial government investment can bring forward the tipping point of mass adoption for a promising technology.

Fiscal policy (revenue recycling)

Many of the policy inputs described above have implications for fiscal balance including carbon taxes, technology subsidies, and government investments. This raises the question of how governments will use additional revenues or fund additional spending. If no further inputs are added to the model, it is implicitly assumed that additional public spending will increase the deficit, and additional revenues will reduce it.

E3ME also offers the option of introducing additional measures to preserve budget neutrality, also known as ‘revenue recycling’. For example, revenues from a higher tax may be distributed through a lump sum payment to households. Equally, they may be used to reduce other taxes, such as income tax or VAT. By the same token, additional spending would be funded by higher taxes. In the case of recycling revenues from a carbon tax, these measures are often referred to as ‘environmental tax reform’.

8.3 Example E3ME scenario applications

1.5C scenario

Over the last few years, there has been an increase in requests for modelling low carbon transition scenarios. As a result, CE now includes a 1.5C scenario in the standard E3ME modelling offer.

According to the IPCC report, global warming has already reached 1.1 degrees, so the urgency of trying to limit global warming to 1.5 degrees Celsius by 2100 is significant. Even the target of 2 degrees (under the old Paris Agreement) is now looking difficult. The IPCC report highlights the different levels of damage caused by differing levels of temperature change such as fewer losses due to rising sea levels and reduced damages due to water shortages. It is important to model the 1.5C degree pathway to test which policies can be implemented to mitigate the consequences of global warming.

E3ME does not model the global temperature change directly but uses CO_2 emissions (a standard model output) to determine the level of global warming, since it accounts for the majority of greenhouse gas emissions.

In E3ME's modelling, carbon pricing and taxation are not sufficient to reach a net zero outcome on their own. Instead, supporting policies are implemented as well, such as:

- Regulations: such as phasing out fossil fuels power plants
- Subsidies: subsidising new low-carbon technologies in power generation to attract investors
- Energy efficiency investment drives: through methods such as public procurement or subsidies
- Support for new technologies

These supporting policies can be modelled in detail in E3ME. The simulation modelling approach used by E3ME helps policymakers to achieve net zero outcomes by trying different policy combinations. This contrasts the optimisation approach, in which policymakers work backwards from a predetermined emissions pathway to find the most cost-effective method of reaching it.

The economic impacts from CE's standard 1.5C scenario are the result of one of many possible pathways and can be changed with combinations of different policies.

Taxshift scenario

A 'taxshift' is the process of transferring the burden of taxation from labour onto resource use. This principle has received greater levels of attention in recent years, being argued for by the European Commission and implemented (to different degrees) across several member states over the last thirty years. International organisations such as the IMF and the UN have also spoken in favour of these principles.

Take, for example, a taxshift scenario in which taxes are imposed on aviation, water consumption, and carbon taxes, while a direct taxation is reduced, payroll tax credits are increased, and income support for the lowest two quintiles is increased. This scenario would be implemented in E3ME in the following way:

- Increased aviation tax: implemented by increasing the tax rate on kerosene fuel use
- Increased water consumption tax: implemented as tax increase on purchases from the water supply sector. This measure impacts all purchases of the sector, be they from households or businesses.
- Extended carbon tax: implemented by extending the carbon tax already modelled in E3ME to sectors previously exempt from it, such as "agriculture, forestry and fishing", "rail transport", and "textiles, clothing, and footwear".
- Decreased direct taxation: implemented by reducing the model's income tax rate variable.
- Increased payroll tax credits: implemented through a reduction on employers' social security contribution.
- Increased income support: implemented as a lump sum transfer to the two lowest quintiles.

In a taxshift scenario conducted by Cambridge Econometrics for Ex'Tax, it was found that a set of 20 measures (including, among others, those mentioned above) yielded a positive economic, societal, and environmental impact for the EU27. Though some policies created an upward pressure on business costs and consumer prices, the net effect on consumer purchasing power was positive, given the lower labour taxes. The measures also resulted in an increased decoupling of GDP from CO_2 emissions and resource consumption due to the incentives towards greater energy and resource efficiency. It should also be noted that, in order to preserve budget neutrality, this modelling exercise utilised revenue recycling, (see Section 8.2).

Automation scenario

The impact which automation may have on labour markets and the economy in the near future is currently a topic of considerable interest and research. Labour saving technologies, such as automation, have, historically, shown to yield short-term job displacement but job creation in the longer-run, as the higher income generated through lower production costs is spent on other goods and services. This generates more jobs than were initially lost due to higher productivity. Some argue that automation differs from previous labour-saving technologies, suggesting that it might lead to lower overall employment after its adoption.

Despite the small amount of data on automation (given its novelty) and the high level of uncertainty associated with projections, E3ME can be used to model the adoption of automation in the economy and the effects it might have. This scenario can be modelled in E3ME in the following ways:

- Implementing a reduction in employment that is attributed to automation across several sectors
- Increasing investment in order to replace workers with machinery or software as well as to provide training for the remaining workers
- Implementing changes on how each sector's supply chain functions, reflecting the changes which automation can cause in the production processes (namely an intensification in the use of IT equipment and software)
- Reducing the working hours of workers or increasing the average hourly wages to compensate the workers that remain for their increased productivity

In another scenario analysis conducted for Eurofound on the potential employment impact of accelerated automation (with a focus on the EU up to 2030), E3ME modelling indicated a net loss of jobs in the long-term. Although the indirect effects of automation on employment are positive, such as the increase in income for the remaining workers and higher demand for certain products/services due to supply chain shifts, they are not enough to supersede the negative direct effect on employment.

Increased protectionism scenario

Protectionist policies have experienced greater prominence ever since the 2008 recession and rose again during Trump's administration of the USA. The increase in these type of measures naturally elicited questions on how the raising of trade barriers would impact the economies of first-, second-, and third-party countries impacted by a trade war.

E3ME is able to simulate increased protectionism by increasing the tariff values utilised when calculating international trade between countries.

CE simulated the hypothetical case of a significant increase in tariffs (25 p.p.) between the major trading areas of the world (USA, EU, and China) for Eurofound, focusing on the effects on employment in Europe up to 2030. The results indicated that the EU would suffer a decrease in GDP and employment of 1% and 0.3% respectively by 2030. China would be the most affected in the short-term, but the EU would be the most affected in the long-term. The EU would also have the slowest recovery period. This is due to the EU having a trade surplus (like China and unlike the USA) but being less able to find alternative markets to export to (compared to China) after the implementation of the higher tariffs. The third-party countries (the rest of the world) were found to experience an increase in GDP due to trade diversion effects.

9 E3ME's Outputs and Key Variables

9.1 Typical Output

After E3ME is executed, an output file is created based on the scenarios applied. The model results include variables pertaining to the economy, society, energy, and the environment across a multitude of geographic regions and time.

As a general model of the economy, based on the full structure of the national accounts, E3ME is capable of producing a broad range of economic indicators as well as a range of energy and environment indicators.

Figure 9.1: Typical E3ME Output

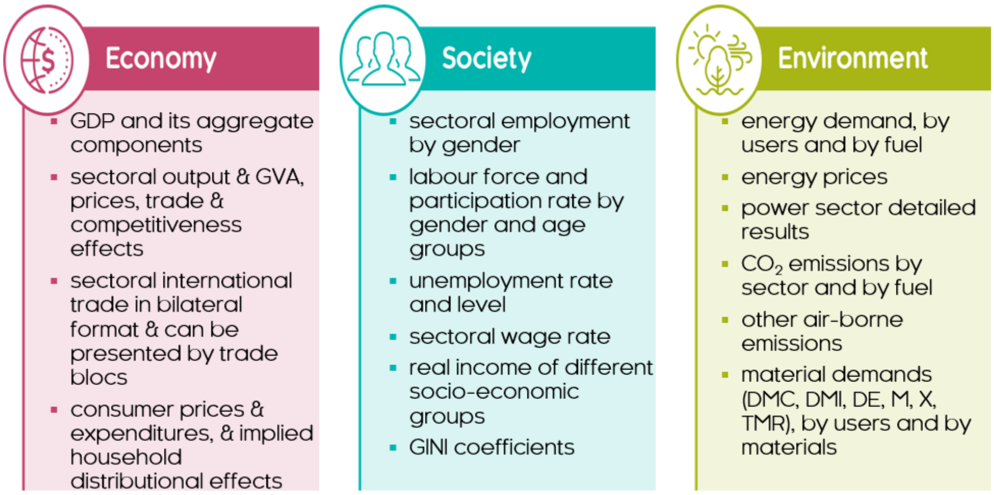


Figure 10.1 provides a summary of the most common model outputs. This list is by no means exhaustive and the delivered outputs often depend on the requirements of the specific application. In addition to the detailed sectoral dimension, all indicators are produced at the national and regional level as well as annually over the period up to 2050 (2100 is also possible).

9.2 Variables

E3ME uses both bi-dimensional (region x time) and tri-dimensional (region x time x third axis) variables. The third axis of tri-dimensional variables include but are not limited to economic sectors, fuel users, fuel types, power, transport, heat, and steel production technologies. In the special case of bilateral trade variables, E3ME uses quad-dimensional variables (region x sector x region of origin x time).

Table 9.1 provides a summary of the most common model outputs:

Table 9.1: Most common model outputs by category

GDP and the aggregate components of GDP (household expenditure, investment, government expenditure, stock building, and international trade)

RGDP	regional GDP expenditure measure at market prices (RSC + RSK + RSG + RSS + RSX - RSM)
RSC	regional total consumers' expenditure
RSK	regional total investment spending
RSG	regional total government final consumption
RSS	regional total stock building
RSX	regional total exports
RSM	regional total imports
Sectoral output and GVA, prices, trade, and competitiveness effects	
YR	industry outputs at basic prices
YRF	industry value-added at factor costs
PYR	prices of industry outputs
QRM	product imports
QRX	product exports
International trade by sector, origin, and destination	
BTRA	bilateral trade data, imports by sector, country of origin, and time
Consumer prices	
PRSC	price index (local currency) consumers expenditure
Sectoral employment, unemployment, sectoral wage rates, and labour supply	
YRE	industry employment (employees + self-employed)
RUNE	regional unemployment
YRW	average earnings by industry
RWPP	regional labour force (working-age population * participation rate)
Energy demand, by sector and by fuel, energy prices	
FRCT	coal use
FR02	coke, other coal use
FR03	crude oil use
FROT	heavy oil use
FR05	middle distillates use
FR06	other gas use
FRGT	natural gas use
FRET	electricity use
FR09	heat use
FR10	combustible waste use

FRBT	biofuel use
FR12	hydrogen use
PF01	energy price - coal
PF02	energy price - other coal
PF03	energy price - crude oil
PF04	energy price - heavy oil
PF05	energy price - middle distillates
PF06	energy price - other gas
PF07	energy price - natural gas
PF08	energy price - electricity
PF09	energy price - heat
PF10	energy price - combustible waste
PF11	energy price - biofuel
PF12	energy price - hydrogen
CO_2 emissions by sector and by fuel	
RCO2	emissions of carbon dioxide
JCO2	fuel emissions of carbon dioxide
FCO2	user emissions of carbon dioxide
Other air-borne emissions	
RGHG	emissions of GHGs as CO_2-equivalent
RSO2	emissions of sulphur dioxide
RNOX	emissions of nitrous oxides
RCO	emissions of carbon monoxide
RCH4	emissions of methane and other hydrocarbons
RBS	emissions of black smoke PM10
RCFC	emissions of chlorofluorocarbons
RN2O	emissions of nitrous oxide
RSF6	emissions of sulphur hexafluoride
RHFC	emissions of hydrofluorocarbons
RPFC	emissions of perfluorocarbons
Material demands	
RDMC	Regional domestic material consumption , Eurostat/IFF measure
RDMI	Regional direct material input, Eurostat/IFF measure

This list is by no means exhaustive, and the delivered outputs often depend on the requirements of the specific application.

10 The E3ME Software

10.1 The model's underlying software

The different software components

There are now several well-established packages that can be used for model building, each with its own advantages and disadvantages. However, there is no one single package that fits the requirements of the E3ME model, so a combination of software packages is used.

The following software is used:

- Fortran: E3ME source code is written in the Fortran95 programming language. It is compiled using the Intel Fortran compiler. The standard development environment is Microsoft Visual Studio.
- IDIOM: This is a programming language which is itself a pre-compiled set of Fortran commands. It provides a user interface for the modeller, for example allowing the user to make certain changes without recompiling the source code. The IDIOM manual (Cambridge Econometrics, 2007) provides further details.
- Java/Python: The model's manager software, which allows the model to be run without requiring any programming expertise (see next section), is programmed in Python and JavaScript.
- Ox/Python: The Ox programming language (Doornik, 2007) and Python are used for data processing, parameter estimation, and manipulation of results.

The source code for E3ME and IDIOM is compiled using a Fortran compiler (currently the Intel compiler). The standard working environment for model development and debugging is Microsoft Visual Studio. The compiler provides an executable that can be run from the Windows command line with a set of arguments that determine the scenario, data inputs and output locations.

At present E3ME is only compiled for Windows systems and a separate guide is available for model users.

How the model 'solves'

There are several simultaneous loops and interactions in E3ME (see, for example, Section 4.1). While it might be theoretically possible to solve all the equations as a system, in practice the model is far too complex, and an iterative approach is required.

The method of solution is Gauss-Seidel iteration, in which the different equations sets are solved in a predetermined order.[9] It starts with the values of the previous year's solution, with values being updated after each equation is solved. Once every equation has been solved, the differences in the values of selected variables from one iteration to the next are calculated; they will usually decrease quite quickly between iterations. This process is then repeated (the 'iteration') until the these differences are small enough that the model can be considered 'converged'.

[9] This version of the Gauss-Seidel method is not solved in matrix form and is instead solved sequentially.

The solution method can be thought of as finding a balance between demand and supply in the economy. This could be described as an 'equilibrium' outcome. However, this outcome is qualitatively different from the outcome in Computable General Equilibrium models, where the balance is between demand and *potential* supply in the economy (see Section 3.2).

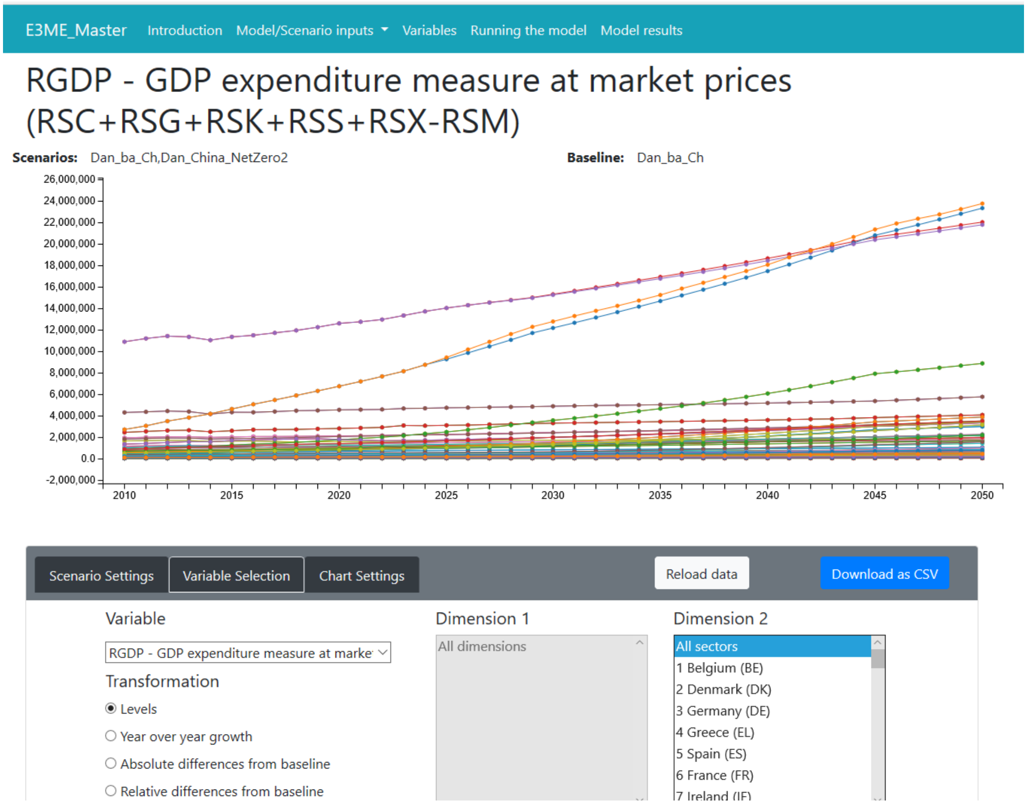
10.2 The manager interface

Most model users outside of Cambridge Econometrics access the model through a graphical interface that is based in a web browser (see Figure 10.1). The latest version of the interface runs in any modern browser. Through the interface the user may:

- set up scenarios
- run the model
- compare results from scenarios

The interface comes with its own installation and operations guide.

Figure 10.1: E3ME's manager interface



11 E3ME Publications, Project Applications, and Affiliated Models

11.1 Selected academic publications

Semieniuk, G, PB Holden, J-F Mercure, P Salas, H Pollitt, K Jobson, P Vercoulen, U Chewpreecha, NR Edwards and JE Viñuales (2022), 'Stranded fossil-fuel assets translate to major losses for investors in advanced economies', *Nature Climate Change*, 12, pp 532–538.

Holehouse J and H Pollitt (2022), 'Non-equilibrium time-dependent solution to discrete choice with social interactions', *PLoS ONE*, 17(5), Article ID e0267083.

Eufrasio, RM, EP Kantzas, NR Edwards, PB Holden, H Pollitt, J-F Mercure, SCL Koh and DJ Beerling (2022), 'Environmental and health impacts of atmospheric CO2 removal by enhanced rock weathering depend on nations' energy mix', *Communications Earth and Environment*, 3, Article 106.

Kantzas, EP, M Val Martin, MR Lomas, RM Eufrasio, P Renforth, AL Lewis, LL Taylor, J-F Mercure, H Pollitt, PV Vercoulen, N Vakilifard, PB Holden, NR Edwards, L Koh, NF Pidgeon, SA Banwart and DJ Beerling (2022), 'Substantial carbon drawdown potential from enhanced rock weathering in the United Kingdom', *Nature Geoscience*, 15, pp 382–389.

Virla, LD, D-J van de Ven, J Sampdero, O van Vliet, A Smith, H Pollitt and J Lieu (2021), 'Risk blindness in local perspectives about the Alberta oil sands hinders Canada's decarbonization', *Environmental and Innovation and Societal Transitions*, 40, pp 569-585.

Mercure, J-F, P Salas, P Vercoulen, G Semieniuk, A Lam, H Pollitt, PB Holden, N Vakilifard, U Chewpreecha, NR Edwards and JE Vinuales (2021), 'Reframing incentives for climate policy action', *Nature Energy*, 6, pp 1133–1143.

Nieto, J, H Pollitt, PE Brockway, L Clements, M Sakal, and J Barrett (2021), 'Socio-macroeconomic impacts of implementing different post-Brexit UK energy reduction targets to 2030', *Energy Policy*, 158.

Pollitt, H, R Lewney, B Kiss-Dobronyi, and X Lin (2021), 'Modelling the economic effects of COVID-19 and possible green recovery plans: a post-Keynesian approach', *Climate Policy*, 21(10), pp 1257-1271.

Kiss-Dobronyi, B, D Fazekas, and H Pollitt (2021), 'Macroeconomic assessment of possible Green Recovery scenarios in Visegrad countries', *Society and Economy*, 43(3), pp 227–252.

Spijker, E, A Anger-Kraavi, H Pollitt, and D-J van de Ven (2020), 'Evaluating integrated impacts of low-emission transitions in the livestock sector'. *Environmental Innovation and Societal Transitions*, 35.

Knobloch, F, S Hanssen, A Lam, H Pollitt, P Salas, U Chewpreecha, MAJ Huijbregts, and J-F Mercure (2020), 'Net emission reductions from electric cars and heat pumps in 59 world regions over time', *Nature Sustainability*, 3, pp 437–447.

Hu, X, H Pollitt, J Pirie, J-F Mercure, J Liu, J Meng, and S Tao (2020) ‘The impacts of the trade liberalization of environmental goods on power system and CO_2 emissions’, *Energy Policy*, 140.

Shaw, D and Y-H Fu (2020), ‘Climate clubs with tax revenue recycling, tariffs, and transfers’, *Climate Change Economics*, 11(4).

Bachner, G, J Mayer, KW Steininger, A Anger-Kraavi, A Smith, and TS Barker (2020), ‘Uncertainties in macroeconomic assessments of low-carbon transition pathways – The case of the European iron and steel industry’, *Ecological Economics*, 172.

Wood, R, M Grubb, A Anger-Kraavi, H Pollitt, B Rizzo, E Alexandri, K Stadler, D Moran, E Hertwich, and A Tukker (2019), ‘Beyond peak emission transfers: historical impacts of globalization and future impacts of climate policies on international emission transfers’, *Climate Policy*, 20, pp S14-S27.

Mercure, J-F, F Knobloch, H Pollitt, L Paroussos, S Scrieciu, and R Lewney (2019), ‘Modelling innovation and the macroeconomics of low-carbon transitions: theory, perspectives and practical use’, *Climate Policy*, 19(8), pp 1019-1037.

Pollitt, H, K Neuhoff, and X Lin (2019), ‘The impact of implementing a consumption charge on carbon-intensive materials in Europe’, *Climate Policy*, 20, pp S74-S89.

Lehmann, P, J Sijm, E Gawel, S Strunz, U Chewpreecha, J-F Mercure, and H Pollitt (2018), ‘Addressing multiple externalities from electricity generation: a case for EU renewable energy policy beyond 2020?’, *Environmental Economics and Policy Studies*, 21(2), pp 255–283.

Mercure, J-F, A Lam, S Billington, and H Pollitt (2018), ‘Integrated assessment modelling as a positive science: private passenger road transport policies to meet a climate target well below 2°C’, *Climatic Change*, 151(2), pp 109–129.

Knobloch, F, H Pollitt, U Chewpreecha, V Daioglou, and J-F Mercure (2018), ‘Simulating the deep decarbonisation of residential heating for limiting global warming to 1.5°C’, *Energy Efficiency*, 12(2), pp 521–550.

Holden, PB, NR Edwards, A Ridgwell, RD Wilkinson, K Fraedrich, F Lunkeit, H Pollitt, J-F Mercure, P Salas, A Lam, F Knobloch, U Chewpreecha, and JE Viñuales (2018), ‘Climate–carbon cycle uncertainties and the Paris Agreement’, *Nature Climate Change*, 8, pp 609-613.

Mercure, J-F, H Pollitt, JE Viñuales, NR Edwards, PB Holden, U Chewpreecha, P Salas, I Sognnaes, A Lam, and F Knobloch (2018), ‘Macroeconomic impact of stranded fossil fuel assets’, *Nature Climate Change*, 8, pp 588–593.

Mercure J-F, H Pollitt, N Edwards, P Holden, U Chewpreecha, P Salas, A Lam, F Knobloch, and J Vinuales (2018), ‘Environmental impact assessment for climate change policy with the simulation-based integrated assessment model E3ME-FTT-GENIE’, *Energy Strategy Reviews*, 20, pp 195–208.

Lee, S, U Chewpreecha, H Pollitt, and S Kojima (2018), ‘An economic assessment of carbon tax reform to meet Japan’s NDC target under different nuclear assumptions using the E3ME model’, *Environmental Economics and Policy Studies*, 20(2), pp 411-429.

Pollitt, H and J-F Mercure (2017), ‘The role of money and the financial sector in energy-economy models used for assessing climate and energy policy’, *Climate Policy*, 18(2), pp 184-197.

Brouwer, F, G Avgerinopoulos, D Fazekas, C Laspidou, J-F Mercure, H Pollitt, E Ramos, and M Howells (2017), ‘Energy modelling and the Nexus concept’, *Energy Strategy Reviews*, 19, pp 1-6.

Lee, S, U Chewpreecha, H Pollitt, and S Kojima (2017), ‘An economic assessment of carbon tax reform to meet Japan’s NDC target under different nuclear assumptions using the E3ME model’, *Environmental Economics and Policy Studies*, 20(2), pp 411-429.

11.2 Selected project applications

Economic benefits of gender equality in the EU

This study was commissioned by The European Institute for Gender Equality , to be delivered in collaboration with an international team, with partners at ICF and Collegio Carlo Alberto. It finds that if the EU stepped up its efforts to improve gender equality, more jobs would be created, GDP per capita would increase and society would be able to adjust better to the challenges related to the ageing population.

The study is unique in the EU context, because it uses a macroeconomic model to estimate socio-economic outcomes of improving gender equality in several broad areas including education, labour market participation, wages, and work-life balance.

A new version of the model was developed for this project, including new equation sets for employment and wages disaggregated by gender.

Hector Pollitt, former Director at Cambridge Econometrics said: “Our macroeconomic model, E3ME, has demonstrated its adaptability in this ground-breaking study. Having developed new equation sets specifically for this sector we have successfully customised the model for our client. As a result, we are confident that we could help deliver further studies in the area of gender equality.”

New Climate Economy – unlocking the inclusive growth story of the 21st Century

Cambridge Econometrics provided empirical inputs to the New Climate Economy 2018 Global Commission Report ‘Unlocking the Inclusive Growth Story of the 21st Century’.

The aim of the modelling exercise was to illustrate examples of policies that can simultaneously promote economic growth and reduce the risks of climate change. Various policies were assessed during the project identifying both potential emission reductions and impacts on the wider economy.

Aside from levels of GDP and CO_2 emissions, key outputs from the analysis include labour market impacts, distributional impacts (for regions where data are available), and other environmental impacts such as changes in air quality and health impacts.

The study finds that ambitious action across key economic systems – energy, cities, food and land use, water, and industry – could:

- Generate over 65 million new low-carbon jobs in 2030

- Avoid over 700,000 premature deaths from air pollution compared with business-as-usual in 2030
- Generate an estimated US$2.8 trillion in government revenues per year in 2030 from subsidy reform and carbon pricing alone

Modelling global renewables targets

This project for the International Renewable Energy Agency (IRENA) looked at the potential impact on energy markets and the global economy of three possible futures using different mixes of renewable energy.

Key stages were:

- A literature review of research on the macroeconomic costs of energy and climate change mitigation policy
- Expansion of our E3ME model to provide a more detailed geographical coverage
- Macroeconomic assessment using the expanded version of E3ME
- Presentation of the results in an accessible form for policymakers

E3ME was expanded to improve its treatment of: South Africa, Ukraine, Saudi Arabia, and Nigeria, while the project also included additional econometric analyses for Iran, Algeria, Malaysia, Egypt, Kenya, and Morocco.

Modelling the impact of Brexit on poverty in the UK

Cambridge Econometrics was commissioned by the Joseph Rowntree Foundation to explore the impact of Brexit on poverty in the UK, focusing specifically at the poorest 1/5th of households.

The analysis models a range of post-Brexit trading agreements, providing detailed results on the potential impacts on the cost of living, wages, and employment looking ahead to 2030. The scenarios considered ranged from staying in the single market (a 'Norway' scenario), to a 'no deal' scenario, considering tariffs and non-tariff barriers to trade, immigration, and investment.

The analysis shows that, in all scenarios, the cost of living is likely to rise and real wages to fall after the UK leaves the EU in the immediate period, however a 'no deal' scenario is likely to have the largest negative effects on costs and wages.

Under a 'no deal' scenario the study estimates that living costs for low-income households are estimated to increase by £480 per year and that food prices would rise by 8%.

Fuelling Europe's Future: How the transition from oil strengthens the economy

Cambridge Econometrics and Element Energy were commissioned by the European Climate Foundation (ECF) to assess the likely economic impacts and the transitional challenges associated with decarbonising the European car fleet in the medium-term (to 2030) and the long-term (to 2050).

E3ME was used to assess how the transition to low carbon vehicles affects household incomes, trade in oil and petroleum, consumption, GDP, employment, CO_2, NO_X and particulates.

Key findings:

- Jobs are created by increased spending on vehicle technology, and spending on fossil fuels is reduced
- Optimising or hybridizing the internal combustion engine reduces the yearly cost of running and replacing the EU car and van fleet. It also increases EU-wide employment
- Moving rapidly to a fleet of advanced hybrid, battery-electric, and fuel-cell vehicles, greatly increases EU-wide employment
- CO_2 is cut in all low-carbon scenarios and air quality is significantly improved

Modelling the impacts of changes in raw material consumption

This study modelled the impacts of changes in raw material consumption. It aimed to provide a quantitative analysis of different EU resource productivity targets, defined as GDP per unit of raw material consumption (RMC).

Cambridge Econometrics developed an RMC indicator and worked to assess the economic, social, and environmental impacts of implementing targets to reduce material consumption, as defined by RMC.

The results were used to develop the EU's Resource Efficiency Roadmap.

11.3 E3ME's affiliated models

E3-India

E3-India is a dynamic macro-econometric simulation model, developed as a tool for state-level analysis in India. It covers 28 states and 4 union territories of India. The model enables policymakers and stakeholders to assess various policy impacts at a significantly higher geographical resolution than has previously been possible in India.

E3-US

E3-US is an innovative tool that allows policy makers to assess policy impacts at the state level, reflecting the diversity of economic conditions across the US. Key economic and social outputs from the model include GDP, employment, and unemployment. The model results also include energy consumption and greenhouse gas emissions.

E3-Brazil

E3-Brazil was originally designed to assess the economic and labour market impacts of Environmental Tax Reform in Brazil. It can also be used to assess a range of economic and environmental measures including fiscal policy, energy efficiency, and renewable electricity generation. Standard outputs from the model include employment, GDP, prices, and trade.

E3-Thailand

E3-Thailand was constructed to quantitatively assess the impacts of different carbon pricing policies. It is also suitable for analysing other energy, climate, economy, and labour market policies. It is designed to assess policy in a highly empirical structure.

12 References

12.1 References for the E3ME model manual

Anderson, PW (1972), ‘More is Different’, *Science*, 177(4047), pp 393-396.

Armington, P (1969), ‘A Theory of Demand for Products Distinguished by Place of Production’, *IMF Staff Papers*, XVI, pp 159-178.

Arthur, WB (2015), *Complexity and the Economy*, Oxford University Press.

Arthur, WB (2010), *The Nature of Technology*, Penguin Books.

Arthur, WB (1999), ‘Complexity and the Economy’, *Science*, 244(5411), pp 107-109.

Barker, TS and B Gardiner (1996), 'Employment, wage formation and pricing in the European Union: empirical modelling of environment tax reform', in Carraro, C and D Siniscalco (eds.), *Environmental Fiscal Reform and Unemployment*, Kluwer, pp 229-272.

Barker, TS, P Ekins, and N Johnstone (1995), *Global Warming and Energy Demand*, Routledge.

Barker, TS and W Peterson (1987), *The Cambridge Multisectoral Dynamic Model of the British Economy*, Cambridge University Press.

Barker, TS and W Peterson (1988), *The Cambridge Multisectoral Dynamic Model*, Cambridge University Press.

Barker, TS (1977), 'International trade and economic growth: an alternative to the neoclassical approach', *Cambridge Journal of Economics*, 1, pp 153-172.

Barrell, R and P Davis (2007), ‘Financial liberalisation, consumption and wealth effects in seven OECD countries’, *Scottish Journal of Political Economy*, 54(2), pp 254-67.

Beinhocker, ED (2007), *The Origin of Wealth*, Random House.

BEIS (2020), *Macroeconomic Modelling of the 2.4% R&D Target*, see https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/897462/macroeconomic-modelling-of-2-4-r-and-d-target.pdf

Bentzen, J and T Engsted, (1993), ‘Short- and long-run elasticities in energy demand: a cointegration approach’, *Energy Economics*, 15(1), pp 9-16.

Bosetti, V, R Gerlagh, and SP Schleicher (2009), *Modelling Sustainable Development: Transitions to a Sustainable Future*, Edward Elgar.

Boulton, J, PM Allen, and C Bowman (2015), *Embracing Complexity*, Oxford University Press.

Briscoe, G, and R Wilson (1992), 'Forecasting economic activity rates', *International Journal of Forecasting*, 8, pp 201-217.

Cambridge Econometrics (2007), *IDIOM User’s Guide Version 8.6*, Cambridge Econometrics Ltd.

Capros, P, D Van Regemorter, L Paroussos, and P Karkatsoulis (2012), *The GEM-E3 model*, IPTS Scientific and Technical report.

Chick, V (2016), 'On Microfoundations and Keynes' Economics', *Review of Political Economy*, 28(1), pp 99-112.

Cohen, AJ and GC Harcourt (2003), 'Whatever Happened to the Cambridge Capital Theory Controversies?', *Journal of Economic Perspectives*, 17(1), pp 199–214.

Daly, H (2019), 'Some overlaps between the first and second thirty years of ecological economics', *Ecological Economics*, 164, ID 106372.

Davidson, J, D Hendry, F Srba, and S Yeo (1978), 'Economic modelling of the aggregate time series relationship between consumers' expenditure and income in the UK', *Economic Journal*, 80, pp 899-910.

DeGennaro, RP and C Robotti (2007), 'Financial market Frictions', *Federal Reserve Bank of Atlanta Economic Review*, Third Quarter, 2007, see https://core.ac.uk/download/pdf/6608995.pdf

Diamond, PA (1982), 'Aggregate Demand Management in Search Equilibrium', *Journal of Political Economy*, 90(5), pp 881-894.

Dixon, PB and MT Rimmer (2002), *Dynamic, General Equilibrium Modelling for Forecasting and Policy: A Practical Guide and Documentation of MONASH*, North-Holland.

Domar, ED (1946), 'Capital Expansion, Rate of Growth, and Employment', *Econometrica*, 14(2), pp 137-147.

Domar, ED (1944), 'The "Burden of the Debt" and the National Income', *The American Economic Review*, 34(4), pp 798-827.

Doornik, J (2007) *Introduction to Ox: An Object-Oriented Matrix Language*, Timberlake Consultants Ltd.

Dosi, G, G Fagiolo, and A Roventini (2010), 'Schumpeter meeting Keynes: a policy-friendly model of endogenous growth and business cycles', *Journal of Economic Dynamics and Control*, 34(9), pp 1748–1767.

Eichner, AS and JA Kregel (1975), 'An Essay on Post-Keynesian Theory: A New Paradigm in Economics', *Journal of Economic Literature*, 13(4), pp 1293-1314.

Engle, RF and CWJ Granger (1987), 'Co-Integration and Error Correction: Representation, Estimation, and Testing' *Econometrica*, 55(2), pp 251–76.

European Commission (2017), 'Case study – technical analysis on capacity constraints and macroeconomic performance', see https://ec.europa.eu/energy/sites/default/files/documents/case_study_2_capacity_constraints_and_macro_performance.pdf

Eurostat (2021), 'Current level of capacity utilization in manufacturing industry', code teibs070.

Federal Reserve (2021), 'Industrial Production and Capacity Utilization - G.17', see https://www.federalreserve.gov/releases/g17/current/default.htm

Franzén, M and T Sterner (1995), ‘Long-run Demand Elasticities for Gasoline’, in Barker, TS, N Johnstone, and P Ekins (eds.), *Global Warming and Energy Elasticities*, Routledge.

Galbraith, JK (1975), *Money: Whence it came, where it went*, reprinted 2017, Princeton University Press.

Gardiner, B (1994), ‘Modelling Employment Demand’, *E3ME Working Paper no. 28*, Cambridge Econometrics.

Gately, D (1993), 'The imperfect price-reversibility of world oil demand', *The Energy Journal*, 14(4), pp 163-181.

Georgescu-Roegen, N (1971), *The Entropy Law and Economic Process*, Harvard University Press.

Goodwin, RM (1967), ‘A Growth Cycle’, in Feinstein, CH (ed.) *Socialism, Capitalism and Economic Growth*, Cambridge University Press, pp 165-170.

Graeber, D (2014), *Debt: The first 5,000 years*, third edition, Melville House Publishing.

Grubb, M (2014), *Planetary Economics*, Routledge.

Grubb, M (1995), 'Asymmetrical price elasticities of energy demand', in Barker, TS, P Ekins, and N Johnstone (1995), *Global Warming and Energy Demand*, Routledge, pp 305-310.

Haldane, AG and AE Turrell (2018), ‘An interdisciplinary model for macroeconomics’, *Oxford Review of Economic Policy*, 34(1-2), pp 219–251.

Harrod, RF (1939), ‘An essay in dynamic theory’, *The Economic Journal*, 49(193), pp 14–33.

Hertel, T (1999), *Global Trade Analysis: Modeling and Applications*, Cambridge University Press.

Hickel, J (2020), *Less is More*, Penguin.

Hidalgo, CA and R Hausmann (2009), ‘The building blocks of economic complexity’, *PNAS*, 106(26), pp 10570-10575.

Hunt, L and N Manning (1989), 'Energy price- and income-elasticities of demand: some estimates for the UK using the cointegration procedure', *Scottish Journal of Political Economy*, 36(2), pp183-193.

Jackson, T (2017), *Prosperity without Growth: Foundations for the economy of tomorrow*, second edition, Routledge.

Jansen, H and G Klaassen (2000), ‘Economic Impacts of the 1997 EU Energy Tax: Simulations with Three EU-Wide Models’ *Environmental and Resource Economics*, 15(2), pp 179-197.

Johansson, O, and L Schipper (1997), 'Measuring the long-run fuel demand of cars', *Journal of Transport Economics and Policy*, XXXI(3), pp 277-292.

Kahneman, D (2012), *Thinking Fast and Slow*, Penguin.

Kaldor, N (1957), ‘A Model of Economic Growth’, *The Economic Journal*, 67(268), pp 591-624.

Kalecki, M (1954), *Theory of Economic Dynamics: An essay on cyclical and long-run changes in capitalist economy*, reprinted 2009, Monthly Review Classics.

Kerdrain, C (2011), 'How important is wealth for explaining household consumption over the recent crisis: An empirical study for the United States, Japan and the Euro Area', OECD Department Working Papers.

Keynes, JM (1939), 'The League of Nations: Professor Tinbergen's Method', *The Economic Journal*, 49(195), pp 558-577.

Keynes, JM (1937), 'The General Theory of Employment', *Quarterly Journal of Economics*, 51(2), pp 209-223.

Keynes, JM (1936), *The General Theory of Employment, Interest and Money*, Macmillan.

Keynes, JM (1930), 'Economic possibilities for our grandchildren', in *Essays in Persuasion*, Classic House Books, pp 192-202.

Keynes, JM (1921), *A Treatise on Probability*, Macmillan.

Khan, RF (1931), 'The Relation of Home Investment to Unemployment', *The Economic Journal*, 41(162), pp 173-198.

King, JE (2015), *Advanced Introduction to Post-Keynesian Economics*, Edward Elgar.

King, JE (2012), *The Microfoundations Delusion: Metaphor and Dogma in the History of Macroeconomics*, Edward Elgar.

Kirman, A (2018), 'Complexity Economics', in Fischer, L, J Hasell, JC Proctor, D Uwakwe, Z Ward-Perkins and C Watson (eds.) *Rethinking Economics: An introduction to pluralist economics*, Routledge, pp 91-106.

Knobloch, F, H Pollitt, U Chewpreecha, R Lewney, MAJ Huijbregts, and J-F Mercure (2021), 'FTT:Heat — A simulation model for technological change in the European residential heating sector', *Energy Policy*, 153 Article ID 112249.

Knobloch, F, H Pollitt, U Chewpreecha, V Daioglou, and J-F Mercure (2018), 'Simulating the deep decarbonisation of residential heating for limiting global warming to 1.5°C', *Energy Efficiency*, 12(2), pp 521–550.

Kregel, JA (1973), *Reconstruction of Political Economy: An Introduction to Post-Keynesian Economics*, Palgrave Macmillan.

Lavoie, M (2020), 'Was Hyman Minsky a post-Keynesian economist?', *Review of Evolutionary Political Economy*, 1, pp 85-101.

Lavoie, M (2014), *Post-Keynesian Economics: New Foundations*, Edward Elgar.

Layard, R, S Nickell, and R Jackman (1991), *Unemployment*, Oxford University Press.

Lee, K and MH Pesaran (1993), 'The Role of Sectoral Interactions in Wage Determination in the UK Economy', *The Economic Journal*.

Lee, K, MH Pesaran, and RG Pierse (1990), 'Aggregation Bias in Labour Demand Equations for the UK Economy', Chapter 6 in Barker, TS, and MH Pesaran (eds) *Disaggregation in Econometric Modelling*, Routledge.

Lee, K, (1988), *Labour Market Adjustment in a Disaggregated Model of the UK Supply Side*, DAE Working Paper No. 8810.

Lucas, R (1976), 'Econometric Policy Evaluation: A Critique', in Brunner, K, and A Meltzer *The Phillips Curve and Labor Markets*, Carnegie-Rochester Conference Series on Public Policy, American Elsevier, pp 19-46.

Mayor, M, A Jesús López, and R Pérez (2007), 'Forecasting Regional Employment with Shift–Share and ARIMA Modelling'. *Regional Studies*, 41, pp 543–551.

McLeay, M, A Radia, and R Thomas (2014), 'Money creation in the modern economy', *Bank of England quarterly bulletin*, 2014Q1.

Meadows, DH (2008), *Thinking In Systems: A Primer*, Chelsea Green Publishing.

Meadows, DH, DL Meadows, J Randers, and WW Behrens (1972), *The Limits to Growth*, Universal Books.

Mealy, P and D Coyle (2021), 'To them that hath: economic complexity and local industrial strategy in the UK', *International Tax and Public Finance*.

Mercure, J-F, F Knobloch, H Pollitt, L Paroussos, S Scrieciu, and R Lewney (2019), 'Modelling innovation and the macroeconomics of low-carbon transitions: theory, perspectives and practical use', *Climate Policy*, 19(8), pp 1019-1037.

Mercure, J-F, A Lam, S Billington, and H Pollitt (2018), 'Integrated assessment modelling as a positive science: private passenger road transport policies to meet a climate target well below 2°C', *Climatic Change*, 151(2), pp 109–129.

Mercure, J-F, H Pollitt, JE Viñuales, NR Edwards, PB Holden, U Chewpreecha, P Salas, I Sognnaes, A Lam, and F Knobloch (2018b), 'Macroeconomic impact of stranded fossil fuel assets', *Nature Climate Change*, 8, pp 588–593.

Mercure, J-F and A Lam (2015), 'The effectiveness of policy on consumer choices for private road passenger transport emissions reductions in six major economies', *Environmental Research Letters*, 10(6), 064008.

Mercure, J-F, H Pollitt, U Chewpreecha, P Salas, AM Foley, PB Holden, and NR Edwards (2014), 'The dynamics of technology diffusion and the impacts of climate policy instruments in the decarbonisation of the global electricity sector', *Energy Policy*, 73, pp 686-700.

Mercure, J-F, and P Salas (2013), 'On the global economic potentials and marginal costs of non-renewable resources and the price of energy commodities', *Energy Policy*, 63, pp 469–483.

Mercure, J-F and P Salas (2012), 'An assessment of global energy resource economic potentials', *Energy*, 46(1), pp 322–336.

Minsky, HP (1986), *Stabilizing and Unstable Economy,* second edition, McGraw Hill.

Minsky, HP (1975), *John Maynard Keynes*, second edition, McGraw Hill.

Moore, BJ (1988), *Horizontalists and Verticalists: The macroeconomics of credit money*, Cambridge University Press.

Neal, AJ and RA Wilson (1987), 'Average Weekly Hours of Work in the United Kingdom, 1948-80: A Disaggregated Analysis', Chapter 9 in Bosworth, DL and DF Heathfield (1987), *Working Below Capacity*, Macmillan.

Nelson, RR (2018), 'Economics from an Evolutionary Perspective', in Nelson, RR (eds.) *Modern Evolutionary Economics: An Overview*, Cambridge University Press, pp 1-34.

Nelson, RR and SG Winter (1982), *An Evolutionary Theory of Economic Change*, Harvard University Press.

Olivier, JGJ and JAHW Peters (2020), *Trends in global CO_2 and total greenhouse gas emissions: 2019 Report*, PBL Publishers.

Pasinetti, LL (1981), Struc*tural Change and Economic Growth: A theoretical essay on the dynamics of the wealth of nations*, Cambridge University Press.

Pauliuk, S, RL Milford, DB Müller, and JM Allwood (2013), 'The Steel Scrap Age', *Environmental Science & Technology*, 47(7), pp 3448-3454.

Pollitt, H and J-F Mercure (2018), 'The role of money and the financial sector in energy-economy models used for assessing climate and energy policy', *Climate Policy*, 18(2), pp 184-197.

Pollitt, H and B Gardiner (2016), 'Capturing the Health Effects of Environmental and Industrial Policy in a Macroeconomic Model', in (eds.) Pacyna, JM and EG Pacyna, *Environmental Determinants of Human Health*, Humana Press, pp 151-168.

Pollitt, H (2008), 'Combining Economic and Material Flows Analysis at the Sectoral level: Development of the E3ME Model and Application in the MATISSE Case Studies', MATISSE project deliverable 8.6.1.

Pollitt, H and U Chewpreecha (2008), 'Development of Labour Supply Projections with the E3ME Framework', Cambridge Econometrics Working Paper.

Pollitt, H (2007), 'Extending E3ME to Include Analysis of Material Flows', scoping report for the Anglo-German Foundation, Cambridge Econometrics.

Ragot L (1994), 'Le commerce extérieur dans MEGEVE. Rapport d'etape 1: les séries disponibles dans CRONOS Sec 2', ERASME.

Romanowska, I, CD Wren, and SA Crabtree (2021), *Agent-Based Modelling for Archaeology: Simulating the complexity of societies*, Santa Fe Institutional Press.

Romer, PM (1990), 'Endogenous Technical Change', *Journal of Political Economy*, 98(5), pp S71-S102.

Schoder, C (2017), 'A Critical Review of the Rationale Approach to the Microfoundation of Post-Keynesian Theory', *Review of Political Economy*, 29(2), pp 171-189.

Schumpeter, JA (1934), *The theory of economic development*, second edition, Harvard.

Scott, MFG (1989), 'A New View of Economic Growth', Clarendon Press.

Scrieciu, SS, N Zimmermann, Z Chalabi, and M Davies (2021), ‘Linking complexity economics and systems thinking, with illustrative discussions of urban sustainability’, *Cambridge Journal of Economics*, 45(4), pp 695-722.

Serletis, A (1992), 'Unit root behaviour in energy future prices', *The Economic Journal*, 13(2), pp 119-128.

Skidelsky, R (2010), *Keynes: The Return of the Master*, second edition, Penguin.

Spash, CL and V Asara (2018), ‘Ecological Economics’, in Fischer, L, J Hasell, JC Proctor, D Uwakwe, Z Ward-Perkins, and C Watson (eds.) *Rethinking Economics: An introduction to pluralist economics*, Routledge, pp 120-132.

Sutherland, H and F Figari (2013), ‘EUROMOD: the European Union tax-benefit microsimulation model’, *EUROMOD Working Papers EM8/13*, EUROMOD at the Institute for Social and Economic Research.

Sutherland, H, C O'Donoghue, and H Immervoll (1999), ‘An introduction to EUROMOD’, *EUROMOD Working Papers EM0/99*, EUROMOD at the Institute for Social and Economic Research.

Thurner, S, R Hanel, and P Klimek (2018), *Introduction to the theory of complex systems*, Oxford University Press.

Ueckerdt, F, R Pietzcker, Y Scholz, D Stetter, A Giannousakis and G Luderer (2017), ‘Decarbonizing global power supply under region-specific consideration of challenges and options of integrating variable renewables in the REMIND model’, *Energy Economics*, 64, pp 665-684.Veblen, T (1899), ‘The Theory of the Leisure Class’, reproduced in *Conspicuous Consumption* (2005), Penguin.

Walker, IO and F Wirl (1993), 'Irreversible price-induced efficiency improvements: theory and empirical application to road transportation'*, The Energy Journal*, 14(4), pp 183-205.

Walras, L (1954), *Elements of Pure Economics*, translated by W Jaffé from original 19th century French version, reprinted 2003, Routledge.

Weaver, W (1948), ‘Science and Complexity’, *American Scientist*, 36, pp 536-546.

Werner, RA (2016), ‘A lost century in economics: Three theories of banking and the conclusive evidence’, *International Review of Financial Analysis*, 46, pp 361-379.

Werner, RA (2014), ‘Can banks individually create money out of nothing? — The theories and the empirical evidence’, *International Review of Financial Analysis*, 36, pp 1-19.

Appendix A E3ME Classification

R Regions
1 Belgium
2 Denmark
3 Germany
4 Greece
5 Spain
6 France
7 Ireland
8 Italy
9 Luxembourg
10 Netherlands
11 Austria
12 Portugal
13 Finland
14 Sweden
15 UK
16 Czech Republic
17 Estonia
18 Cyprus
19 Latvia
20 Lithuania
21 Hungary
22 Malta
23 Poland
24 Slovenia
25 Slovakia
26 Bulgaria
27 Romania
28 Norway
29 Switzerland
30 Iceland
31 Croatia
32 Turkey
33 Macedonia
34 USA
35 Japan
36 Canada
37 Australia
38 New Zealand
39 Russian Federation
40 Rest of Annex I
41 China
42 India
43 Mexico
44 Brazil
45 Argentina
46 Colombia
47 Rest of Latin America

R Regions (cont.)
48 Korea
49 Taiwan
50 Indonesia
51 Rest of ASEAN
52 Rest of OPEC
53 Rest of world
54 Ukraine
55 Saudi Arabia
56 Nigeria
57 South Africa
58 Rest of North Africa OPEC
59 Rest of Central Africa OPEC
60 Malaysia
61 Kazakhstan
62 Rest of North Africa
63 Rest of Central Africa
64 Rest of West Africa
65 Rest of East Africa
66 Rest of Southern Africa
67 Egypt
68 Democratic Republic of the Congo
69 Kenya
70 UAE
71 Pakistan

Q, Y Products, Industries
1 Crops, animals, etc
2 Forestry & logging
3 Fishing
4 Coal
5 Oil and Gas
6 Other mining
7 Food, drink & tobacco
8 Textiles & leather
9 Wood & wood prods
10 Paper & paper prods
11 Printing & reproduction
12 Coke & ref petroleum
13 Other chemicals
14 Pharmaceuticals
15 Rubber & plastic products
16 Non-metallic mineral prods
17 Basic metals
18 Fabricated metal prods
19 Computer, optical & electronic
20 Electrical equipment
21 Other machinery & equipment
22 Motor vehicles

Q, Y Products, Industries (cont.)
23 Other transport equipment
24 Furniture; other manufacturing
25 Repair & installation machinery
26 Electricity
27 Gas, steam & air conditioning
28 Water, treatment &supply
29 Sewerage & waste management
30 Construction
31 Wholesale/retail motor vehicles
32 Wholesale excl. motor vehicles
33 Retail excluding motor vehicles
34 Land transport, pipelines
35 Water transport
36 Air transport
37 Warehousing
38 Postal & courier activities
39 Accommodation & food services
40 Publishing activities
41 Motion picture, video, television
42 Telecommunications
43 Computer programming, info services
44 Financial services
45 Insurance
46 Aux to financial services
47 Real estate
48 Imputed rents
49 Legal, account, & consulting services
50 Architectural & engineering
51 R&D
52 Advertising & market research
53 Other professional
54 Rental & leasing
55 Employment activities
56 Travel agency
57 Security & investigation, etc.
58 Public administration & defence
59 Education
60 Human health activities
61 Residential care
62 Creative, arts, recreational
63 Sports activities
64 Membership organisations
65 Repair computers & personal goods
66 Other personal services.
67 Households as employers
68 Extraterritorial organisations
69 Unallocated
70 Hydrogen supply

C Consumers' Expenditure	M Global Commodities	LG Labour groups
1 Food	1 Food/Feed	1 Male 15-19
2 Drink	2 Wood	2 Male 20-24
3 Tobacco	3 Construction minerals	3 Male 25-29
4 Clothing and footwear	4 Industrial minerals	4 Male 30-34
5 Actual rent	5 Ferrous metals	5 Male 35-39
6 Imputed rentals	6 Non-ferrous metals	6 Male 40-44
7 Maintenance and repair	7 Energy- Coal	7 Male 44-49
8 Water and misc. services	8 Energy- Brent oil	8 Male 50-54
9 Electricity	9 Energy- Gas	9 Male 55-59
10 Gas	10 World Inflation	10 Male 60-64
11 Liquid Fuels		11 Male 65+
12 Other Fuels	G Govt sectors	12 Female 15-19
13 Furniture and flooring	1 Defence	13 Female 20-24
14 Household textiles	2 Education	14 Female 25-29
15 Household appliances	3 Health	15 Female 30-34
16 Glassware tableware	4 Other	16 Female 35-39
17 Tools and equipment	5 Unallocated	17 Female 40-44
18 Household maintenance		18 Female 45-49
19 Medical products	SE Socio-economic groups	19 Female 50-54
20 Medical Services	1 All households	20 Female 55-59
21 Purchase of vehicles	2 First quintile	21 Female 60-64
22 Petrol etc.	3 Second quintile	22 Female 65+
23 Rail Transport	4 Third quintile	23 Total 15-19
24 Air Transport	5 Fourth quintile	24 Total 20-24
25 Other Transport	6 Fifth quintile	25 Total 25-29
26 Postal services	7 Manual workers	26 Total 30-34
27 Photographic equipment	8 Non-manual workers	27 Total 35-39
28 Other recreational durables	9 Self-employed	28 Total 40-44
29 Other recreational items	10 Unemployed	29 Total 45-49
30 Recreational/cultural services	11 Retired	30 Total 50-54
31 News, books, stationery	12 Inactive	31 Total 55-59
32 Package holidays	13 Densely populated	32 Total 60-64
33 Education (pre & prim)	14 Sparsely populated	33 Total 65+
34 Catering services		
35 Accommodation	T Taxes	
36 Personal care	1 Motor spirit	
37 Other personal effects	2 DERV	
38 Social protection	3 Other oil	
39 Insurance	4 Coal	
40 Other financial services	5 Gas	
41 Other services	6 Electricity	
42 CVM Residuals	7 Carbon/energy tax	
43 Unallocated	8 VAT	
	9 Import duties	
	10 Material taxes	
	11 Other indirect taxes	

PA Population groups
1 Male Children
2 Male 15-19
3 Male 20-24
4 Male 25-29
5 Male 30-34
6 Male 35-39
7 Male 40-44
8 Male 44-49
9 Male 50-54
10 Male 55-59
11 Male 60-64
12 Male OAPs
13 Female Children
14 Female 15-19
15 Female 20-24
16 Female 25-29
17 Female 30-34
18 Female 35-39
19 Female 40-44
20 Female 45-49
21 Female 50-54
22 Female 55-59
23 Female 60-64
24 Female OAPs

AR Regional assumptions
01 YEAR
02 Exchange rate
03 SR Interest rate
04 LR interest rate
05 Total govt spending
06 Defence spending
07 Education spending
08 Health spending
09 Indirect tax rates
10 VAT rates
11 Direct tax rates
12 Benefit rates
13 Employees' Soc Sec rate
14 Employers Soc Sec rate
15 Unused

SF Stochastic Functions
1 BFR0 Agg Energy Demd
2 BFRC Coal Demd
3 BFRO Heavy Oil Demd
4 BFRG Nat Gas. Demd
5 BFRE Electricity Demd
6 BRSC Agg Consumption
7 BCR Disag Consumption
8 BCR Disag Consumption
9
10 BKR Ind. Investment
11 BQEX External Exports
12 BQIX Internal Exports
13 BQEM External Imports
14 BQIM Internal Imports
15 BYRH Hours Worked
16 BYRE Ind. Employment
17 BPYH Ind. Prices
18 BPQX Export Prices
19 BPQM Import Prices
20 BYRW Ind. Ave. Earn
21 BLRP Participation
22 BRRI Residual Income
23 BRDW Invst Dwellings
24 BYRN Normal Output
25
26 BRPT Agg Passenger
27 BRFT Agg Freight
28 BPMR Disag Passenger
29 BFMR Disag Freight
30
31 BMU1 Food
32 BMU2 Feed
33 BMU3 Wood
34 BMU4 Construction Min
35 BMU5 Industrial Mins
36 BMU6 Ferrous Ores
37 BMU7 Non-Ferrous ores
38 BMU8 Water
39
40

MT Materials
1 Food
2 Feed
3 Forestry
4 Construction Minerals
5 Industrial Minerals
6 Ferrous Ores
7 Non-ferrous ores
8 Water
9 Waste
10 Unallocated

MU Material Users
1 Agriculture
2 Mining
3 Energy
4 Food, Drink & Tobacco
5 Wood and Paper
6 Chemicals
7 Non-metallic Minerals
8 Basic Metals
9 Engineering etc
10 Other Industry
11 Construction
12 Transport
13 Services
14 Households
15 Unallocated

J Fuel types
1 Hard coal
2 Other coal etc
3 Crude oil etc
4 Heavy fuel oil
5 Middle distillates
6 Other gas
7 Natural gas
8 Electricity
9 Heat
10 Combustible waste
11 Biofuels
12 Hydrogen

EM Emissions

1 Carbon dioxide
2 Sulphur dioxide
3 Nitrogen oxides
4 Carbon monoxide
5 Methane
6 Particulates
7 VOCs
8 Radiation - air
9 Lead - air
10 CFCs
11 N2O (GHG)
12 HFCs (GHG)
13 PFCs (GHG)
14 SF6 (GHG)

ET Energy Technologies

1 Nuclear
2 Oil
3 Coal
4 Coal + CCS
5 IGCC
6 IGCC + CCS
7 CCGT
8 CCGT + CCS
9 Solid Biomass
10 S Biomass CCS
11 BIGCC
12 BIGCC + CCS
13 Biogas
14 Biogas + CCS
15 Tidal
16 Large Hydro
17 Onshore
18 Offshore
19 Solar PV
20 CSP
21 Geothermal
22 Wave
23 Fuel Cells
24 CHP

VT Vehicle Technologies

1 Petrol Econ
2 Petrol Mid
3 Petrol Lux
4 Adv Petrol Econ
5 Adv Petrol Mid
6 Adv Petrol Lux
7 Diesel Econ
8 Diesel Mid
9 Diesel Lux
10 Adv Diesel Econ
11 Adv Diesel Mid
12 Adv Diesel Lux
13 LPG Econ
14 LPG Mid
15 LPG Lux
16 Hybrid Econ
17 Hybrid Mid
18 Hybrid Lux
19 Electric Econ
20 Electric Mid
21 Electric Lux
22 motorcycles Econ
23 motorcycles Lux
24 Adv motorcycles Econ
25 Adv motorcycles Lux

FU Fuel Users

1 Power own use & trans.
2 O.energy own use & tra
3 Hydrogen production
4 Iron & steel
5 Non-ferrous metals
6 Chemicals
7 Non-metallics nes
8 Ore-extra.(non-energy)
9 Food, drink & tob.
10 Tex., cloth. & footw.
11 Paper & pulp
12 Engineering etc
13 Other industry
14 Construction
15 Rail transport
16 Road transport
17 Domestic aviation
18 Other transp. serv.
19 Households
20 Agriculture, forestry
21 Fishing
22 Other final use
23 Non-energy use
24 Aviation bunkers
25 Marine bunkers

Non-EU regions product/industry and consumer expenditure classifications

Q, Y Products, Industries	C Consumers' expenditure
1 Agriculture etc	1 Food
2 Coal	2 Drink
3 Oil & Gas etc	3 Tobacco
4 Other Mining	4 Clothing and footw.
5 Food, Drink & Tob.	5 Gross rent and water
6 Text., Cloth. & Leath	6 Electricity
7 Wood & Paper	7 Gas
8 Printing & Publishing	8 Liquid fuels
9 Manuf. Fuels	9 Other fuels
10 Pharmaceuticals	10 Furniture etc
11 Chemicals nes	11 Household text. etc
12 Rubber & Plastics	12 Major appliances
13 Non-Met. Min. Prods.	13 Hardware
14 Basic Metals	14 Household operation
15 Metal Goods	15 Domestic services
16 Mech. Engineering	16 Medical care etc
17 Electronics	17 Cars etc
18 Elec. Eng. & Instrum.	18 Petrol etc
19 Motor Vehicles	19 Rail transport
20 Oth. Transp. Equip.	20 Buses and coaches
21 Manuf. nes	21 Air transport
22 Electricity	22 Other transport
23 Gas Supply	23 Communication
24 Water Supply	24 Equipment etc
25 Construction	25 Entertainment etc
26 Distribution	26 Exp rest and hotel
27 Retailing	27 Misc. goods and serv
28 Hotels & Catering	28 Unallocated
29 Land Transport etc	
30 Water Transport	
31 Air Transport	
32 Communications	
33 Banking & Finance	
34 Insurance	
35 Computing Services	
36 Prof. Services	
37 Other Bus. Services	
38 Public Admin. & Def.	
39 Education	
40 Health & Social Work	
41 Misc. Services	
42 Unallocated	
43 Forestry	
44 Hydrogen supply	