Department for
Business, Energy
& Industrial Strategy

MACROECONOMIC MODELLING OF THE 2.4% R&D TARGET

Analysis with the E3ME model

BEIS Research Paper Number 2020/009

cambridge econometrics
clarity from complexity

February 2020

Acknowledgements

The analysis in this report was carried out by the modelling team at Cambridge Econometrics, including Hector Pollitt, Unnada Chewpreecha and Malin Berg von Linde.

Any enquiries regarding this publication should be sent to us at:
enquiries@beis.gov.uk

Contents

Executive Summary

Introduction

This report assesses the potential future impacts of increasing R&D expenditure in the UK. Specifically, it considers the impacts on GDP, employment and productivity of meeting a target in which the share of R&D expenditure in GDP increases to 2.4% by 2027, compared to a current rate of around 1.7%.

The report also assesses different ways in which the R&D target might be met, including different weightings of R&D expenditure across sectors and in different parts of the country. It considers possible funding measures for additional R&D. Finally, it includes estimates of the impacts of two specific technologies on the UK economy: digitalisation and the electrification of transport.

Basic approach

The assessment approach used in this report is a model-based one, specifically drawing on the E3ME macroeconomic model that is maintained by Cambridge Econometrics.

The E3ME model was first developed in the 1990s through a series of European Commission research projects. The current version of the model is global in scope. E3ME has previously been used in a series of high-profile European Commission Impact Assessments[1]. The model's treatment of R&D and innovation was recently enhanced in a European research project[2] and it is currently being applied to estimate the economic impact of European research partnerships through the Horizon Europe programme.

The model was designed specifically to assess the impacts of policy interventions, both in the short and long terms. As described below, the starting point is a current-policy reference case simulation. The results from simulations with additional policies (e.g. higher R&D expenditure) are then compared to the reference case.

E3ME is a macro-econometric model that is based on post-Keynesian economic theory, meaning that it does not assume optimal use of available resources. Behavioural parameters in the model are estimated from historical data. The model disaggregates the UK's economy to 70 sectors and includes trade linkages to other countries.

E3ME is not a Computable General Equilibrium (CGE) model, although it is used to answer the same sorts of economic questions. In E3ME, assumptions about perfect markets and fully rational behaviour are relaxed. The result is a framework in which production levels are determined by the level of aggregate demand in the economy and multiplier effects are possible. The demand for labour is determined by the level of production and involuntary unemployment exists.

[1] Including for example contributions to the Work-Life Balance Directive, Long-Term Climate Strategy and several trade Sustainability Impact Assessments.
[2] https://www.monroeproject.eu/

The model accounts for both process innovation (producing more efficiently) and product innovation (making new products). The measures of innovation are defined at sectoral level as technology indices based on accumulated R&D (i.e. the stock of knowledge) and accumulated investment (capital stock). These indices in turn feed into the econometric equations for prices and trade (reflecting product innovation), energy consumption and production capacity (reflecting process innovation). Technological progress may also affect employment levels directly and increases in R&D expenditure may stimulate additional investment in new products.

Through the national accounting framework, these changes to macroeconomic indicators impact on GDP. Positive impacts on trade and investment will lead to increases in GDP. Higher GDP growth rates will boost employment, which may further stimulate consumption and GDP through multiplier effects.

A description of the E3ME model, including its treatment of R&D and innovation, is provided in the appendix; the full model manual is available online at the model website www.e3me.com and a full list of equations is provided in Mercure et al (2018).

Limitations of the approach

As with all models, E3ME presents a simplification of reality. The model makes various assumptions in forming this simplification and it is important to be aware of these assumptions.

The most important assumption relates to the model's behavioural parameters, which are estimated econometrically from historical data. Although this approach is highly empirical, the development of new technologies could lead to disruptive change and different behavioural responses to the past. The model parameters therefore represent unbiased estimates of uncertain future behaviour, but the results from the model should not be viewed as forecasts.

Despite its relatively high level of sectoral disaggregation, the fixed structure of the model is another important limitation. E3ME cannot be used to estimate the impacts of changes within sectors. It also cannot predict the emergence of new sectors related to technological advances.

The scenarios assessed

The reference case represents a case in which there is no additional policy. The UK's population increases to 71m by 2030, in line with Eurostat projections. GDP growth is set to match standard BEIS projections. Sectoral growth rates are formed by constraining previous E3ME projections (based on European Commission analysis) with the aggregate GDP levels.

R&D levels in the reference case follow a fixed path, with R&D as a share of GDP remaining at current levels. The split of R&D between sectors also remains similar to the shares we see today. A general trend in upskilling is assumed implicitly in the projections, which allows the absolute level of R&D to grow in line with GDP (and continues existing trends). Although productivity increases in the reference case, it is largely at existing trend rates based on long-term time series and there are no shocks due to AI or other new technologies.

The core questions about the economic impacts of additional R&D expenditure were assessed through a set of scenarios that were compared to the reference case. Ten scenarios were constructed to test specific aspects of R&D expenditure with a time horizon of 2040. These scenarios were compared to a standard reference case in which the level of R&D (as a share of GDP) remains broadly constant.

The first scenario assumes a scaling up of R&D to 2.4% of GDP. The other scenarios assess variants relating to:

- How the R&D is financed
- Different sectoral or regional shares of higher R&D spending
- The potential impacts of two specific technologies (digitalisation and electrification of transport)

A full list of the scenarios is provided in Table 3 of this report. The results from the model include the impacts of the additional R&D on a range of macroeconomic and sectoral economic indicators (e.g. GDP, consumption, investment, trade and prices) and labour market indicators (e.g. employment and incomes). The key insights from these results are summarised below.

Key findings

The full set of results from the scenarios is presented in Chapter 4 of this report. Six key findings have emerged from the analysis, which are presented below.

Key finding 1: Higher R&D expenditure will boost GDP, employment and productivity.

In all the scenarios with higher R&D expenditure, there are increases in GDP, employment and productivity. If R&D expenditure increases to 2.4% of GDP by 2027, annual GDP will be higher by 1.2-1.4% and employment by 0.2-0.3%, compared to the reference case. In absolute terms, an extra £15bn in annual R&D spending will lead to annual GDP being higher by £30.5bn and 80,000 extra jobs in 2027. If R&D spending continues to increase, by 2040 the impacts on GDP and employment will be up to £180bn and 923,000 jobs, respectively.

The higher GDP is caused by both product and process innovation (see below). These lead to a boost in trade performance (exports are 1.4% higher by 2027 than in the reference case) and an increase in investment (0.8%). There are also positive impacts on consumption (0.2%) that result from the higher employment levels.

It is important to note that many of the impacts of higher R&D expenditure occur several years after the R&D has taken place. In this report we test a scenario in which the level of R&D spending (as a share of GDP) increases up to 2027 but then does not increase further. The model results show that it takes time for the benefits to be realised, for example for products to get to market, prices to adjust and demand to respond. By 2027, GDP is 1.3% higher than in the reference case, but by 2040 the difference is 2.9% (and exports are 14.3% higher).

There is a further lagged effect in employment impacts because employers typically wait for production levels to increase before employing additional workers. In the same scenario, 80,000 additional jobs are created by 2027 but the figure is almost 300,000 by 2040.

Key finding 2: R&D spillover effects are important but the magnitude of these effects is uncertain.

The term spillover is used to assess impacts on companies or sectors other than the one that carries out the R&D. Spillovers may occur between companies within a sector, between sectors or between countries. For example, if a company invests to develop a new product, other companies may start to develop similar products; companies in other sectors may benefit from using the product and the product will eventually be sold internationally.

The modelling in this report is carried out at sectoral level, so an estimate of spillovers between sectors and countries is required. In the preparation of this report, several different ways of estimating the size of spillover effects were assessed. Unfortunately, there is no reliable empirical approach for estimating the size of spillover effects because it is not possible to attribute definitively improvements in economic performance in one sector to research carried out elsewhere in the economy.

The modelling therefore used estimates based on previous studies. Of the total £30.5bn increase in GDP in 2027, £3.9bn is accounted for by R&D spillovers between sectors. In 2040, £100bn of the £170bn total GDP impact is due to spillover effects. As with the direct economic impacts, it can take some time for the spillovers to have an impact on economic outcomes.

Key Finding 3: Product and process innovation both make important contributions to GDP growth.

The model results above include the combined impacts of product and process innovation (and subsequent indirect effects). A further analysis of the model results showed that the channels of impacts through both product and process innovation are important in determining GDP outcomes.

The relative importance of the different types of effect varies by sector. The impacts of product innovation are more pronounced in the manufacturing sectors that have scalable products and participate in international trade. The combination of being able to increase production rapidly and having a large potential market for sales could lead to the largest economic benefits per unit of additional R&D expenditure (see below).

Typically, the effects of process innovation take longer to realise because it takes time for prices and the wider economic system to adjust. Once a successful new product is developed, the benefits in terms of higher sales may be realised soon afterwards. For process innovation to have a positive impact on GDP, however, first prices must respond and then demand must respond to prices. At each stage there may be a delay in impact.

Key Finding 4: The funding source for the additional R&D is less important in determining economic outcomes.

The modelling in this report presents ‘net’ outcomes, meaning that it includes both the positive impacts of the R&D expenditure, and also any negative impacts from measures used to fund the R&D (e.g. higher tax rates). In the scenarios, we consider three main sources of funding for the additional R&D expenditure: domestic public, domestic private and overseas investment.

The source of funding for the additional R&D expenditure may be important from the perspective of political feasibility. However, the model results suggest that the outcomes do not vary by much when the source of funding changes. The key finding is therefore that the priority should be to ensure that the additional R&D activities take place and to select the funding mechanism that is most practicable.

Key Finding 5: Manufacturing sectors are likely to benefit more from additional R&D expenditure.

The results from the modelling show a higher potential return for manufacturing sectors from increases in R&D expenditure. The reason is that manufacturing sectors often operate in global markets and are more likely to participate in international trade. The main positive impacts on production arise from boosts to trade and therefore these sectors benefit the most. To put it another way, manufacturing sectors operate in a larger, global marketplace and therefore have a larger potential market to sell improved products.

However, it should be noted that large increases in R&D in any one sector could result in that sector hitting capacity constraints. In the modelling it is assumed that the constraints only have limited impact but it is possible that, at a more detailed level, bottlenecks prevent a rapid expansion of output. Further analysis at sectoral level would be required to better understand the potential for higher rates of production.

The policy implications from this finding are therefore somewhat mixed. While the largest returns could come from favouring manufacturing sectors, an approach that increases R&D spending in all sectors could eventually yield the largest overall economic benefits.

Key Finding 6: Each new technology will have specific impacts on the economy that go beyond the scope of the modelling exercise.

The benefits of higher R&D expenditure are likely to be spread across the economy and most of the scenarios assessed in this report do not consider specific technologies. This makes the modelling tractable but the academic literature on innovation shows that technological advances tend to occur in clusters within sectors over time.

This report therefore also includes two examples of new technologies that could have profound impacts on business and society. It shows that the impacts of digitalisation will be felt primarily through a realignment of trade relationships and therefore the sectors that are most dependent on trade (either through imports or exports) are likely to be most affected. Given the UK's expected continued deficit in trade of manufactured goods, any reshoring of production due to 3D printing could lead to improvements in the trade balance and GDP.

The electrification of transport could also affect trading patterns through a large reduction in fossil fuel imports. Although it is not yet clear where the production of batteries and other components for electric vehicles would take place, a shift to domestic expenditure could provide a modest stimulus to the UK economy.

The modelling in these two scenarios highlights the potential complexity of new technological developments and how they might interact in future. The modelling provides a best estimate of future outcomes but it cannot account for every possible future technology.

Overall conclusions

Technological progress is generally seen as the key long-run driver of productivity growth and GDP. R&D expenditure is generally seen as a key driver of technological development. The links between R&D expenditure and GDP growth presented in this report are therefore already quite well understood.

In the context of the current global economy, new technology will continue to play an important role in economic development in the coming decades. Increasingly, these technologies are global in scope and appear to be subject to network effects, meaning that the benefits may be highly concentrated in specific geographical areas.

Measures to increase the volume of R&D expenditure in the UK could therefore shape the UK's future role in technological advancement and its position in the global economy. The modelling in this report suggests that such an outcome could directly translate into higher levels of GDP, employment and productivity. The focus for policy makers is therefore to find ways to increase overall R&D spending in the UK.

1 Introduction

Introduction to this report

Since the financial crisis and subsequent recession, the UK economy has followed a low-growth trajectory. Although unemployment is currently at low levels, productivity growth has remained low and average incomes have stagnated. Economists continue to grapple with the ‘Productivity Puzzle’. The Economic and Social Research Council has set up a ‘Productivity Insights Network’ specifically to address this challenge. Raising productivity is a key goal of the Industrial Strategy.

The ‘dark matter’ of economic growth is still not well understood, but there is a consensus that innovation is a key driver of long-term growth. The Solow Residual of Total Factor Productivity that cannot be attributed to changes in labour or capital inputs is often thought of as relating to innovation. This leads to discussions about what leads to innovation and what policies can promote it. Most quantitative analysis concentrates on a stock of knowledge that can be enhanced by promoting expenditure on R&D activities. This knowledge can be used both to develop new products and to improve production processes.

The innovation chain

The innovation pathway to bring a new product to market is now recognised as highly complex and with multiple phases (Grubb, 2004). Early-stage basic research takes place in laboratories and is usually funded with public money. New technologies are then transferred to new products; and often the private sector begins to take over. Finally, companies develop finished products and allow them to diffuse into the marketplace.

Process innovation (producing goods and services more efficiently) is more likely to occur within firms and closer to the market. Finding new ways of carrying out existing activities is an important way to improve productivity.

Innovation is usually regarded by economists as having positive externalities, because of spillover effects. If one company develops new technologies, these technologies can later be adopted and incorporated into products by other companies in other sectors, providing wider societal benefits. Market mechanisms alone therefore do not support innovation to its full extent, suggesting that there is a clear and unambiguous role for public policy to promote innovation activities.

The role for R&D and R&D policy

With the exception of the final phase of bringing a product to market (where market research is more important), R&D facilitates each stage of the innovation chain. Increased R&D expenditure can both accelerate product development and improve production processes. However, there are substantial differences between the research activities of different sectors, as the R&D expenditure data show. For example, the potential benefits for services sectors are often thought to be smaller (important for the UK economy) because it is more difficult to scale most service-sector activities for a global market. Companies in sectors with lower degrees of competition, or those that produce commoditised products (notably the energy sectors) also tend to invest less in R&D, because they have less need/capability to differentiate themselves from rivals.

All this points towards the need for tailored policy to boost R&D and therefore innovation. In this report we consider a range of different ways of stimulating R&D, and assess how this would impact on UK productivity and economic growth.

Structure of this report

Table 1 summarises the structure of this report.

Table 1 Structure of this report

Chapter	Description
1. Introduction	This chapter.
2. Modelling innovation	A description of the E3ME macroeconomic model that is used throughout this report.
3. Scenario design	An overview of the reference case and ten scenarios that we assess.
4. Results	The results from the modelling exercise and supplementary analysis.
5. Key findings	A summary of the main messages to take from the analysis.

2 Modelling Innovation

Introduction

The assessment in this report is a model-based one and so it is important to lay out how innovation is modelled. The treatment of innovation can vary substantially between different macroeconomic models. The next section provides an overview of the main approaches that are used. The following sections introduce the E3ME model and how it treats innovation. The final section discusses how some of the specific technologies described in the scenarios are modelled.

Overview of approaches to modelling innovation

Overview

It is only relatively recently that macroeconomic models have begun to include measures of innovation as standard. There are still many Computable General Equilibrium (CGE) models in which technological progress is 'exogenous', meaning that technology developments happen for reasons outside the economic system.

This specification partly reflects the main purposes of the models, which is to work out the most efficient way of allocating resources under a fixed set of technological assumptions. This static approach ignores the dynamics of technological change almost by assumption.

Real Business Cycle theory, which has since been encapsulated in Dynamic Stochastic General Equilibrium (DSGE) macroeconomic models has relaxed these assumptions, but only partially. DSGE models assume that shocks caused by rapid technological change can knock the economy away from its equilibrium position. However, these shocks are only temporary and in the long run the economy will return to its equilibrium position.

Endogenous Growth Theory

Despite the limitations in standard models, economists have long stated that innovation and technological change are key drivers of long-term growth. Endogenous Growth Theory, which is strongly associated with Nobel prize winner Paul Romer (see review in Romer, 1994) provides one such formalisation. Simply put, endogenous growth theory suggests that an accumulation of knowledge and ideas will lead to a more efficient use of labour and capital resources, boosting output. The stock of knowledge can be boosted through R&D activities or other policies to increase the diffusion of new ideas in the economy. Acemoglu (2009) provides an overview.

Importantly from a modelling perspective, Endogenous Growth Theory can be fitted into the production functions used in standard CGE models. The basic models have more recently been improved in several different ways, for example putting more emphasis on the role of human capital. An endogenous treatment of technological change thus became possible in the models used for policy analysis.

Other representations of technological progress

Prior to the work of Romer and his colleagues, perhaps the best-known economist to work on innovation was Joseph Schumpeter. Schumpeter's work focused on the economy from the perspective of the entrepreneur. He was one of the first people to link developments of new technologies with activities in the financial sector and impacts on the wider economy (Schumpeter, 1934). There are many similarities between his ideas and those of the determinants of growth put forward by Keynesian economists (e.g. Kaldor, 1940); a more recent revival of evolutionary economics has further broadened these connections.

More recently, complexity theory has shown how innovation may result from the interaction of different people, or groups of people, which generate ideas for improving products and processes (Beinhocker, 2007; Arthur, 2010). In many ways the insights from complexity theory are also consistent with Schumpeter and Keynes, although viewed from a different perspective. The importance of interactions is also consistent with Romer's hypothesis that larger populations could lead to more innovation.

Complexity economics is usually represented through agent-based models, but these have not yet been developed to a full macroeconomic framework. However, some of the key insights are now being adopted to understand technology diffusion (Mercure, 2012).

Product and process innovation

There is now a general agreement amongst the different modelling approaches that innovation is a long-run driver of economic growth, and that higher rates of R&D expenditure will drive innovation. This agreement means that process innovation is now fairly well-defined in modelling terms, even if the formal representation may differ between models.

There is less agreement on product innovation (creating new, more advanced products), which can be more difficult to quantify in economic models because it is based on non-price effects. Relatively few models cover product innovation and it is therefore difficult to compare the approach in the E3ME model (see next section) to other tools.

Summary

To summarise, as is often the case in macroeconomics, there are competing theories about the interactions between innovation and economic growth. There is now a consensus that the path of innovation can influence the rate and direction of economic growth; and also that the rate of growth can influence the rate and direction of innovation. Economic growth and innovation are therefore 'endogenous', i.e. part of the same social system.

There is also a consensus that an accumulation of knowledge and ideas is the driver of innovation and growth. R&D expenditure is a core component of the knowledge accumulation process, but it may not be the only one; education and human capital also play important roles.

As more data become available, the representations of R&D and innovation in macroeconomic models are also becoming more detailed. There are differences in specification between the models being used but many of the underlying principles are similar.

Introduction to the E3ME macroeconomic model

Introduction and theoretical background

E3ME is a computer-based model of the world's economies, linked to energy demand and emissions. It was originally developed through the European Commission's research framework programmes and is now widely used in Europe and beyond for policy assessment, for forecasting and for research purposes. Version 6.1 of the model splits the world into 61 regions, with 70 sectors in each European region. The UK represents one of the regions in the model.

E3ME's theoretical origins lie in post-Keynesian economic theory. Following from the early writing of Keynes, E3ME accepts that there is fundamental uncertainty in the economy. Economic agents are not able to optimise their decision making and base behaviour on their limited knowledge. This approach contrasts with that in standard CGE models, in which agents are assumed to have perfect knowledge and behave in an optimal manner. E3ME also rejects assumptions of perfect competition and fully flexible prices.

The result is that in E3ME the economy does not automatically operate at full capacity. The level of output is determined by the level of aggregate demand, which is usually less than the level of potential output[3]. This approach is consistent with reality, as data on involuntary unemployment and economists' attempts to measure the 'output gap' show. A realistic treatment of the financial sector is also key to understanding how changes in policy and behaviour can lead to stimulus or austerity effects (Pollitt and Mercure, 2018).

The next section describes how innovation is treated in E3ME but it is important to understand the linkages with respect to the theoretical underpinnings. Process innovation allows the level of potential output to increase through efficiency improvements. Product innovation may boost levels of aggregate demand and close some of the output gap.

Data and econometric parameter estimation

For European countries, the primary data source in E3ME is Eurostat. Using a single source allows comparability between countries and is particularly important for modelling trade (which drives many of the positive impacts in Chapter 4).

Eurostat data are supplemented with figures from other international organisations, including the OECD, ILO and World Bank. In the present exercise, ONS data are also used to ensure consistency in the approach.

Most data series are processed as time series that cover the period back to 1970 on an annual basis. In most cases the data are disaggregated by sector.

The econometric approach

Because E3ME rejects theories of optimising behaviour, an alternative way of modelling human behaviour is required. Behavioural parameters are obtained from econometric estimates based on time-series historical data. This is why E3ME is often referred to as a macro-econometric model.

[3] Even in scenarios with large increases in GDP, we do not reach full employment in the simulations in this report.

The econometric techniques used to specify the functional form of the equations are the concepts of cointegration and error-correction methodology, particularly as promoted by Engle and Granger (1987) and Hendry et al (1984).

The estimation process involves two stages. The first stage is a levels relationship, in which an attempt is made to identify the existence of a cointegrating relationship between the chosen variables, selected on the basis of economic theory and a priori reasoning. If a cointegrating relationship exists then the second stage regression is known as the error-correction representation, and involves a dynamic, first-difference, regression of all the variables from the first stage, along with lags of the dependent variable, lagged differences of the exogenous variables, and the error-correction term (the lagged residual from the first stage regression). Further information about the approach is available in the model manual.

Modelling innovation with econometrics

The econometric approach makes E3ME highly empirical in design. However, there is an inevitable contradiction in using historical data to estimate the impacts of unknown future technologies. If new technologies change the structure of the economy, then economic behaviour is likely to change too.

This is sometimes referred to as a special case of the 'Lucas Critique' (Lucas, 1976). The Critique suggests that parameters derived from one policy situation may not be valid when applied to a world in which policy has changed; essentially saying that the behavioural constants in our analysis should change when the policy inputs change. As noted below, this affects all modelling approaches.

Regardless of the modelling approach, it must always be acknowledged that the degree of uncertainty around model results increases when long-term scenarios with new technologies and potential structural change are assessed. However, to carry out the modelling exercise, a set of model parameters is required. The econometric estimates, when plausible assumptions are met, provide an unbiased estimate of economic behaviour. Previous in-sample analysis at Cambridge Econometrics has shown that the parameter values are reasonably stable over time.

Splitting the UK into regions

Although the E3ME model operates at national level, in this report we present results for UK regions and also assess two scenarios that have a regional disaggregation of inputs. Additional off-model calculations are required in both cases.

The mapping exercise is quite basic in approach. The sectoral data in the model are used to apportion impacts to the regions based on each region's sectoral composition. The same approach is used both for estimating regional impacts and in designing inputs for the place-based scenarios.

For assessing the regional impacts of the place-based scenarios an additional assumption is required. We allocate all direct R&D impacts to the region in which the R&D takes place. Spillover effects (see next section) are assumed to happen across the UK, meaning that additional R&D in one region can benefit the economy in other UK regions.

Further information

A longer description of the E3ME model is provided in Appendix A. The full model manual is available from the model website, www.e3me.com

The treatment of innovation in E3ME

Introduction

The model manual describes the treatment of innovation in E3ME. The model combines different approaches based on the level of available data in different sectors. In some cases, scenarios in E3ME are designed around specific technologies.

The difference between explicit and implicit treatments is often discussed in terms of 'bottom-up' and 'top-down' models. Bottom-up models are defined by a specific list of technologies, each of which has a fixed set of characteristics (e.g. costs, efficiency). They therefore often come from an engineering background. Top-down models tend to be based on macro or sectoral elasticities, which may be obtained through econometric methods or other calibration techniques.

Bottom-up models include a lot more detail but are usually defined only for a small number of sectors; otherwise they would need detail on every technology in existence. The methods used to parameterise top-down models may be applied to all sectors, but provide a lower level of detail.

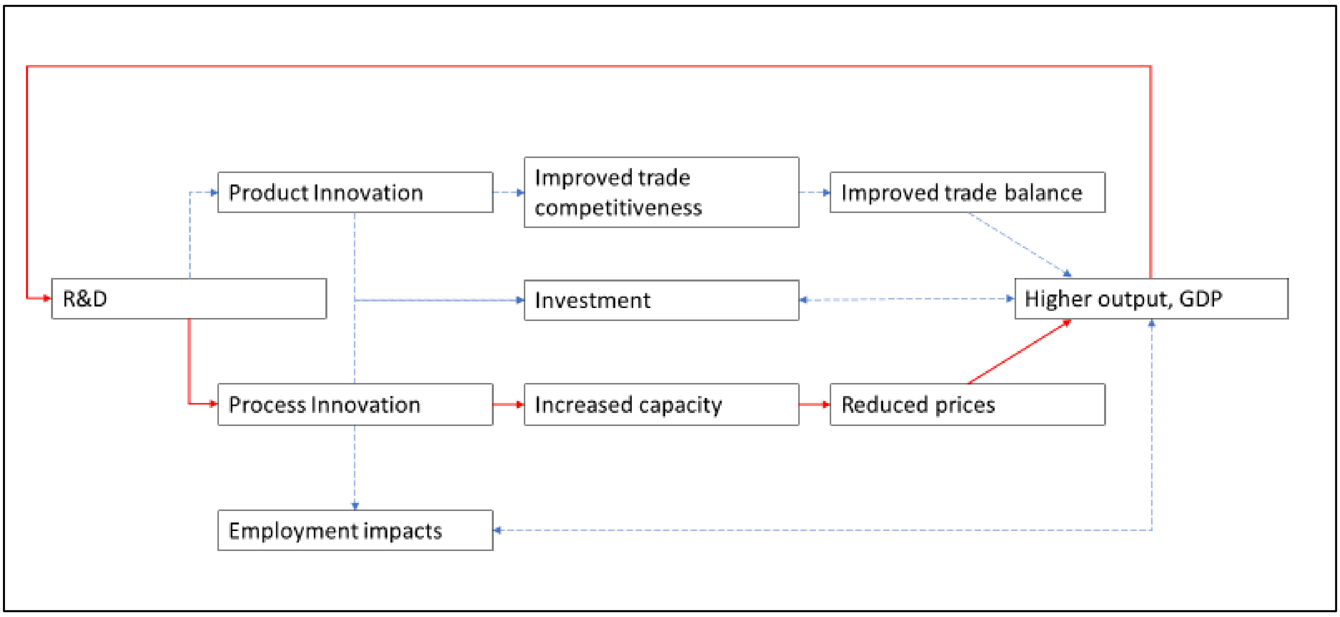
As a whole-economy model, E3ME is top-down in design, although it is linked to the bottom-up FTT[4] sub-models for the energy sector (Mercure, 2012). However, because we do not consider the adoption of new energy technologies in most scenarios, our description in this section focuses on the top-down treatment of technology. Most of the scenarios draw on the implicit approach described above, so we focus attention there. Towards the end of the section we discuss the approach to modelling some specific technological changes.

Basic model structure

Figure 1 shows the main linkages in the E3ME modelling framework. R&D expenditure leads to the model's technology indices, which are labelled as product and process innovation in the figure. These indices in turn impact on other model variables. In the figure, process innovation is shown with the red solid arrows, whereas product innovation is shown through the blue dashed arrows.

[4] Future Technology Transformations.

Figure 1 Innovation in the E3ME model



The exceptions are the links through investment and employment, which may result from either product or process innovation, and are also impacted by other economic developments.

It should be noted that the figure is a reduced form of the complex relationships within the E3ME model. In the scenarios in this report, the level of R&D in each year is given by assumption and therefore the long arrow across the top of the diagram is excluded.

Modelling process innovation

Process innovation provides the source of endogenous growth in E3ME, as the loop shown by the red solid arrows in the chart can become self-perpetuating over time. Higher levels of R&D expenditure lead to process innovation, which improves efficiency in production. These efficiency gains boost the level of potential production supply in the economy (i.e. capacity), leading to lower prices that in turn boost demand. Final consumers respond, boosting the level of output and GDP.

Although in the scenarios in this report the level of R&D is fixed, the same mechanisms can lead to higher GDP in a scenario where R&D expenditure increases. However, these impacts can take some time to have an effect because there may be some lag before prices adjust and then again before demand responds to lower prices.

Improvements to process innovation can have positive impacts in all economic sectors, regardless of the type of production or share of international trade.

Modelling product innovation

Improvements to the quality of products can also have positive impacts, but here the channel is more through the level of aggregate demand. Better products will be more competitive in international markets and therefore higher R&D expenditure can lead to improvements in the trade balance and GDP.

These effects can also be to some extent self-perpetuating, but they face limits in that improvements to the trade balance can only boost GDP while there is spare capacity in the economy (e.g. unemployed workers).

The sectors that will benefit the most from product innovation are the manufacturing sectors that export their goods to a global market. There is also scope for exporting services sectors to benefit.

Direct investment effects

Higher R&D expenditure may lead to higher investment because the creation of new capital equipment (that either produces better goods, or the same goods at lower cost) could lead to higher levels of investment. However, these effects have tended to be relatively minor at aggregate level.

Direct employment effects

In E3ME, the technology indices also feed into the employment equations. The sign may be positive or negative, depending on whether the technology is labour-saving or labour-augmenting. At macro level, the effects in different sectors may cancel out and we do not expect to see a major direct impact on total employment.

Formulation of key variables

The technology indices in E3ME are measured as accumulations:

CAPS(t) = K(t) + 0.9 * CAPS(t-1)

KNOS(t) = RD(t) + 0.9 * KNOS(t-1)

The capital and knowledge stocks (CAPS and KNOS) at time t are equal to the previous year's stock minus a 10% depreciation rate, plus the current year's additions to the stock (K=investment[5], RD=recorded R&D expenditure).

Both technology indices feature in the econometric equations for:

- capacity
- exports
- imports
- employment
- prices

The knowledge stock also features in the econometric equations for:

- investment

The econometric equations are estimated and solved by sector. The signs of the coefficients are restricted so that they do not produce counter-intuitive results. The parameter estimates are otherwise derived from the time-series historical data.

[5] Gross Fixed Capital Formation.

Restricting export volumes

In some cases, the responses to higher R&D expenditure were found to be large in magnitude. For example, in the main 2.4% scenario, there is a long-term increase in R&D expenditure of more than 60% (from 1.7% of GDP in 2017 to 3.0% in 2040). If the estimated elasticity in the export equation is unit, then the model would show an increase in exports of the same scale.

Such outcomes are possible, but it seems likely that there would be diminishing returns to scale on R&D (for example due to capacity constraints) and a smaller impact could be expected. We therefore added a further constraint that once exports in any sector had increased by 50%, the pace of further growth in that sector slowed by a factor of three.

Estimating R&D spillover effects

The R&D spillover effects are intended to capture the fact that R&D in one sector can have positive impacts on another sector. For example, new communications technologies can benefit all the sectors that use these technologies.

The way the spillovers are modelled is through a measure of ‘virtual R&D’. This is R&D that may benefit the sector but without any direct expenditure or entry in the national accounting system. Effectively it is a potential ‘free lunch’ for the sector involved; potential benefits to productivity and product quality without needing to make an initial investment.

As noted in the previous section, it is difficult to measure spillover effects, which are usually unobservable in nature. In this exercise we initially used a method based on patent citations. However, we found that this approach tended to suggest larger spillovers in the manufacturing sectors, which may be less appropriate for the UK’s service-oriented economy.

The final approach used was therefore based on input-output coefficients to link the sectors together. Essentially, firms that purchase equipment from the sectors that undertake the R&D may benefit from being able to use better quality products[6].

The input-output tables provide us with the relative sizes of spillover effects between sectors, but not the overall size of the effects. The magnitudes of the spillover effects were therefore scaled to be consistent with previous BEIS analysis that was carried out at macro level. The size of the spillover effects varies over time but, on average, after five years £1m of additional R&D plus spillovers has a similar impact to £1.3m of R&D excluding spillover effects.

A model run without the spillover effects was included in the analysis as a sensitivity test. We do not report the results from this run separately but it is used in the disaggregation of results in Chapter 4.

Limitations to the modelling approach

Like all other models, E3ME represents a simplified version of reality. In abstracting from reality to the model equations, a number of assumptions need to be made. Here we discuss some of the most important ones and how they might influence the overall model results.

[6] They may already benefit from lower input prices due to process innovation; this is part of the standard modelling framework.

Accounting system and technology representation

Like most other macroeconomic models, E3ME is based on the standard system of national accounts. Although there is a debate about the merits of GDP as an indicator and what should and should not be counted as economic production (see review in Mazzucato, 2019), the indicators are well-defined and, as long as interpreted correctly, non-controversial.

There is more discussion about the representation of human behaviour in the model (see below). However, of particular relevance is the way that technology is represented. As noted earlier in this chapter, there are many different ways of representing R&D and technological links in the model. While the approach in E3ME can be argued to be empirical (i.e. if it is not a good representation then the econometrics will not find significant relationships), this finding can only be applied to the historic data where the range of technologies was different.

There are some other more practical limitations in the modelling that reflect the available data. It does not make much distinction between different types of R&D, beyond the sector carrying it out. A large proportion of R&D is allocated to the R&D sector, which is likely carrying out research on behalf of other sectors (see figure in the next chapter). There is therefore a reasonable degree of uncertainty in the model results.

Econometric approach

The E3ME model is highly empirical in approach. It is based on real-world data, with time series that go back to 1970. These data are used to estimate the model's behavioural parameters, using the econometric approach summarised in the previous section.

However, estimates of past behaviour may not always provide an accurate basis for predicting future behaviour. As noted earlier in this section, this point is especially applicable to future scenarios with new technologies which, by definition, will be different from those in the past and may represent a structural break in time series.

The argument is a generalisation of the Lucas Critique (Lucas, 1976; see previous section), which was used against macro-econometric models in the 1970s. It is still applicable today and, as recently noted in Haldane and Turrell (2018), the critique is applicable to all modelling approaches.

The scenarios in this report are ambitious in terms of R&D expenditure, but are not attempting to illustrate a world that is dramatically different to todays. It is always important to acknowledge the uncertainty in model results but, in the absence of alternative information about future behavioural patterns, our present-day estimates aim to provide the best unbiased parameter values.

Model disaggregation

The E3ME model is one of the most disaggregated macroeconomic modelling tools currently in operation, with 70 sectors defined. However, it has limits in disaggregation that are mainly imposed by the level of detail in the sectoral and input-output data.

Within each of the 70 sectors, there is an assumption that the composition of that sector does not change. For example, if the basic metals sector grows then it is assumed that production of steel, copper and all other metals grows proportionately; otherwise the input-output coefficients and other parameters (e.g. number of jobs per unit of production) would change.

It is therefore difficult to infer conclusions at a higher level of detail than the sectors in the model, even though we know that in reality there could be quite different effects within different segments of a sector.

A similar issue applies when making subnational estimates. The procedure described in the previous section uses sectoral information as a proxy but is unable to draw on any specific regional characteristics.

Modelling specific technologies

Two of the scenarios presented in this report are based on the development and deployment of specific technologies:

- digitalisation
- electrification of transport

For these scenarios, we construct specific model inputs to reflect the characteristics of the technologies in question – at least, as much as we know about them now.

Digitalisation

Digitalisation is the trickier of the two technologies to assess, because it is a broad, platform technology that will affect multiple sectors. It is also still at quite early stage, so there is more uncertainty about how it will develop.

The model inputs are therefore designed from the results of an assessment of the relevant literature (see Chapter 3). The main focus is on 3D-printing, which at present is expected to have the largest economic impact. There is also an improvement in the efficiency of the construction sector due to pre-fab and other techniques that benefit from the technology.

These two factors are set as exogenous inputs to the E3ME model. It is assumed that the effects of digitalisation occur on top of any technological developments in the baseline. In order to isolate the impacts of digitalisation in the modelling, we do not increase R&D expenditure in this scenario.

Electrification of transport

In this scenario, the technology is more specifically defined. There has also been considerable work carried out in the area, including using the E3ME model (Cambridge Econometrics, 2015). In this report we adopt the same scenario inputs.

In summary, there is a shift towards hybrid and fully electric light-duty vehicles, which are less expensive to run, but which have a higher up-front cost. The shift is modelled through changes to fuel/energy consumption and vehicle prices in the model. There is also a change in the vehicle supply chain, with each car having fewer mechanical components and a large battery cost instead; these changes are modelled by adjusting input-output coefficients in the model.

The scenario assumes that the same number of vehicles is purchased and that the same share of vehicles is manufactured in the UK. The modelling results thus show the impacts of a shift to electric vehicles, rather than a change in the total number of vehicles produced.

3 Scenario Design

Introduction

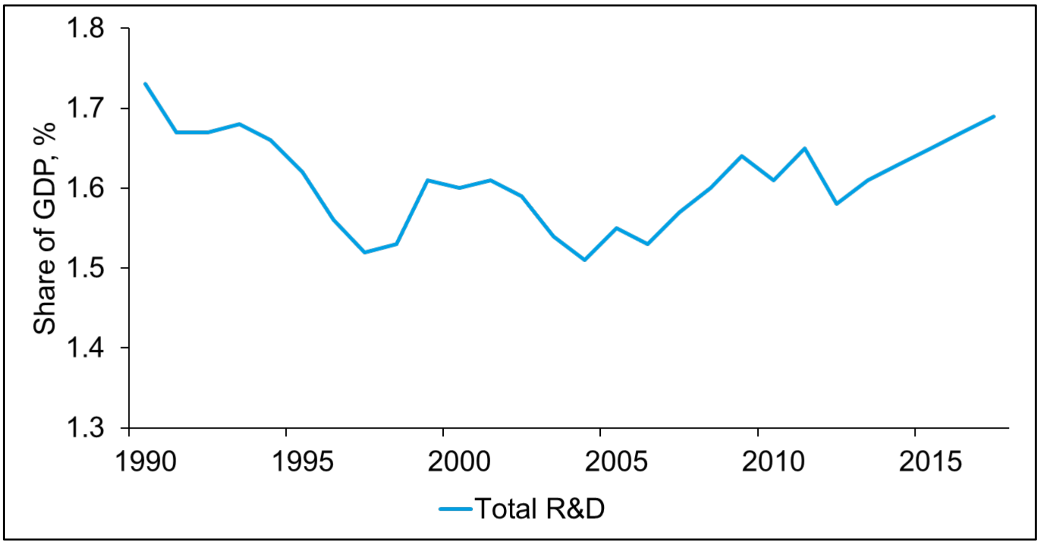
This chapter describes in detail the reference case and scenarios that were used in the model-based analysis.

The next section describes recent trends in R&D expenditure in the UK. We then present the reference case and the R&D scenarios. The table at the end of this chapter summarises all the model runs that were carried out.

Recent trends in R&D expenditure in the UK

Figure 2 shows R&D expenditure as a share of GDP since 1970. The chart shows a steady decline in the share of R&D in GDP in the 1970s, followed by flat progress and an increase after 2000 (with a general upward trend recently). Overall in the historical period, R&D expenditure has not got close to 2.4% of GDP and for most of the period has been at about two-thirds of that rate.

Figure 2 R&D as a share of GDP, UK



One reason that R&D expenditure has not increased as a share of GDP, is that high R&D-intensity sectors have become relatively less important in the UK economy. Notably, the share of manufacturing in GDP has declined over this period from around 24% of total value added to around 12%. Much of that share of activity has been taken by business services, which typically invest a lot less in R&D (see Figure 3).

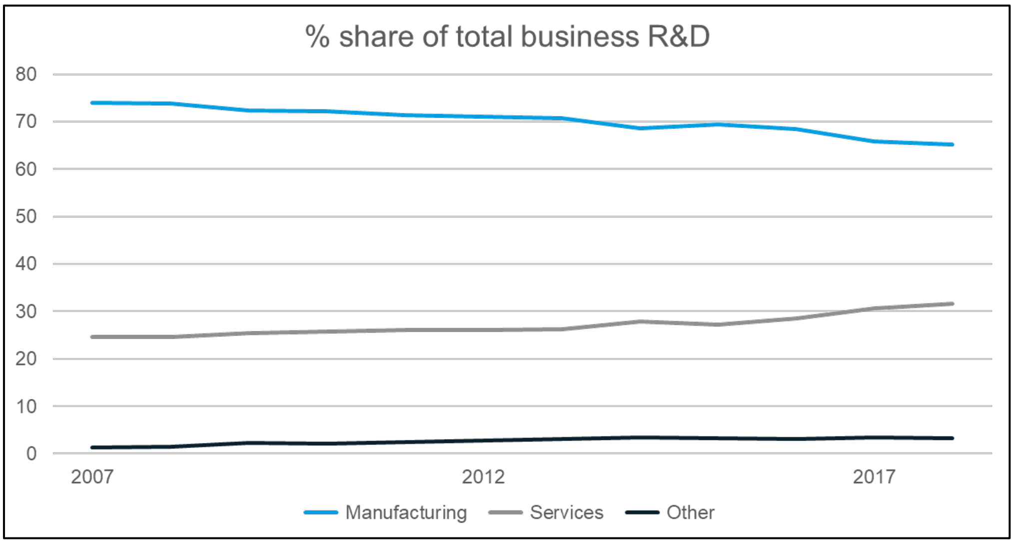
Figure 3 in fact understates the difference between industry and business services in terms of R&D expenditure. The line for business services in the chart includes R&D that has been outsourced to the R&D services sector, including outsourcing by industry. The R&D sector accounts for around one third of total R&D allocated to business services.

Nevertheless, the trend has been for higher rates of R&D expenditure in both public and private services sectors, which accounts for the total increase in rates of R&D expenditure after

2000. This trend compensates for the loss of R&D in industry after the financial crisis, which has since only partially recovered.

Other sectors (agriculture, energy, construction, transport and consumer services) have very low rates of R&D expenditure.

Figure 3 Sectoral R&D shares



The reference case

This section describes the reference case that was used for the analysis.

The model reference case is calibrated to match the figures provided by BEIS for GDP and R&D (converted to a constant price base). The previous model baseline, which was based on a wider set of indicators from the European Commission has been scaled for consistency.

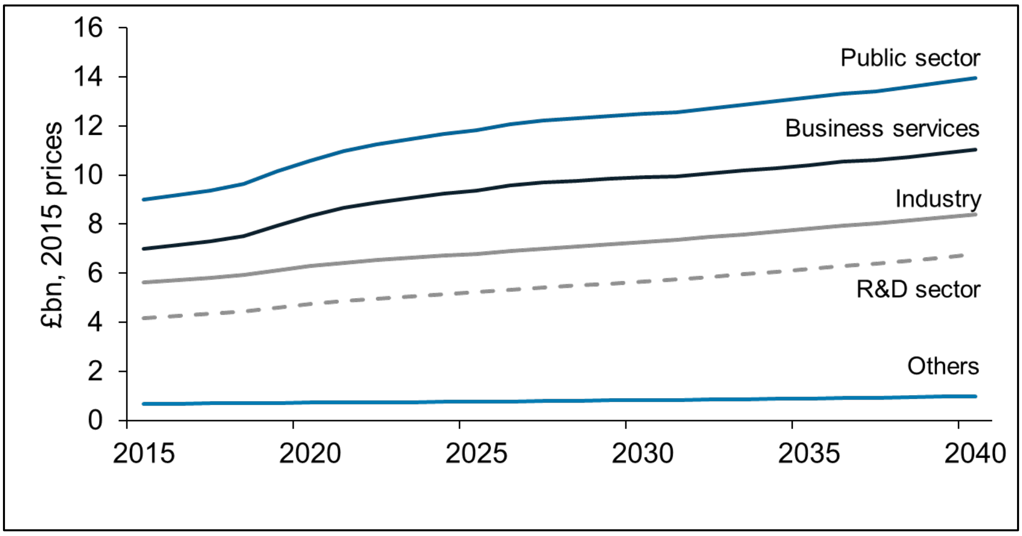
The reference case can be thought of as a ‘business as usual’ case, meaning that most policy inputs remain the same as in the last year of historical data. In general, no additional policy is added beyond that which is already in place.

Sectoral composition

While the macro values in the reference case are assumed to be consistent with the values provided by BEIS, the sectoral composition of future growth can have an important bearing on the results.

The sectoral growth rates in the reference case have been obtained by extrapolating historical growth and scaling the outcomes to be consistent with the macro indicators. R&D expenditure in the reference case follows a similar trend (see Figure 4).

Figure 4 R&D expenditure in the reference case



The largest share of R&D expenditure is attributed to the public sector, which includes expenditure by universities and other educational establishments. The rest is roughly split between business services, industry and the R&D sector itself.

Demographic assumptions

Population, split by gender and age group, is set to match the Eurostat projections. The UK's population continues to grow, reaching 71.3m by 2030 and 74.5m in 2040. Population is largely determined by non-economic factors and is therefore treated as exogenous in the E3ME model.

Labour supply is determined by multiplying working age population by participation rates; trends in participation rates are projected forwards and match the EU projections (which are also produced using the E3ME model).

Fiscal and monetary policy

Tax rates are held constant in line with the last year of data. The level of final government spending grows at 1.5% pa. Transfer payments (e.g. benefits) grow in line with wage inflation.

Interest rates are set to increase to 1% in 2019 and 2% thereafter. Exchange rates remain constant at around 2018 levels.

The sectoral composition of the economy

In some cases the European Commission projections provide long-term sectoral projections for production levels. If there is no information available then we extrapolate historical trends and then constrain them to be consistent with the aggregate GDP figures.

Employment projections are formed using E3ME's own equations and the sectoral rates of growth in production. These form the official EU forecast.

Growth in trade is projected to slow to similar rates as GDP growth. This pattern reflects the most recent trends in the data that show faster growth due to globalisation coming to an end.

Future trends in trade are particularly uncertain, with potential for more globalisation but also 3D printing, localisation and environmental concerns leading to reductions in trade.

R&D and innovation

The level of R&D matches the figures provided by BEIS (in relation to GDP), converted to absolute levels in real terms. A general trend in upskilling is assumed implicitly in the projections, which allows higher levels of R&D to take place (and continues existing trends). Although productivity increases in the baseline, it is largely at existing trend rates based on long-term time series and there are no shocks due to AI or other new technologies.

Rest of the world

GDP in the rest of the world is projected to grow at rates specified by the European Commission (EU countries) and OECD (other countries). No additional policies are added in the scenarios.

The scenarios

In addition to the reference case, ten main scenarios were assessed. They are described in turn below.

The 2.4% scenario

Our central scenario is one in which R&D expenditure increases in all sectors, such that total R&D expenditure reaches a target rate of 2.4% of GDP by 2027 and 3.0% of GDP by 2040. It is assumed that all sectors increase their expenditures proportionately so that the overall structure of R&D spending remains unchanged. This scenario could therefore be thought of as 'more of the same'.

It is assumed that the additional public R&D expenditure is funded by an increase in income tax rates. Additional private R&D expenditure is added to the costs of the businesses carrying out the R&D and may as a result lead to higher final product prices.

The 2.4% 'flat' scenario

In this scenario, R&D expenditure as a share of GDP also increases to 2.4% by 2027. Beyond 2027 the level of publicly funded R&D remains constant in real terms. Private R&D varies slightly due to lagged leverage effects but over time the ratio of R&D to GDP decreases, settling back at 2.4%. The aim of this scenario is to assess the potential long-run impacts of meeting the 2027 target for R&D expenditure, without further increases in expenditure.

High FDI scenario

This scenario is also based on the central 2.4% case. The same amount of R&D expenditure takes place and the sectoral split is also unchanged.

The assumptions about the funding for the R&D are different, however. In this scenario, it is assumed that 49% of the funding comes from abroad instead of 32% in the main 2.4% scenario. In other words, there is an increase in real investment (in R&D activities) from overseas. There is otherwise no change in the composition of the R&D expenditure.

Initially, this means that the costs for British businesses are lower but, in the longer term, there is a repatriation of profits outside the UK. The scenario thus depicts an alternative way of increasing UK R&D.

Changing the location of R&D expenditure

There are two scenarios that consider the different impacts of R&D expenditure in different parts of the UK. In the first scenario, R&D expenditure grows much faster within the ‘Golden Triangle’ for research activities in the South East of England[7], at 8.9% pa (4.2% in other parts of the country). In the second scenario it is assumed that R&D expenditure grows faster in other parts of the country, at 9.6% pa (4.8% in the Golden Triangle).

These scenarios are compared to both the reference case and the central 2.4% scenario in which the increase in R&D is apportioned in line with current shares.

As noted in the previous chapter, the E3ME model does not have a sub-national disaggregation and so proxies must be used to allow the scenarios to be modelled. The regional inputs are translated to sectors based on the shares of sectors in each region. This approach implicitly assumes that the direct returns on R&D are the same in each part of the country, aside from sectoral differences between geographical locations. Some caution should therefore be used when interpreting results.

When allocating the impacts to regions, it is assumed that the direct benefits of higher R&D expenditure accrue to the region in which it is carried out. However, the R&D spillover effects are assumed to be felt across the UK.

Allocating R&D to large and small sectors

Two further scenarios test the allocation of R&D across sectors based on their current relative R&D contributions. The first of these scenarios considers a case in which the additional R&D is fully concentrated in sectors that already contribute a large share of the UK’s total R&D expenditure. These are:

- Pharmaceuticals
- Electronics
- Motor vehicles
- Other transport equipment
- Computer services
- R&D
- Public administration and defence
- Education

These sectors are assumed to already have the infrastructure to carry out the R&D, even if they do not typically commercialise it themselves (e.g. R&D or Education).

[7] Defined as the South East, East and London regions used by the ONS.

In the small sectors scenario the situation is reversed. All the additional R&D is carried out in other sectors, with the share allocated in the same way as in the main 2.4% scenario.

The Tax Credit scenario

All the scenarios above assume that the R&D targets are met, without explicitly saying why. A public increase in R&D is expected to lead to higher R&D expenditure in the private sector as well.

In this scenario, an explicit measure, tax credits, is put in place to incentivise higher R&D expenditure in the private sector. The tax credits lead to an increase in R&D expenditure that is similar to that in the 2.4% scenario. The difference between this scenario and the 2.4% scenario is therefore the funding mechanism used; here, the private investment is incentivised financially by the public sector. As in the other scenarios, it is assumed that the government increases standard income tax rates to cover the costs of the scheme.

The Digitalisation scenario

The final two scenarios focus on the potential impacts of specific technologies. First, we consider digitalisation. The design of the scenario is based on the findings from two previous reports:

- ING (2017) - 3D printing: a threat to global trade
- McKinsey & Co (2017) - Digitization, AI, and the future of work: Imperatives for Europe

The inputs to the modelling are summarised in Table 2. The key assumptions are a reduction in trade, reduced transport demand and a boost to productivity in construction. This scenario does not include any impacts from AI, which are highly uncertain and would be expected to have much larger direct labour market impacts.

The Electric Vehicle scenario

The final scenario focuses on an electrification of light-duty vehicles in the UK. It builds on previous work by Cambridge Econometrics (2015). The key inputs to the E3ME model are a change in vehicle composition and prices (i.e. more batteries making vehicles more expensive) and changes to the fuel consumption by vehicles.

A fixed path of uptake of electric vehicles is assumed, based on previous discussion with industry experts. By 2040, more than one third of light-duty vehicles are fully decarbonised, and the remaining vehicles are hybrids (mostly plug-in hybrids).

Possible alternative scenarios not considered in this report

The scenarios in this report cover a range of ways to meet a 2.4% R&D target and consider some of the most important dimensions (e.g. sector or region) in meeting the target. There are many other possible scenarios, however.

For example, regulatory instruments could be used to boost private sector expenditure and there are other potential sources of financing for R&D expenditure, including retained profits, bank loans or other forms of taxation (for public R&D expenditure). There are also other specific technologies that will impact the UK economy in the coming decades, including AI/automation, nanotechnology and advanced biotechnology.

The final selection of scenarios is designed to reflect policy interest but also considers more practical aspects from a modelling perspective, including the degree of available data and range of uncertainty in model inputs.

Table 2 Inputs to the Digitalisation scenario

Feature	In E3ME	Sectors	Source
50% of manufacturing from 3D printing by 2060	Imported manufactured goods replaced with domestic production. We make gradual adjustments to imports, exports and domestic production accordingly.	Manufacturing	ING (2017) - 3D printing: a threat to global trade
Investments in 3D printers. $1.85 bn in Europe	Capital investment in affected industries, paid for by industry increasing unit costs. European investment value disaggregated to obtain UK value.	Manufacturing	ING (2017) - 3D printing: a threat to global trade
Services connected to trade in manufactured goods will decline	Decreased demand for transport services. Decrease proportion of value that is shifted to domestic proportion.	Transport	ING (2017) - 3D printing: a threat to global trade
Digitalisation of construction sector could increase sector productivity by 40%	Adding incremental productivity boosts in line with investment growth.	Construction	McKinsey & Co (2017) - Digitization, AI, and the future of work: Imperatives for Europe

Summary of scenarios

The full set of scenarios is summarised in Table 3.

Table 3 Summary of the scenarios

Short Name	Description
Ref	The reference case for the modelling
2.4%	A scenario in which R&D expenditure increases to 2.4% of GDP by 2027, and 3.0% of GDP by 2040
2.4%_flat	As the 2.4% scenario, but public R&D remains constant after 2027; private R&D increases slightly due to lagged leverage effects
2.4%_FDI	The 2.4% scenario with a high share of R&D costs met through FDI
2.4%_GT	The 2.4% scenario with a larger share of R&D taking place in the South East ‘Golden Triangle’
2.4%_nonGT	The 2.4% scenario with a larger share of R&D taking place outside the South East ‘Golden Triangle’
2.4%_BigS	The 2.4% scenario with a larger share of R&D taking place in sectors with a current large R&D share
2.4%_SmS	The 2.4% scenario with a larger share of R&D taking place in sectors with a current small R&D share
TaxCred	A scenario in which tax credits boost R&D expenditure
Digit	A scenario with a high level of digitalisation
ElecT	A scenario in which transport is electrified

4 Results

Introduction

This chapter presents the results from the model-based analysis. The next section discusses the central case in which the amount of R&D expenditure in the UK increases but there are not structural changes. The following sections present results from variants in which key aspects of the profile of R&D across different sectors, regions and firm size change. The final two sections present the impacts of specific technology scenarios.

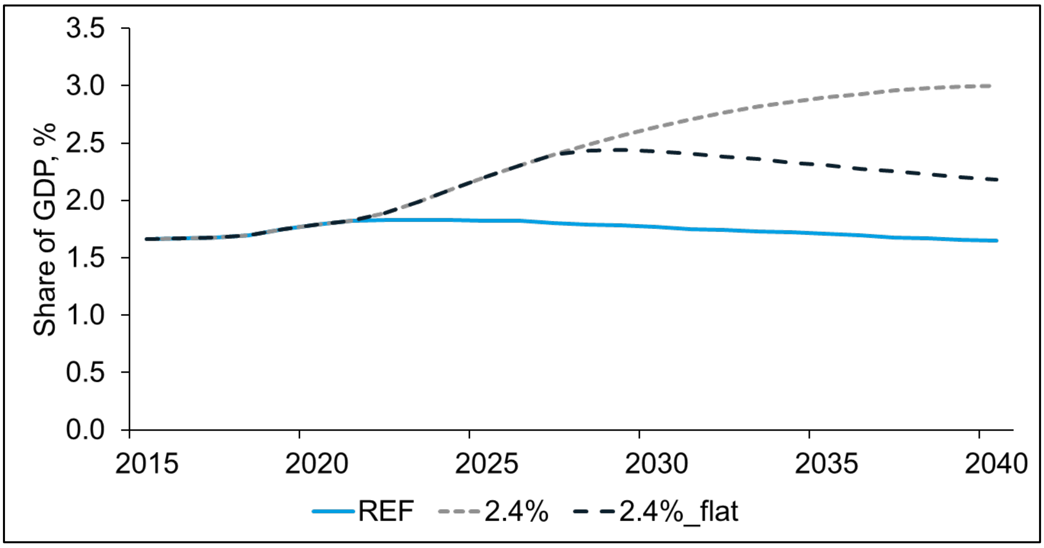
Impacts of meeting the 2.4% R&D target

R&D profiles

In this section we present the main results from the 2.4% scenario. The profile of R&D expenditure in relation to UK GDP is given in Figure 5. The figure also gives the R&D profile for the REF case and the 2.4%_flat scenario, which is described later in this section.

As noted in Chapter 3, the shares of R&D across sectors grow in line with the different rates of Gross Value Added[8] (GVA) expected for each sector. These shares are maintained in the scenarios, so that each scenario shows only the impacts of general increases in R&D, rather than changes in sectoral composition.

Figure 5 R&D as a share of GDP



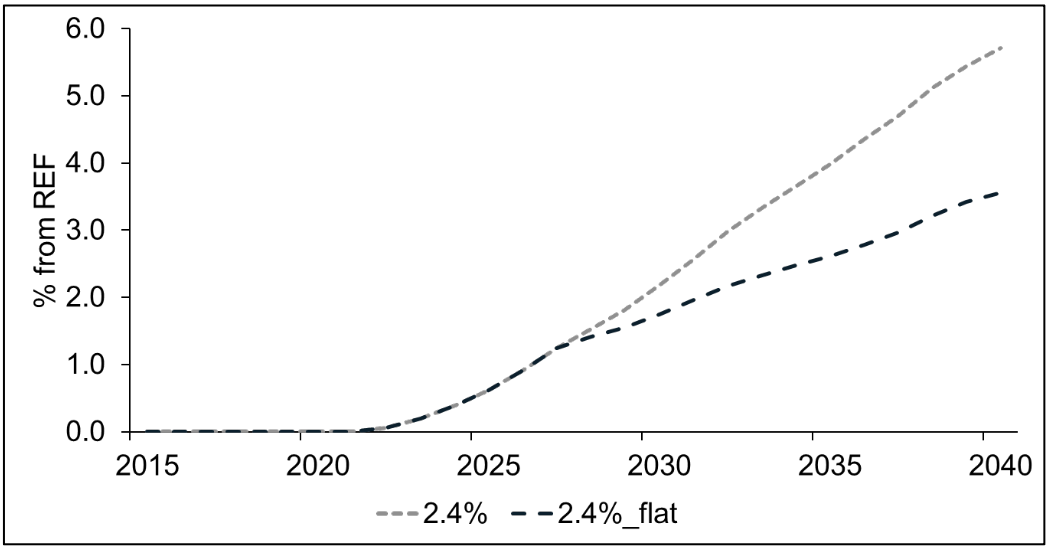
[8] Gross Value Added is a measure similar to GDP, but expressed at sectoral level.

GDP impacts

The GDP impacts are given in Figure 6. By 2027, GDP is expected to be 1.3% higher in both scenarios than it is in the reference case. This compares to an increase in R&D expenditure worth 0.6% of GDP.

Beyond 2027 there could be further increases in GDP due to lagged effects. Even if R&D expenditure remains at 2.4% of GDP, by 2040 the increase compared to reference case is 2.9%. If R&D expenditure expands further to 3.0% of GDP then the boost to GDP could be 5.7% by 2040. Because of lagged effects, it is difficult to do a basic cost-benefit estimate, but the ratio of higher GDP to R&D input costs in 2040 is 4.2.

Figure 6 GDP impacts in the 2.4% and 2.4%_flat scenarios



How do the boosts to GDP come about?

As described Chapter 2, higher rates of R&D expenditure boost both process and product innovation. Process innovation boosts the supply side of the economy, improving efficiency and the capacity to produce more goods and services. Product innovation leads to higher quality products that improve the (non-price) competitiveness of UK production.

Table 4 provides estimates of the splits between the different components of the GDP impacts. The categories are:

- Direct R&D effects, which come directly from the national accounting framework. R&D expenditure counts towards GDP and therefore higher R&D expenditure means higher GDP.
- Funding costs. Companies may increase prices to pay for higher R&D; the government must raise taxes to fund public R&D. Both would be expected to have a negative economic impact.
- The impacts of higher R&D expenditure on process innovation, expected to be positive.
- The impacts of higher R&D expenditure on product innovation, also expected to be positive.

- The impacts of R&D spillovers, again expected to be positive.

It is not always easy to separate the effects, and there are interactions between the different categories. The figures in the table thus represent a combination of additional off-model calculations and additional scenarios (e.g. removing spillover effects) to isolate certain impacts.

Table 4 Breakdown of GDP impacts in the 2.4% scenario

	2027	2040
Direct R&D effects	0.6	1.3
R&D funding costs	-0.3	-0.7
Process innovation effects	0.2	0.8
Product innovation effects	0.6	1.9
Spillovers	0.2	2.4
Total	1.3	5.7

Productivity effects

One of the expected impacts of higher rates of R&D expenditure is an improvement in productivity. The link between process innovation and productivity is clear, as more efficient production processes will lead to higher productivity. However, product innovation could also boost productivity (for example if product demand increases, leading to opportunities for scale economies).

Table 5 summarises the productivity impacts in the 2.4% scenario. In this report we consider three measures of productivity:

- GDP per capita is the average production of each person in the UK
- GDP per job is the average production of each person in work, and so accounts for changes in employment
- GDP per hour worked is the average production per working hour, and so accounts for changes in both employment levels and working hours[9]

The results for GDP per capita are the same as for GDP because we assume that the rate of population growth is the same in each scenario. However, there is some variation in the results for GDP per job and GDP per hour worked.

By 2027, most of the GDP impacts come through higher productivity and there is only a small change in employment because of the lagged effects that result from companies taking time to recruit and hire additional workers (see below). By 2040, productivity effects still dominate, but higher innovation also leads to higher employment levels. There is also a notable difference between GDP per job and GDP per hour worked, indicating that working hours have been

[9] The measure of jobs is a headcount figure, i.e. does not account for changes in working hours.

reduced in this scenario (by around 1%). Higher productivity thus allows the same amount of production with shorter working hours.

In summary, the long-run model results show that higher rates of R&D expenditure are expected to boost GDP, employment and productivity, leading to slightly lower average working hours.

Table 5 Productivity impacts in the 2.4% scenario, % from reference case

	2027	2040
GDP per capita	1.3	5.7
GDP per job	1.0	3.0
GDP per hour worked	1.1	4.0

Impacts on employment and other macro indicators

As noted above, higher R&D expenditure could lead to an increase in employment as well as higher productivity. Although the employment impacts are limited by 2027, by 2040 employment could be 2.7% higher than in the reference case (see Table 6). The way that changes in employment lag impacts on output is not unusual and reflects the time that companies needed to find and recruit new workers (especially in high-skilled positions). As there are also lagged effects in the output impacts (e.g. the time for prices to adjust and then demand to respond), it may take several years for the full employment effects to be felt.

We present results by sector below, but these results are conditional on the available workers having the necessary skills (and location, see later section) to take up the available positions.

Table 6 also provides a breakdown of the GDP results into component parts. It is clear from the table that much of the additional economic growth in the long run is driven by exports, due to:

- Product innovation effects – higher quality products, particularly manufactured goods, capturing global market share.
- Process innovation effects – more efficient production leading to lower prices and improved price competitiveness.

Imports also increase compared to the reference case but not by as much as exports. Most of the increase in imports is either through supply-chain effects (e.g. equipment components) or to meet some of the growing demand from households.

Total household expenditure (consumption) could be higher by 2.5% by 2040 in response to both higher employment levels and higher incomes driven by productivity improvements. The increase in investment is less than the increase in GDP; although higher R&D expenditure leads to higher investment in the model (i.e. due to new products becoming available), the econometric equations show that the linkages are quite weak overall. In addition, more efficient use of existing capital through process innovation dampens the need for new investment.

Consumer prices fall overall compared to the reference case, despite faster GDP growth. The reason for lower prices is the boost to capacity through process innovation (i.e. more productive firms are able to produce more), which puts downward pressure on prices. It should be noted that the results do not suggest deflation, but lower rates of inflation than in the reference case.

Table 6 Impacts in the 2.4% scenario, % from reference case

	2027	2040
Consumption	0.2	2.5
Investment	0.8	4.2
Exports	1.4	14.3
Imports	0.1	6.3
Employment	0.2	2.7
Consumer Prices	-0.4	-2.7

Table 7 Change in GVA in the 2.4% scenario, % from reference case

	2027	2040
1. Agriculture	0.4	10.6
2. Mining and energy sectors	0.5	3.5
3. Industries	3.1	18.3
4. Construction	0.6	3.2
5. Retail and trade	0.2	2.2
6. Transport and comms.	4.0	7.0
7. Hotels and catering	0.0	0.7
8. Business services excl R&D	0.8	4.6
9. Business R&D	18.0	44.9
10. Public services incl universities	1.7	4.5

Sectoral impacts

Table 7 summarises the impacts by broad sector[10]. Although the model shows positive impacts in all sectors, the magnitude of the impacts may differ considerably between sectors, especially by 2040.

The R&D sector itself stands out as a major beneficiary in the scenario, both in 2027 and in 2040. A large increase in overall R&D expenditure benefits the sector through supply chain effects. The education sector also benefits in the same way, although to a lesser extent because less business R&D is outsourced directly to universities.

The other sectors that benefit the most are those that operate in global markets and can gain a potential competitive advantage in the scenario. Principally this is manufacturing sectors. The model results suggest that by 2027 the impacts could be modest because it takes time for new products and markets to be developed; however, by 2040 the industrial sector could see an increase in GVA of 18.3% compared to the reference case.

The positive impacts in other sectors arise mainly from either supply-chain effects or from improvements to productivity that boost demand in the long run. Again, many of the positive effects only become apparent in the long run.

Location effects in the 2.4% scenario

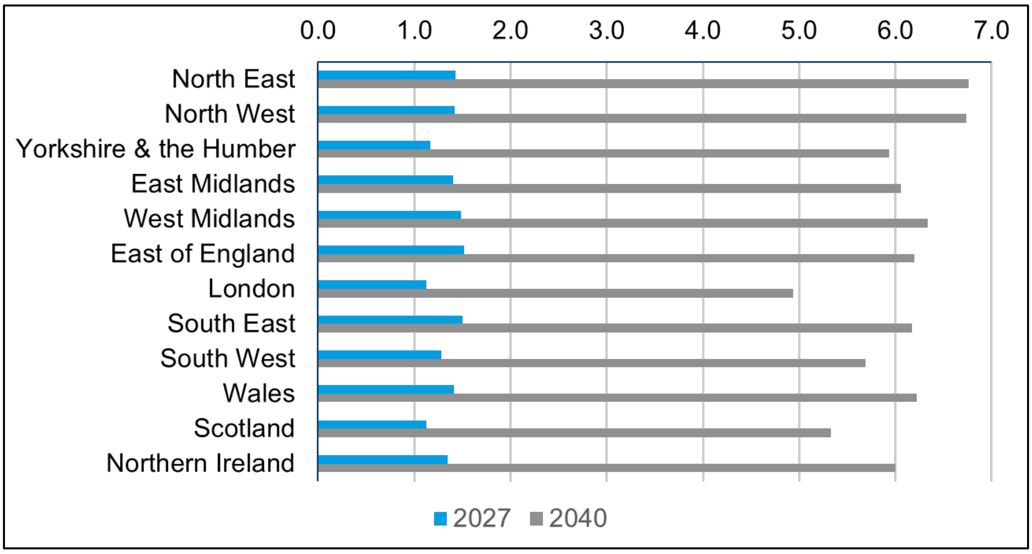
The E3ME model does not provide an explicit disaggregation at regional level, and so additional calculations are required to estimate regional impacts. We did this through an allocation of sectoral impacts according to the sectoral composition of production in each region.

Figure 7 presents the results for 2027 and 2040. According to the results of the calculation, all regions gain in the 2.4% scenario. The gains are relatively evenly spread across the country, with slightly larger benefits in the north and midlands. The reason for the differences between regions can be traced to the sectoral composition in each case; regions with a higher manufacturing share are typically those that show more positive results.

Scenarios in which the location of the R&D changes are assessed later in this section.

[10] The full list of sectors in the model is given in Appendix A.

Figure 7 GVA impacts across regions, 2027 and 2040, % from REF



Impacts of increasing FDI-funded R&D

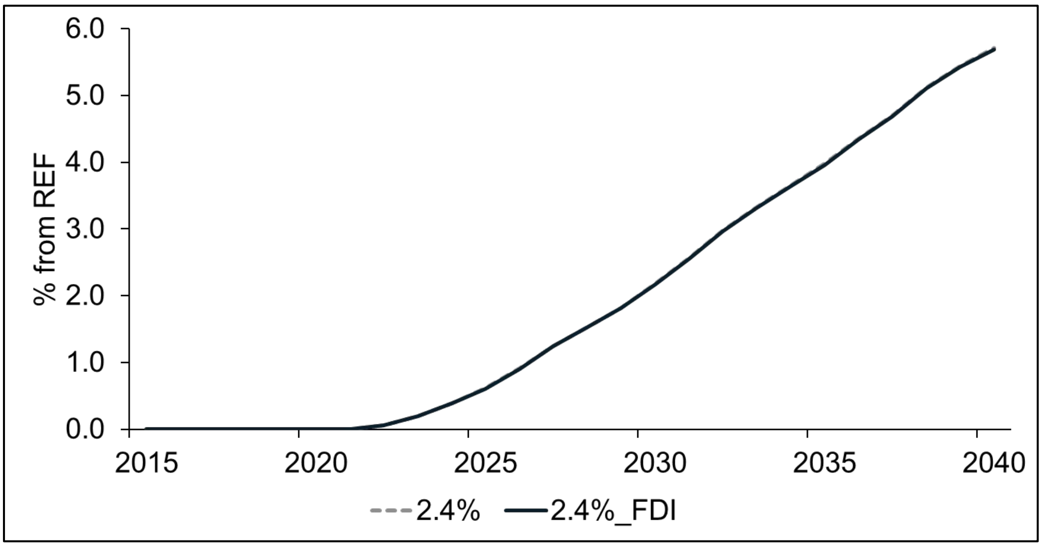
GDP impacts

Figure 8 shows the GDP impacts in the central 2.4% scenario and the 2.4%_FDI scenario. The only difference between these two scenarios is the funding source for the R&D.

In the modelling, it is assumed that FDI-funded R&D does not pose an initial cost to businesses (so does not impact on product prices) but, in the long run, a larger share of profits flows overseas. The figure suggests that these two effects roughly cancel out.

Overall, the scenario with high FDI has a slightly lower positive impact on GDP than the central 2.4% scenario; the difference is around 0.02% of GDP by 2040 and too small to see on the chart. The results suggest that it is much more important to ensure that the R&D is undertaken, regardless of source of funding.

Figure 8 GDP impacts with higher FDI-funded R&D



Impacts on other indicators and sectors

The pattern of results is the same for the other main macroeconomic indicators. Overall, there is very little difference between the 2.4%_FDI and 2.4% scenarios. Similarly, the pattern of sectoral impacts also does not vary by much between the two different scenarios.

Location effects

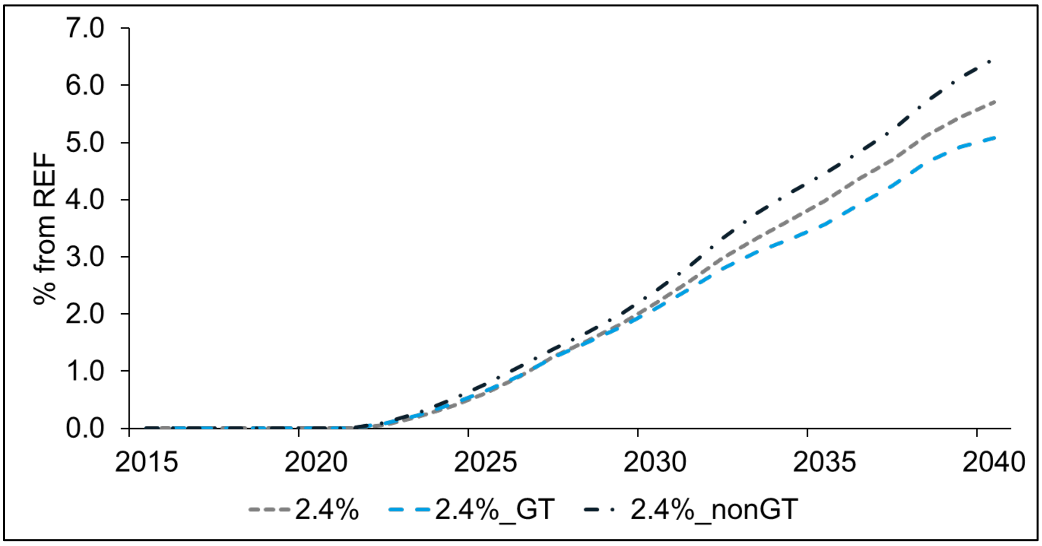
Regional results for the 2.4% scenario were presented earlier in this chapter. In this section we estimate the impacts from varying where the R&D takes place. Two of the scenarios consider location impacts:

- 2.4%_GT: a larger share of R&D takes place on the South East 'Golden Triangle'
- 2.4%_nonGT: a larger share of R&D takes place outside the South East 'Golden Triangle'

The exact quantitative definitions of the scenarios are provided in Chapter 3. It should be noted that the regional results are at least in part driven by sectoral shares; in particular, regions with a higher manufacturing share benefit more in the scenarios.

The results in Figure 9 suggest that there is a higher long-run GDP impact when the R&D is concentrated outside the South East. In 2040, the additional positive impact (compared to the main 2.4% scenario) is 0.8% of GDP. In 2027, however, the difference is only 0.1%.

Figure 9 GDP impacts in the location scenarios



Explaining the differences in GDP results

Discussion of location effects in R&D expenditure often focuses on the potential positive effects of clustering, and the potential negative effects of saturation and capacity crowding out within a region. These effects are both important but unfortunately go beyond the capability of the E3ME model, which does not include the UK regions explicitly.

Instead, in the same way as described previously, economic sectoral shares are used as a proxy for shifting R&D expenditure across the UK. The model results therefore show that the sectors with a greater concentration outside the South East tend to have larger impacts from additional R&D expenditure.

The reasons for this are broadly the same as those give at the start of this section. Outside the South East there is a larger manufacturing share in production. The manufacturing sectors are more trade-focused and operate in more global markets. Additional R&D could potentially give these sectors a competitive edge in a much larger marker, leading to larger gains in potential production.

These results should be considered in the context of the assumptions underpinning the modelling. The model does not say anything about potential limitations on the capacity of industry in each region to increase production, such as shortages of skilled staff. A more detailed analysis specific to each region would be required to confirm the findings in this report.

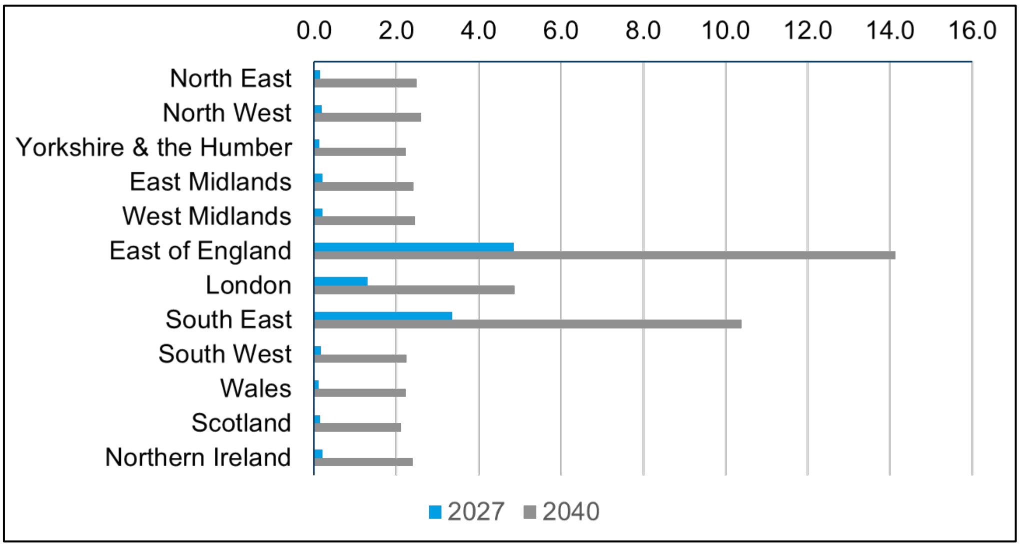
Regional impacts in the place scenarios

As a final step in assessing regional impacts, we consider how each region is affected in the scenarios where R&D expenditure varies by region. Again, it is necessary to make assumptions that go beyond the standard E3ME modelling approach. We assume that the direct benefits of higher R&D spending accrue to the region in which the expenditure takes place, but R&D spillover effects may occur anywhere in the UK.

Figure 10 shows the impacts on GVA in each region in the scenario in which additional R&D expenditure is concentrated in the East and South East of England. In 2027 almost all the benefits are realised in these regions. By 2040, there are potential large benefits (more than 10%) in the East of England and South East. GVA increases in London by around 5% and in most other regions by around 2% (almost all from spillover effects).

It is notable that, even when R&D is concentrated around London, the benefits in London are limited. This reflects the large share of finance and other service sectors in London’s economy, which are less responsive to increases in R&D expenditure.

Figure 10 Regional GVA impacts, 2.4%_GT scenario (% from REF)



The picture is reversed in the scenario in which R&D is concentrated outside the East and South East of England. In this scenario, GVA could be higher than in the reference case by 2-

3% by 2027, and by 8-12% by 2040 in the regions with higher R&D expenditure. Again, differences in results between these regions relate to sectoral shares in each region. As was shown in the previous chart, there are still modest benefits to regions in which the R&D is not concentrated, due mainly to spillover effects.

Figure 11 Regional GVA impacts, 2.4%_nonGT scenario (% from REF)

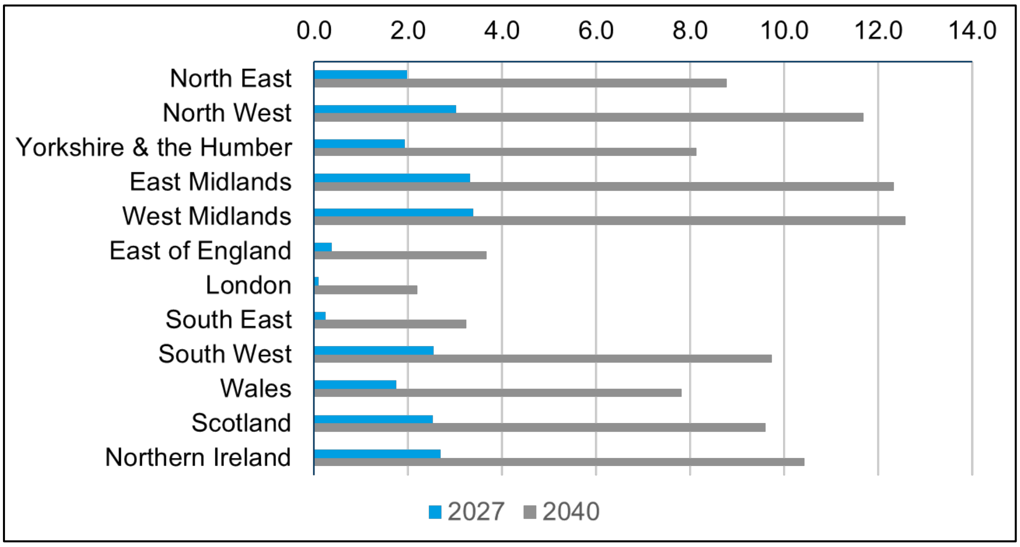
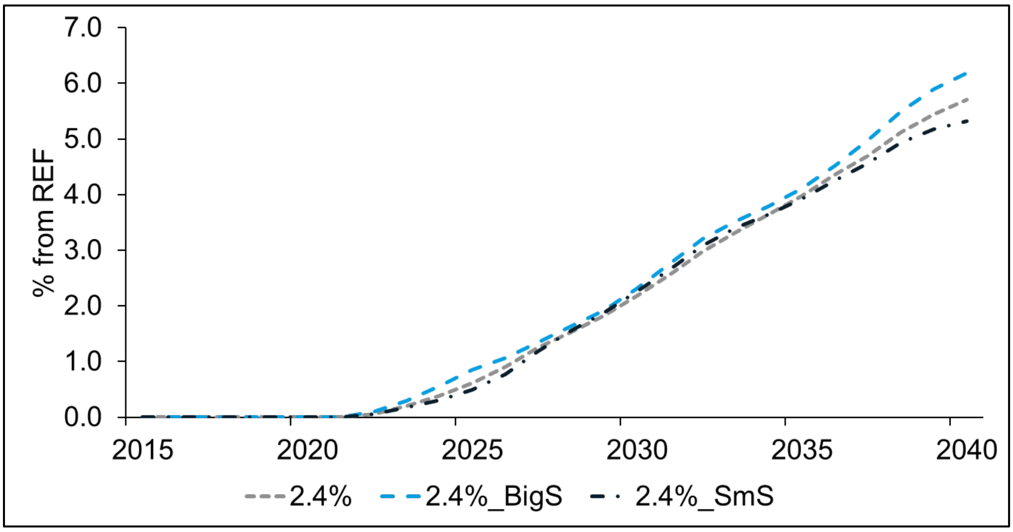


Figure 12 GDP impacts with different sectoral R&D concentrations



Focusing R&D in specific groups of sectors

We assessed two scenarios that consider different shares of R&D across sectors:

- 2.4%_BigS: a larger share of R&D takes place in sectors with a current large R&D share
- 2.4%_SmS: a larger share of R&D takes place in sectors with a current small R&D share

GDP impacts

Figure 12 shows the GDP impacts in the two different scenarios, with the central 2.4% scenario shown for reference. The figure shows that there is an initial benefit from targeting R&D at sectors that are already R&D-intensive. Although the differences become small over 2030-2035, there is a similar pattern in the long-run results.

Sectoral impacts

In general, we would expect to see greater impacts from sectors that already have high R&D shares; this would explain why they already carry out R&D activities. Overall, however, the effect appears small. There are several potential reasons why this might be the case, including the types of R&D that are carried out (and reported in statistics) and how R&D feeds into the production process in different sectors. Variations between spillover effects between sectors (i.e. how closely the sectors link together) will also cause differences in results.

Table 8 provides the impacts on GVA for selected sectors in the scenario in which R&D is targeted at sectors that already have large expenditures on R&D (compared to the central 2.4% scenario). These are typically the sectors that benefit overall, including pharmaceuticals, vehicles and electronics.

The sectors that could lose out in this scenario are ones in which R&D is important but reduced in volume compared to the 2.4% scenario. They include machinery and equipment and several basic manufacturing sectors, including (non-pharmaceutical) chemicals. The agricultural sectors also fall into this category.

It is notable that almost all the sectors mentioned in Table 8 are manufacturing sectors, again indicating how these sectors are more sensitive to changes in R&D expenditure levels.

If the R&D is instead allocated to sectors that currently do not have a large share of total R&D expenditure, the picture is largely reversed (Table 9). The sectors that benefit the most are those in agriculture and basic manufacturing.

It is interesting to note that these are sectors which typically operate in commoditised markets with low profit margins. These sectors usually do not have much available funding for R&D activities, but the model results suggest that they could benefit if they were able to differentiate their products through higher quality.

Table 8 Sectoral GVA impacts in the 2.4%_BigS scenario, % from 2.4% scenario

2027		2040	
Sector	**% diff**	**Sector**	**% diff**
Electronics	8.0	Pharmaceuticals	22.3
Other transport equipment	6.2	Other transport equipment	16.2
Motor vehicles	3.4	Motor vehicles	9.8
Computer services	2.4	Electronics	9.7
Pharmaceuticals	2.2	Computer services	4.7
R&D activities	1.8	Repair & installation	4.6
…		…	
Metal products	-1.2	Non-metallic minerals	-2.9
Machinery, equipment	-1.3	Machinery, equipment	-3.0
Basic metals	-2.0	Other chemicals	-11.3

Table 9 Sectoral GVA impacts in the 2.4%_SmS scenario, % from 2.4% scenario

2027		2040	
Sector	**% diff**	**Sector**	**% diff**
Other chemicals	3.2	Other chemicals	16.0
Basic metals	2.3	Machinery, equipment	3.8
Electrical equipment	2.2	Electrical equipment	3.8
Machinery, equipment	2.1	Crop production	3.5
Metal products	2.1	Fishing	3.3
R&D activities	1.8	Non-metallic minerals	2.7
…		…	
Motor vehicles	-3.7	Electronics	-12.0
Other transport equipment	-8.7	Other transport equipment	-15.8
Electronics	-9.0	Pharmaceuticals	-27.8

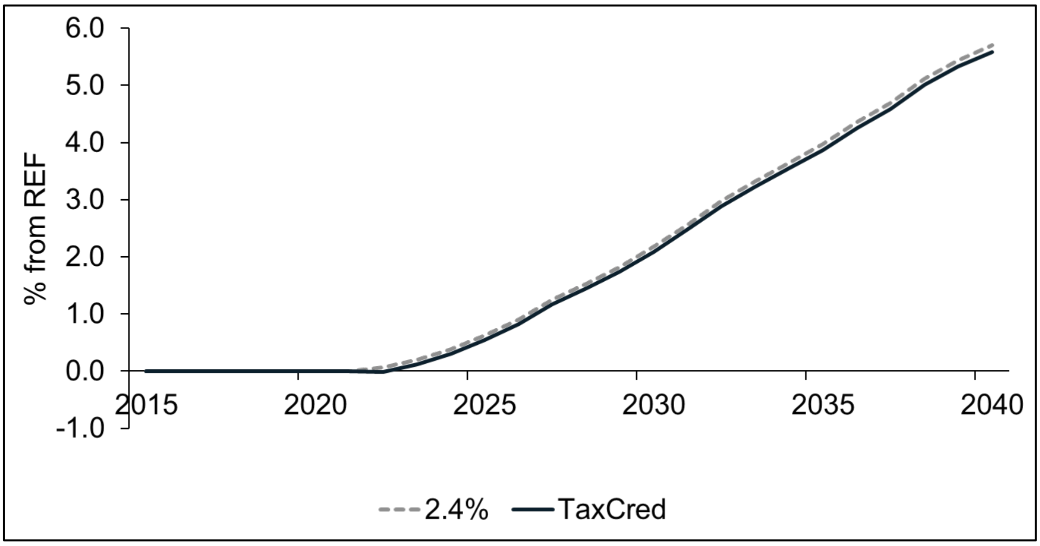
Using tax credits to boost R&D expenditure levels

The scenarios so far have not been explicit in how the extra R&D expenditure takes place. In general, there is an increase in public R&D expenditure which encourages further R&D in the private sector as well.

An alternative way to boost R&D expenditure in the private sector would be to offer direct financial incentives in the form of tax credits. The TaxCred scenario assesses this option.

The level and sectoral composition of the additional expenditure remains the same as in the main 2.4% scenario, with only a different method of financing. The scenario is therefore similar in some ways to the 2.4%_FDI scenario. As shown in Figure 13, again we see only a small deviation from the results in the main 2.4% scenario.

Figure 13 GDP impacts in the TaxCred scenario



The figure shows that the results in the TaxCred scenario come out close to the results in the main 2.4% scenario, with a difference of only 0.1% of GDP in favour of the 2.4% scenario.

It should be noted that the results are dependent on how the tax credits are financed (through higher income tax rates). Results are also sensitive to further assumptions about how additional R&D is allocated to sectors (i.e. a market mechanism like tax credits may be more efficient than allocation through the public sector) and how responsive R&D expenditure is to the tax credits.

Given the small difference in results to the main 2.4% scenario and the uncertainty surrounding these assumptions, it is difficult to draw overall conclusions from this scenario.

The digitalisation scenario

The final two scenarios focus on specific technologies. Here we consider what the impacts of those technologies might be, separate from any R&D activities in the wider economy.

The digitalisation scenario is described in Table 2 but can be summarised as a reduction in trade in manufactured goods because of 3-D printing, causing reductions in transport demand. There is also an increase in productivity in the construction sector. As this scenario focuses on the specific effects of digitalisation, there is no increase in R&D expenditure.

Macroeconomic impacts

The macro-level impacts in the scenario are presented in Table 10. There is a modest positive effect on the UK's GDP, which is largely driven by changes in trading patterns.

The results suggest that the UK could benefit from the impacts of digitalisation on trade. The UK is a net importer of manufactured goods, which could effectively be reshored through 3-D printing technologies. However, the UK's more service-focused exports are less susceptible to digitalisation. Hence we see a larger fall for imports than for exports.

The scenario also sees higher investment. Partly, this is the result of investment in 3-D printing systems, but improved efficiency in the construction sector also provides a boost to investment. As this investment leads to higher production in labour-intensive sectors, employment is also higher than in the reference case.

Table 10 Impacts in the digitalisation scenario, % from reference case

	2027	2040
GDP	0.5	2.0
Consumption	0.0	0.9
Investment	0.8	2.5
Exports	-2.7	-7.0
Imports	-3.8	-9.7
Employment	0.4	1.8
Consumer Prices	0.3	-0.2

Overall, this basic analysis suggests that the UK is less exposed to the potential negative effects of digitalisation. In the long run the technology could provide benefits to the economy in terms of higher production levels and jobs.

Sectoral impacts

The largest positive impacts are in sectors in which the UK is currently a large net-importer of goods (Table 11). For example, if 3-D printing allows for a more localised and efficient means of producing clothing and footwear, the UK textiles sector could increase in size (albeit from a small base). 'Other manufacturing', which includes furniture and toys, could see a similar outcome.

Table 11 Sectoral GVA impacts in the digitalisation, % from reference case

2027		2040	
Sector	**% diff**	**Sector**	**% diff**
Textiles & leather	41.3	Textiles & leather	16.0
Other manufacturing	12.2	Other manufacturing	3.8
Electronics	10.2	Electrical equipment	3.8
Electrical equipment	9.8	Electronics	3.5
Rubber & plastics	3.1	Rubber & plastic	3.3
Metal products	2.4	Metal products	2.7
…		…	
Coal	-0.2	Oil and Gas	-12.0
Other retail	-0.2	Coal	-15.8
Machinery, equipment	-1.4	Machinery, equipment	-27.8

The main sector that could lose out is the machinery and equipment sector, in which the UK has a more substantial export presence. The energy sectors also show a small decline in production, which is mainly due to reduced transport activity.

Electrification of transport

Another technology that could have far-reaching effects is the electrification of transport[11]. We model electrification as a shift from conventional to electric vehicles. In general, these vehicles have a higher up-front cost but lower running costs over their lifetimes.

Table 12 summarises the macroeconomic impacts in the scenario. Overall, there is a modest increase in GDP and employment.

A shift to more expensive vehicles has a negative impact on the demand for cars but the impact is assumed to be small because the share of cars produced in the UK remains unchanged (so UK factories receive higher revenues). The effect is outweighed by an investment stimulus, lower running costs in the long term and a reduction in fuel imports, which are replaced with domestic expenditure and therefore create a stimulus effect.

[11] Autonomous vehicles could have an even larger impact with diverse effects across many different sectors of the economy. Like other AI technologies, they are not considered in this study because of the high range of uncertainty.

Although there is a reduction in fuel imports, overall imports are slightly positive as a result of higher demands for other goods and services.

Table 12 Impacts in the transport electrification scenario, % from reference case

	2027	2040
GDP	0.3	0.5
Consumption	0.3	0.8
Investment	0.9	1.2
Exports	0.6	1.0
Imports	0.2	0.3
Employment	0.3	0.3
Consumer Prices	0.0	-0.3

The sectoral impacts are presented in Table 13. In this scenario we do not see a large reduction in UK oil production because the reduced demand for oil is met by a reduction in imports. As such it does not affect domestic oil sector which is expected to continue to meet remaining demand[12]. Lower vehicle sales do affect the motor vehicles sector, however. Sale of cars and Other wholesale activities (parts etc) suffer as a result.

In the short to medium term, the sectors that benefit are those associated with electric vehicle infrastructure investment and the manufacturing of electric vehicles. In the longer term, savings from lower running costs mean that consumers have higher disposable incomes to spend on other things. Sectors related to consumer expenditure (e.g. food) are therefore expected to benefit.

[12] In this scenario we considered only partial electrification in road transport and there are other uses of oil that remain unchanged.

Table 13 Sectoral GVA impacts in the electrification scenario, % from reference case

2027		2040	
Sector	**% diff**	**Sector**	**% diff**
Basic metals	5.0	Crop production	5.7
Metal products	2.8	Pharmaceuticals	4.1
Machinery, equipment	2.0	Food, drink & tobacco	3.4
Other personal services	1.9	Basic metals	3.3
Electronics	1.8	Other personal services	3.2
Rubber & plastics	1.6	Electronics	3.2
…		…	
Pharmaceuticals	-0.8	Other wholesale	-0.7
Sale of cars	-1.4	Sale of cars	-4.7
Motor vehicles	-6.2	Motor vehicles	-11.0

5 Key Findings

Key findings from this report

From the analysis we can draw out six key findings. They are summarised in Table 5.1, which also provides key references within the report. The remainder of this section discusses further each key finding.

Table 14 Key findings from this report

Key finding	Report location
Higher R&D expenditure will boost UK GDP, employment and productivity	Figure 6, Table 5 and Table 6
Spillover effects are important but are uncertain in magnitude	Table 4
Product and process innovation will both make important economic contributions	Table 4
The source of funding is less important in determining the economic outcomes	Figure 8 and Figure 13
Manufacturing sectors are likely to benefit more than services sectors	Table 7
Each new technology will have specific impacts on the economy	Table 10 to Table 13

Key Finding 1: Higher R&D expenditure will boost UK GDP, employment and productivity

This report covers eight scenarios in which the amount of R&D expenditure in the UK increases to 2.4% of GDP by 2027. All eight scenarios show an increase in GDP, employment and labour productivity when compared to the reference case, both in 2027 and in 2040 (Table 15).

These positive impacts result from both product and process innovation (see Key Finding 3), and both demand and supply-side impacts. The UK is able to produce more outputs using fewer inputs, but a higher overall demand for production means that employment increases as well.

The model results show that there may be quite strong lagged effects because it takes time for the additional R&D to translate into commercialised production. That is why the impacts are much larger in 2040 than in 2027, even for the 2.4%_flat scenario in which R&D expenditure does not increase after 2027.

The positive impacts are felt across almost all economic sectors, although are in general larger for manufacturing sectors (see Key Finding 5).

Table 15 GDP, employment and productivity impacts, % from reference case

	2027			2040		
	GDP	**Empl**	**Prod**	**GDP**	**Empl**	**Prod**
2.4%	1.3	0.2	1.0	5.7	2.7	3.0
2.4%_flat	1.3	0.2	1.0	2.9	0.9	2.0
2.4%_FDI	1.2	0.2	1.0	5.7	2.7	3.0
2.4%_GT	1.2	0.2	1.0	5.1	2.5	2.6
2.4%_nonGT	1.4	0.3	1.1	6.5	2.9	3.5
TaxCred	1.2	0.2	1.0	5.6	2.6	2.9
2.4%_BigS	1.3	0.4	1.0	6.2	3.2	2.9
2.4%_SmS	1.2	0.2	1.0	5.3	2.6	2.7

Key Finding 2: R&D spillover effects are important but the magnitude of these effects is uncertain

R&D spillover effects are defined as the benefits accruing to one firm from another firm's R&D expenditure. Spillover effects could arise for a number of reasons, including benefits from buying and using more efficient products or imitating design. Because the benefits from R&D do not fully accrue to the company carrying out the R&D, it is usually assumed that the level of R&D is below optimal levels (which economists refer to as a 'market failure').

The modelling in this report tested different ways of assessing spillover effects. The conclusion is that spillover effects are important; they account for 20-40% of the total increases in GDP in the main 2.4% scenario (Table 4). However, the magnitude and timing of the effects is uncertain and is difficult to capture with the available data.

The model results therefore represent a 'best estimate', in part based on previous work carried out within BEIS. If the spillover effects were zero, then then the positive GDP impacts in the 2.4% scenario would be 1.1% in 2027 and 3.4% in 2040. If they were double the size modelled, then the impacts would be 1.4% in 2027 and 8.1% in 2040.

Key Finding 3: Product and process innovation both make important contributions to GDP growth

As shown in Figure 1, the modelling approach includes pathways in which both product and process innovation can impact on the wider economy. Because of interactions between the different sectors and model variables, it is not possible to formally separate the two effects, but Table 4 provides a rough breakdown based on the different economic indicators.

The results show that product and process innovation could both play an important role in developing the UK economy through higher rates of innovation and R&D expenditure.

Both types of innovation have different short and long-term impacts, but the benefits of product innovation may be realised sooner. The reason is that it takes time for process innovation to impact on total production levels; first greater efficiency must be realised, then prices lowered and finally a demand response.

It is also important to note that the relative impacts of product and process innovation may vary considerably between sectors. Product innovation will be more important in sectors that can sell to a global audience (mainly manufacturing sectors). This result is an important component of Key Finding 5.

Key Finding 4: The funding source for the additional R&D is less important in determining economic outcomes

Table 15 shows the net impacts of higher R&D expenditure on GDP. The results for GDP include a positive contribution from the higher R&D expenditure itself (which counts towards GDP) but also a negative impact from the funding for the R&D.

For example, if the pharmaceuticals sector increases R&D expenditure, then there will be a boost to GDP through R&D but the costs of the R&D may be passed on in the form of higher prices for drugs, which would reduce GDP in real terms. In the modelling, higher public R&D is offset through higher tax rates.

The scenarios have tested three different funding mechanisms for the additional R&D. The main 2.4% scenario includes a mixture of public and private financing, the 2.4%_FDI scenario includes more foreign capital in-flows and the TaxCred scenario provides a public stimulus for private R&D.

However, the model results show almost the same outcomes in all three cases. At one decimal place, the results are identical in 2027 and only 0.1% different in 2040. The scenario with tax credits has a slightly worse outcome but the conclusion is that the priority is to ensure that the R&D takes place, regardless of financing approach.

Key Finding 5: Manufacturing sectors are likely to benefit more from additional R&D expenditure

According to the model results, two broad sectors stand out as gaining from higher R&D expenditure:

- industry
- the R&D sector

The R&D sector benefits if the demand for R&D services increases but makes up a relatively small share of total GDP.

The largest positive contribution comes from industry (Table 16). Within industry, the sectors that benefit the most are those that produce finished goods, meaning that they are able to differentiate their production from competitors’ (Table 17). A degree of differentiation allows these sectors to benefit from product innovation as well as process innovation.

These sectors also operate within global markets. This means that improvements to product quality may be used to capture a much larger potential market and the net benefits increase in size. In Chapter 4 we showed that focusing R&D on these sectors could yield the highest positive outcomes for GDP.

This result needs to be caveated with potential capacity constraints. Although there are some constraints accounted for in the model, an assessment of whether a sector could absorb a large amount of R&D and increase production this quickly would need to be carried out separately.

In addition, this finding should not be interpreted as saying there is no benefit from R&D in services sectors. The modelling results show benefits from R&D expenditure in services sectors as well. In the case of services, it is likely that a larger share of the benefits would accrue to households, for example from improved efficiency of processes and lower prices. In addition, it must be noted that services accounts for a much larger share of total GDP in the UK economy, and is also where the UK often has an existing technological advantage. An approach that increases R&D across the economy therefore seems most beneficial.

Table 16 GVA increase in industry, 2.4% scenario, % from reference case

	2027	2040
Industries	3.1	18.3
All sectors	1.3	5.8

Table 17 Largest sectoral GVA increases, 2.4% scenario, % from reference case

	2027	2040
Pharmaceuticals	2.0	46.8
Electronics	11.7	40.5
Electrical equipment	1.4	29.7
Other chemicals	1.4	28.7
Metal products	5.7	27.0
Other transport equipment	9.9	25.1

Key Finding 6: Each new technology will have specific impacts on the economy

The last key finding relates to the two technology-specific scenarios that were assessed. The results from these scenarios show some consistency with the broader R&D scenarios, but also illustrate why it is important to bear in mind the uncertainty linked to the overall modelling exercise.

For example, the 2.4% scenario shows that the UK could benefit from an improved trade balance if it carried out more R&D. However, the digitalisation scenario shows that trade volumes could fall because of 3-D printing. The electrification scenario also shows a unique potential benefit to the UK from reducing its imports of fossil fuels.

It is clear that each new technology that is developed will have its own impact, within the sector and potentially on other sectors as well. These impacts may differ from developments that we can see in the historical data. Thus, while the modelling shows the estimated impacts of an 'average' increase in R&D expenditure, the reality will likely be a complex mixture of different new technologies interacting with each other.

Overall conclusions

In conclusion, the analysis in this report finds that the UK would benefit from higher R&D expenditure, perhaps considerably so. All sectors could potentially gain, but the largest benefits are likely to arise from sectors that participate in global markets.

The scenarios have shown that the means with which the additional R&D is funded is only of secondary importance to the positive impact of the R&D itself, and so the challenge for policy makers is to ensure that the conditions for research to take place are met. The importance of public R&D should not be neglected.

Technological change continues at a rapid pace and the coming decades are likely to see substantial shifts in automation, digitalisation, health and environmental technologies. There will also be less-discussed changes in other sectors, and the world in 2040 could be quite different to what it is now.

The modelling in this report shows that the UK has the capacity to help to shape these future technologies by expanding its research activities. The outcome would be higher GDP, productivity and an increase in overall employment levels.

6 References

References for this report

Acemoglu, D (2009) ‘Introduction to Modern Economic Growth’, Princeton.

Arthur, W B (2010) ‘The Nature of Technology: What It Is and How It Evolves’, Penguin.

Beinhocker, E (2007) ‘The Origin of Wealth’, Random House Business.

Berden K G, J Francois, M Thelle, P Wymenga and S Tamminen (2009) ‘Non-Tariff Measures in EU-US Trade and Investment – An Economic Analysis (Annexes)’, see http://trade.ec.europa.eu/doclib/docs/2009/december/tradoc_145614.pdf

Cambridge Econometrics (2015) ‘Fuelling Britain’s Future’, see https://www.camecon.com/what/our-work/fuelling-britains-future/

Engle, R F and C W J Granger (1987) 'Cointegration and error correction: representation, estimation and testing', Econometrica, 55, pp 251-76.

Grubb, M (2004) ‘Technology Innovation and Climate Change Policy: an overview of issues and options’, Keio Economic Studies, Volume 41(2), pp 103-132.

Haldane, A G and A E Turrell (2018) ‘An interdisciplinary model for macroeconomics’, Oxford Review of Economic Policy, Volume 34, Issue 1-2, Spring-Summer 2018, pp 219–251.

Hendry, D F, Pagan, A and J D Sargan (1984) ‘Dynamic specification, in Handbook of Econometrics’, Vol II, Griliches, Z and M D Intriligator (eds), Amsterdam, North Holland.

Kaldor, N (1940) ‘A Model of the Trade Cycle’, The Economic Journal, Volume 50, Number 197, pp 78-92.

Lucas, R (1976) ‘Econometric Policy Evaluation: A Critique’, in Brunner, K and A Meltzer (eds.) ‘The Phillips Curve and Labor Markets’, Carnegie-Rochester Conference Series on Public Policy, Elsevier, New York.

Mazzucato, M (2019) ‘The Value of Everything: Making and Taking in the Global Economy’, Penguin, London, UK.

Mercure, J-F (2012) 'FTT:Power A global model of the power sector with induced technological change and natural resource depletion', Energy Policy, 48, pp 799–811.

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

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, Volume 18, Issue 2, pp 184-197.

Romer, P M (1994) ‘The Origins of Endogenous Growth’, The Journal of Economic Perspectives, Volume 8 (1): pp 3–22.

Schumpeter, J A (1934) ‘The theory of economic development - An inquiry into profits, capital, credit, interest and the business cycle’ (translated from original 1911 version), Harvard University Press.

Appendix A The E3ME Model

Introduction

E3ME is a dynamic, computer-based, global macroeconomic model which represents the three pillars of sustainability: economy, society and environment. E3ME's detailed sectoral disaggregation is important for assessing interactions between the pillars. The model is highly empirical in its approach.

E3ME was originally built in the 1990s through the EU's research framework programmes. Its structure has been developed from the UK MDM-E3 model, which has its roots in the work of the Cambridge Growth Project in the 1970s.

The model is now frequently used for policy analysis, in the UK, EU and globally. The types of policies assessed with the model include a range for different socio-economic and environmental measures. Recent developments to the model have been aimed to ensure it is fit for purpose to meet society's greatest 21st century challenges.

E3ME's basic structure and data

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, also including the components of GDP (consumption, investment, international trade), prices, energy demand and materials demand. Each equation set is disaggregated by country and by sector.

E3ME's historical database covers the period 1970-2016 and the model projects forward annually to 2050. The main data sources for European countries are Eurostat, supplemented by the OECD's STAN database and other sources where appropriate. For this study, data were adjusted to ensure consistency with ONS figures.

The main dimensions of the model

The main dimensions of E3ME are:

- 61 countries – all major world economies, the EU28 and candidate countries plus other countries' economies grouped
- 70 industry sectors, based on standard international classifications
- 43 categories of household expenditure
- Annual solutions to the year 2050 (2040 used in this report)

The sectors covered by the model are listed at the end of this appendix.

The national accounting framework

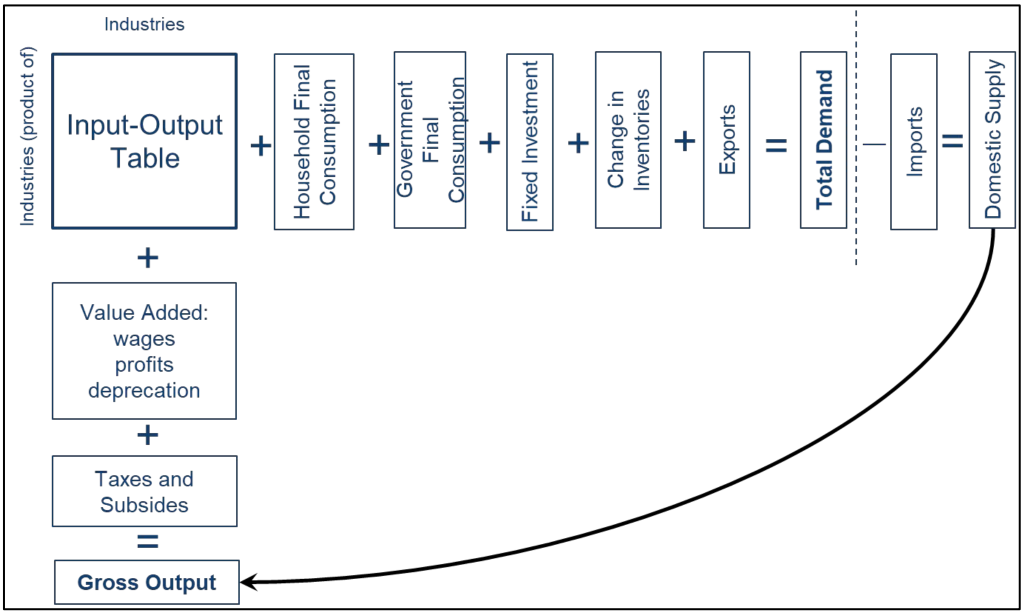
E3ME follows a standard accounting framework, as defined by the international System of National Accounts (SNA). Figure 14 presents the basic structure.

The model is demand-driven, meaning that the level of production is determined by the level of aggregate demand in the economy. Aggregate demand is in turn determined by the sum of intermediate demand and the components of final demand. The figure shows a feedback loop that is similar to a multiplier analysis.

Intermediate demands are determined by input-output relationships, while final demands are determined by the econometric equations (except for government expenditure, which is treated as exogenous). Each econometric equation includes a combination of price and quantity-based relationships (for example, consumption is determined both by incomes and product prices).

There are also measures of capacity in the model. Most notably, there are limits on employment imposed by the available working age population, and wage rates increase as the economy moves towards full employment. In each economic sector, there are also implicit capacity constraints that are estimated through econometric equations. These capacity constraints may be eased through technological progress from R&D.

Figure 14 National accounting structure



The econometric specification

The behavioural parameters in E3ME are estimate using econometric techniques. The form of the equations are the concepts of cointegration and error-correction methodology, particularly as promoted by Engle and Granger (1987) and Hendry et al (1984).

In brief, the process involves two stages. The first stage is a levels relationship, whereby an attempt is made to identify the existence of a cointegrating relationship between the chosen variables, selected on the basis of economic theory and a priori reasoning.

If a cointegrating relationship exists then the second stage regression is known as the error-correction representation, and involves a dynamic, first-difference, regression of all the variables from the first stage, along with lags of the dependent variable, lagged differences of the exogenous variables, and the error-correction term (the lagged residual from the first stage regression). Due to limitations of data size, however, only one lag of each variable is included in the second stage.

Stationarity tests on the residual from the levels equation are performed to check whether a cointegrating set is obtained. Due to the size of the model, the equations are estimated individually rather than through a cointegrating VAR. For both regressions, the estimation technique used is instrumental variables, principally because of the simultaneous nature of many of the relationships, e.g. wage, employment and price determination.

Comparison to the CGE approach

E3ME is often compared to other macroeconomic models. The Computable General Equilibrium (CGE) model has become the standard tool for long-term macroeconomic analysis. The use of these models is widespread all over the world. 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 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.

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 two types of model come from distinct economic backgrounds; while they are in general consistent in their accounting, identity balances, they differ substantially in their treatment of behavioural relationships.

Ultimately this comes down to assumptions about assumptions of perfect knowledge and optimal behaviour. The CGE model favours fixing behaviour in line with economic theory, for example by assuming that individuals act rationally in their own self-interest and that prices adjust to market clearing rates; in this way aggregate demand automatically adjusts to meet potential supply and output levels are determined by available capacity. However, agents in the model need to have perfect knowledge to be able to optimise behaviour in this way.

In contrast, econometric models like E3ME assume that there are gaps in knowledge and agents are faced with fundamental uncertainty. E3ME interrogates historical data sets 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 any constraints), but at a level that is likely to be below maximum capacity.

This has important practical implications for scenario analysis. While the assumptions of optimisation in CGE models mean that all resources are fully utilised, it is not possible to increase output and employment by adding regulation. However, E3ME allows for the possibility of unused capital and labour resources that may be utilised under the right policy conditions; it is therefore possible (although certainly not guaranteed) that additional regulation could lead to increases in investment, output and employment.

Many of the assumptions that underpin CGE (and DSGE) models have been increasingly questioned as to whether they provide an adequate representation of complex real-world behaviour. Examples include perfect competition, perfect knowledge and foresight, and optimal rational behaviour and expectations. Some CGE models have been adapted to relax certain assumptions but the underlying philosophy has not changed.

The main drawback of the E3ME approach in comparison is its reliance on having high-quality time-series data. There is at present no equivalent to the GTAP database for time series, so a large amount of resources must be put into compiling suitable data sets.

Model classifications

Table 18 Main dimensions of the E3ME model

	Regions	Industries	Consumption categories
1	Belgium	Crops, animals, etc	Food
2	Denmark	Forestry & logging	Drink
3	Germany	Fishing	Tobacco
4	Greece	Coal	Clothing and footwear
5	Spain	Oil and Gas	Actual rent
6	France	Other mining	Imputed rentals
7	Ireland	Food, drink & tobacco	Maintenance and repair
8	Italy	Textiles & leather	Water and misc. services
9	Luxembourg	Wood & wood prods	Electricity
10	Netherlands	Paper & paper prods	Gas
11	Austria	Printing & reproduction	Liquid Fuels
12	Portugal	Coke & ref petroleum	Other Fuels
13	Finland	Other chemicals	Furniture and flooring
14	Sweden	Pharmaceuticals	Household textiles
15	UK	Rubber & plastic products	Household appliances
16	Czech Rep.	Non-metallic mineral prods	Glassware tableware
17	Estonia	Basic metals	Tools and equipment
18	Cyprus	Fabricated metal prods	Household maintenance
19	Latvia	Computers etc	Medical products
20	Lithuania	Electrical equipment	Medical Services
21	Hungary	Other machinery/equipment	Purchase of vehicles
22	Malta	Motor vehicles	Petrol etc.

	Regions	Industries	Consumption categories
23	Poland	Other transport equip	Rail Transport
24	Slovenia	Furniture; other manufacture	Air Transport
25	Slovakia	Machinery repair/installation	Other Transport
26	Bulgaria	Electricity	Postal services
27	Romania	Gas, steam & air cond.	Photographic equipment
28	Norway	Water, treatment & supply	Other recreational durables
29	Switzerland	Sewerage & waste	Other recreational items
30	Iceland	Construction	Recreational/cultural services
31	Croatia	Wholesale & retail MV	News, books, stationery
32	Turkey	Wholesale excl MV	Package holidays
33	Macedonia	Retail excl MV	Education (pre & prim)
34	USA	Land transport, pipelines	Catering services
35	Japan	Water transport	Accommodation
36	Canada	Air transport	Personal care
37	Australia	Warehousing	Other personal effects
38	New Zealand	Postal & courier activities	Social protection
39	Russian Fed.	Accommodation & food serv	Insurance
40	Rest of Annex I	Publishing activities	Other financial services
41	China	Motion pic, video, television	Other services
42	India	Telecommunications	CVM Residuals
43	Mexico	Computer programming etc.	Unallocated
44	Brazil	Financial services	
45	Argentina	Insurance	
46	Colombia	Aux to financial services	
47	Rest Latin Am.	Real estate	
48	Korea	Imputed rents	
49	Taiwan	Legal, account, consult	
50	Indonesia	Architectural & engineering	
51	Rest of ASEAN	R&D	

	Regions	Industries	Consumption categories
52	Rest of OPEC	Advertising	
53	Rest of world	Other professional	
54	Ukraine	Rental & leasing	
55	Saudi Arabia	Employment activities	
56	Nigeria	Travel agency	
57	South Africa	Security & investigation, etc	
58	Rest of Africa	Public admin & defence	
59	Africa OPEC	Education	
60	Malaysia	Human health activities	
61	Kazakhstan	Residential care	
62		Creative, arts, recreational	
63		Sports activities	
64		Membership orgs	
65		Repair comp. & pers. goods	
66		Other personal serv.	
67		Hholds as employers	
68		Extraterritorial orgs	
69		Unallocated/Dwellings	
70		Hydrogen production	

Conversion to the broad sectors reported in Chapter 4

The table below provides the aggregation used in this report.

Broad sector	Detailed industries above
1. Agriculture	1-3
2. Mining and energy sectors	4-6, 12, 26-29
3. Industries	7-25, excl 12
4. Construction	30
5. Retail and trade	31-33
6. Transport and comms.	34-38
7. Hotels and catering	39
8. Business services excl R&D	40-57, excl 51
9. Business R&D	51
10. Public services incl universities	52-69

This publication is available from: www.gov.uk/government/publications/research-and-development-macroeconomic-modelling-of-24-target