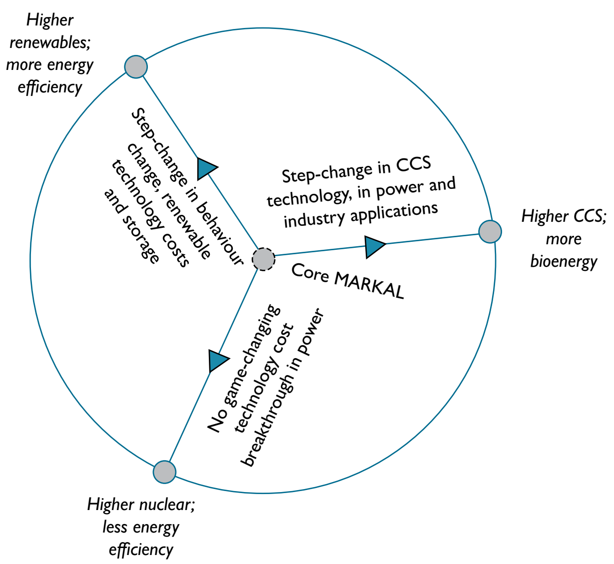
Annex A: 2050 analytical annex

A1 This annex provides further detail on the 2050 futures and their implications, in particular for costs. The analysis in this annex refers to impacts in 2050 and does not look at the trajectory for getting there. For details of the implications of climate and energy policy during the 2010s and 2020s, please refer to Annex B.

2050 futures

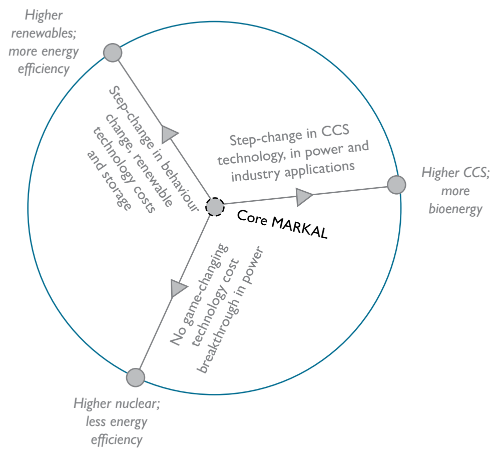


A2 To illustrate a typical cost-optimising model run,[1] we have described a **core MARKAL** (MARKet ALlocation) pathway, one of the runs produced as part of the analysis that the Government used to set the level of the fourth carbon budget target. This run provides a benchmark against which the **three 2050 futures**, referenced in Part 1 and constructed using the 2050 Calculator, can be compared. It should be noted that some environmental impacts, such as noise, landscape and biodiversity, are not quantified here. These are discussed further at Annex B.

A3 To develop 2050 futures, the Government has used the MARKAL and ESME (Energy System Modelling Environment) cost-optimising models in order to understand what levels of ambition in the deployment of technologies may be plausible in 40 years' time. There are many thousands of plausible pathway combinations which could be constructed using the Calculator, and the electricity generation mixes, levels of electrification and levels of demand reduction chosen in these futures should not be seen as the only likely or available combinations. The three futures are consistent with the Government's stated ambitions on specific technologies up to 2020, but do not assume any specific policy measures thereafter.

1 Cost-optimising models are explained in more detail later in this annex.

Core MARKAL



Energy saving per capita: 50%
Electricity demand: 470 TWh

A4 The core MARKAL run was created using the UK MARKAL model. Further information on the assumptions and modelling structure supporting the core MARKAL (described as run 'DECC-1A') can be found at: www.decc.gov.uk/assets/decc/11/cutting-emissions/carbon-budgets/2290-pathways-to-2050-key-results.pdf

A5 These outputs were produced with a number of underlying assumptions imposed on the model. The results below should be interpreted in the light of these assumptions.

- The UK MARKAL model covers CO_2 emissions from energy use and does not model non-CO_2 greenhouse gases (GHGs), land use, land use change and forestry (LULUCF) and international aviation and shipping sectors. As a consequence, the 80% 2050 target covering all GHGs on the net UK carbon account was translated to a 'MARKAL equivalent' of a 90% reduction for the core MARKAL run.[2]
- The core MARKAL run included the impact of the draft Carbon Plan[3] commitments to 2020 on the basis that policy and initiatives are already in place to achieve them. For key technologies and policies this representation is explicit; actual penetrations of specific technologies and targets were included. For other policies the representation is indirect, and a UK-wide CO_2 emissions constraint in 2020 was imposed to mimic the assumed impact.
- The core MARKAL run was based on **central estimates of fossil fuel prices and central estimates of service demands.**[4]

What is the sectoral picture in 2050?

A6 Electricity generation capacity is split between carbon capture and storage (CCS) (29 gigawatts (GW)), nuclear (33 GW) and renewables (45 GW). Wind power is installed earlier as part of the Carbon Plan commitments, with 28 GW in place by 2020. In terms of energy supplied, nuclear and CCS together deliver the majority (74%). Unabated gas plays a significant back-up role in 2050 to balance the system, but largely fades out as a baseload technology from 2030 onwards. Electricity imports and small-scale combined heat and power (CHP) also contribute. CCS with power generation is an important technology from 2020 onwards, generating more than a third of all electricity. The MARKAL run uses this technology to achieve negative emissions rates for electricity by sequestering the CO_2 associated with the biomass share (25% of fuel input to these generators in 2050 is biomass).

A7 In buildings, a reduction in space and water heating demand is accompanied by a large reduction in final energy consumption. Natural gas disappears from heating almost entirely, while electricity consumption increases significantly. Heat pumps, which draw heat from the surrounding environment with the help of some electricity, serve a larger proportion of heating service demand than any other technology.

A8 The chemicals, iron and steel, and non-ferrous metals sectors all exhibit the maximum allowable demand reductions of 25% from the central estimate of service demand, driven by

[2] The core MARKAL run was constrained both to mimic the achievement of the UK's 80% target in 2050 and to ensure a plausible trajectory for getting there.
[3] HM Government and DECC (2011) *Carbon Plan*.
[4] These two central conditions are also applied to the MARKAL runs used to cost the three 2050 futures which follow.

MARKAL's demand-response assumptions. This central estimate does not reflect the Updated Energy and Emissions Projections that the Government has used in this report, and posits a higher baseline level of demand. The MARKAL model suggests that some industries might scale back operations significantly. Industry also benefits from the ability to adopt CCS in the MARKAL model. By 2050, 48 million tonnes carbon dioxide equivalent ($MtCO_2e$) a year is sequestered from industrial processes.

A9 Of all the end-use sectors, transport shows the lowest demand response in the core MARKAL run, with approximately 5% reductions for most service demand categories. The mix of end-use technologies is extremely varied in 2050 when compared with today. Battery electric, biomass-to-liquids and hydrogen fuelled vehicles are all used. However, conventionally fuelled vehicles are not expected to be significantly used by 2050 under this optimised pathway.

A10 As the MARKAL model does not account for non-CO_2 emissions, much of agriculture's GHG impact is not explicitly accounted for (other than as part of the overall 90% decarbonisation constraint). LULUCF emissions and removals are also not considered. If domestic forestry were to make a significant contribution to bioenergy feedstock supplies, carbon sequestration associated with land use change would deliver additional abatement. The core MARKAL run demands 350 terawatt hours (TWh) of bioenergy a year by 2050.

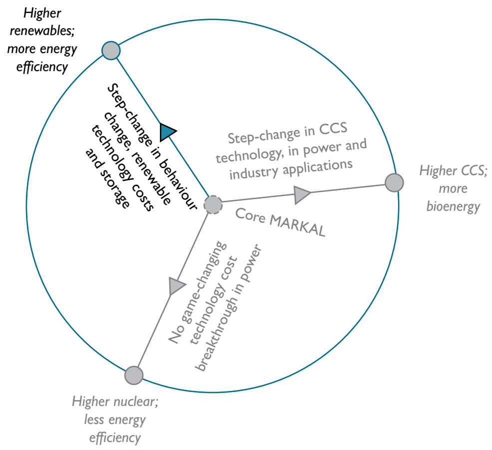
What does this scenario imply for security of supply and wider impacts?

A11 A balanced generation mix with a relatively high deployment of intermittent renewable generation technologies such as wind and marine power means that the back-up requirements of this run are significant. An additional 33 GW of gas plant is needed to meet the system balancing requirements imposed by the model.

A12 Per capita energy demand falls by 50% compared with 2007, while total electricity demand increases by almost a quarter from 2007 levels.

A13 In order to meet the demands of CCS and system back-up generation, natural gas remains an important part of the fuel mix in 2050, with 264 TWh of imports. Oil plays a much smaller role than it does today, with the UK importing roughly a sixth of what was brought into the country in 2000, despite declining natural reserves.

'Higher renewables; more energy efficiency'



Energy saving per capita: 54%

Electricity demand: 530 TWh

A14 **The 'Higher renewables; more energy efficiency' future was created using the 2050 Calculator.** This scenario is presented in the web tool of the Calculator which can be found at: http://2050-calculator-tool.decc.gov.uk

A15 The **'Higher renewables; more energy efficiency' future** is based on a step-change in per capita energy demand reductions and a major reduction in the cost of renewable generation. This is accompanied by innovations to develop a large expansion in electricity storage capacity to manage the challenges of intermittent generation.

What is the sectoral picture in 2050?

A16 'Higher renewables; more energy efficiency' chooses a generation mix with a relatively high installation of renewable generation capacity compared with the other two futures, with wind delivering 55% of the total electricity supply. Other renewable technologies, such as solar PV, marine and hydroelectric power, also play a role. To meet baseload needs and ensure security of supply, there is still a requirement for baseload capacity from nuclear and CCS. Some 20 GW of pumped storage provides 400 GWh of extra storage capacity, compared with 9 GWh today.

A17 Some 7.7 million solid walls and 8.8 million cavity walls are insulated by 2050. In buildings, behaviour change and smarter heating controls result in lower average home temperatures (one and a half degrees below today) complementing more energy efficient homes. All domestic heating demand across the UK is met through house-level electrified heating systems.

A18 Industry grows steadily and achieves energy demand reductions of a third. Some 48% of remaining emissions are captured by CCS.

A19 All cars and buses are fuelled by batteries or hydrogen fuel cells. These technologies create improved energy efficiency, allowing people to drive as far as today while using less energy than they do today. There is an increase in the use of public transport, walking and cycling; 63% of the distance travelled domestically is made by cars in 2050, compared with 83% in 2007.

A20 Thanks to high levels of demand reduction, extensive electrification of both heating and transport, and the deployment of CCS in industrial applications, sustainable bioenergy has a relatively small role in comparison with the other scenarios, delivering 182 TWh of final energy demand.

What does this scenario imply for security of supply and wider impacts?

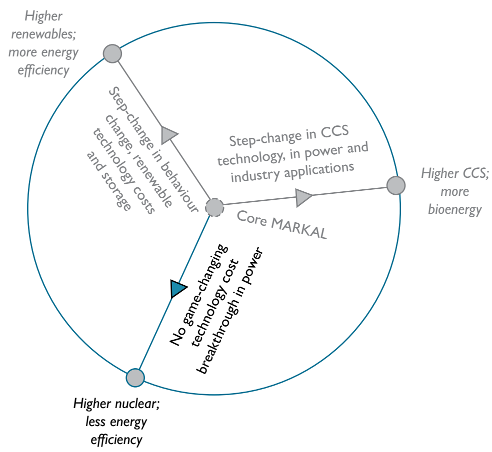
A21 A generation mix with a high proportion of intermittent generation means that there is a pressing need to balance the system to cope with adverse weather conditions, such as a drop in North Sea wind. Twenty-four GW of back-up gas plant is required to meet a five-day wind lull and demand peak across the UK as well as innovation success and cost reductions in electricity storage.

A22 Because of efforts made to improve energy efficiency across the economy, the increase in electricity demand is not the highest of the three scenarios despite having the highest proportion of energy demand being met by electric low carbon technologies. However, electricity demand is still over a third higher than in 2007.

A23 Apart from its electricity back-up role, gas plays a much smaller role than it does today, as the UK becomes more energy independent. Net natural gas imports are almost zero in 2050 with total domestic consumption at 100 TWh a year.

A24 Bioenergy is harvested from approximately 25,000 km^2 of land area in the UK and other countries. Local air quality is likely to be better in this pathway than it is today. In particular, the damage to human health arising from air pollution, principally particulate matter, could be around 60%–85% lower in 2050 compared with 2010.

'Higher nuclear; less energy efficiency'



Energy saving per capita: 31%
Electricity demand: 610 TWh

A25 **The 'Higher nuclear; less energy efficiency' future was created using the 2050 Calculator.** This scenario is presented in the web tool of the Calculator which can be found at: http://2050-calculator-tool.decc.gov.uk

A26 The **'Higher nuclear; less energy efficiency' future** describes what we might do if it proved difficult to deploy newer technologies (such as CCS technology in power and industry). The extent to which individuals change their behaviour and energy consumption patterns to reduce energy demand is lower in this future.

What is the sectoral picture in 2050?

A27 'Higher nuclear; less energy efficiency' relies heavily on nuclear power (75 GW of installed capacity) with the lowest deployment of CCS, wind and other renewable generation in 2050 across the three futures. Although deployment is relatively low, there is still 20 GW of wind capacity present on the grid, as the UK's natural advantages and previous investments in earlier years mean that some installations will remain cost effective.

A28 Some 5.6 million solid walls and 6.9 million cavity walls are insulated by 2050. Average internal temperatures by 2050 are half a degree higher than they are today. Domestic and commercial heating is largely decarbonised through a combination of air- and ground-source heat pumps, while 10% of demand is met through local-level district heating.

A29 CCS is not successful at a commercial scale and, alongside steady growth, this means that industry is responsible for a large proportion of remaining emissions, making up more than half of the total by 2050.

A30 Around 80% of cars are ultra-low emission vehicles (ULEVs), powered by batteries or hydrogen fuel cells. People travel 6% further than today, but there is a gradual movement away from using cars towards more efficient public transport. Some 80% of distance travelled domestically is made by cars in 2050, 3% lower than in 2007.

A31 As it is not possible for CCS to generate 'negative emissions' in this scenario, sustainable bioenergy is extremely important for decarbonising 'hard to reach' sectors like industry. Bioenergy supply is 461 TWh of final energy demand, with industry the second highest demand sector after transport.

What does this scenario imply for security of supply and wider impacts?

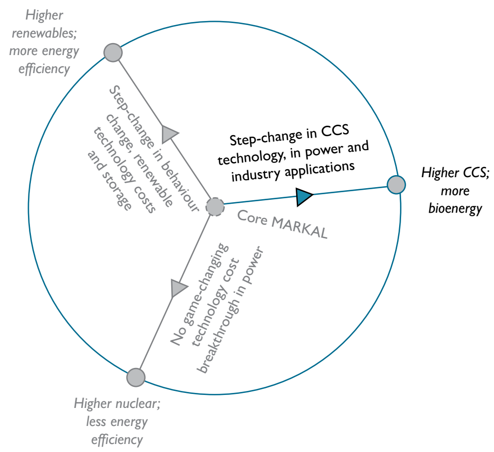
A32 Nuclear power's role means less back-up is required to balance the system. An additional 14 GW of gas plant is required to meet a five-day wind lull and demand peak across the UK.

A33 Per capita energy demand reductions are the smallest of the three futures. Because of electrification technologies being widely deployed for heating and transport, the demand for electricity is the highest, increasing by more than 50% compared with 2007.

A34 Natural gas imports fall by 2050 as the lack of CCS removes the most important long-term low carbon role for the fuel. The UK imports less than a quarter of the amount of gas bought in 2010, with total domestic use of 189 TWh in 2050.

A35 Local air quality is likely to be better in this pathway than it is today. In particular, the damage to human health arising from air pollution, principally particulate matter, could be around 45%–80% lower in 2050 compared with 2010. The land use impact is considerable – bioenergy is harvested from approximately 45,000 km^2 of land area in the UK and other countries.

'Higher CCS; more bioenergy'



Energy saving per capita: 43%
Electricity demand: 490 TWh

A36 **The 'Higher CCS; more bioenergy' future was created using the 2050 Calculator.** This scenario is presented in the web tool of the Calculator which can be found at: http://2050-calculator-tool.decc.gov.uk

A37 The **'Higher CCS; more bioenergy' future** assumes the successful deployment of CCS technology on a commercial scale and its use in power generation and industry, supported by significant gas use. CCS is also used with sustainable and plentiful biomass supplies (BECCS) to generate 'negative' emissions.

What is the sectoral picture in 2050?

A38 Electricity generation is provided by a balanced mix of cost competitive renewables (36 GW of capacity), CCS (40 GW of capacity) and nuclear power (20 GW of capacity). Biomass-fired CCS technology plays a major role, and helps to bring about negative net emissions from the power sector by 2050.

A39 People embrace new technologies and smart controls in their homes, as well as insulation measures: 5.6 million solid walls and 6.9 million cavity walls are insulated, and domestic and commercial heating is almost entirely decarbonised. Half of domestic heat demand is met by house-level electric heat pumps, with the other half generated using network-level systems such as district heating and CHP.

A40 Industry grows steadily and achieves energy demand reductions of one third. Some 48% of remaining emissions are captured by CCS. Geosequestration has an appreciable impact, taking one million tonnes of CO_2 out of the atmosphere every year by 2050.

A41 Some 65% of cars and all buses are run using ultra-low emission fuel sources. People still travel 6% more than they do today, but there is a substantial shift towards cycling and using public transport more often. Some 74% of distance travelled domestically is still made by cars.

A42 Sustainable bioenergy use in this future is highest of the three futures, delivering 471 TWh of final energy demand. Much of the supply is directed towards power generation in order to meet demand from CCS stations and help create 'headroom' for the continued use of fossil fuels.

What does this scenario imply for security of supply and wider impacts?

A43 A balanced generation mix and a much lower reliance on electrified demand-side technologies mean that the back-up requirements of this scenario are the lowest of the three futures. No additional gas plant is required to meet a five-day wind lull and demand peak across the UK in 2050.

A44 Per capita energy demand falls by 43% compared with 2007, while total electricity demand increases by 29% from 2007 levels. This is the lowest of the three scenarios, as a consequence of a widespread roll-out in non-electric low carbon technologies in heating and transport.

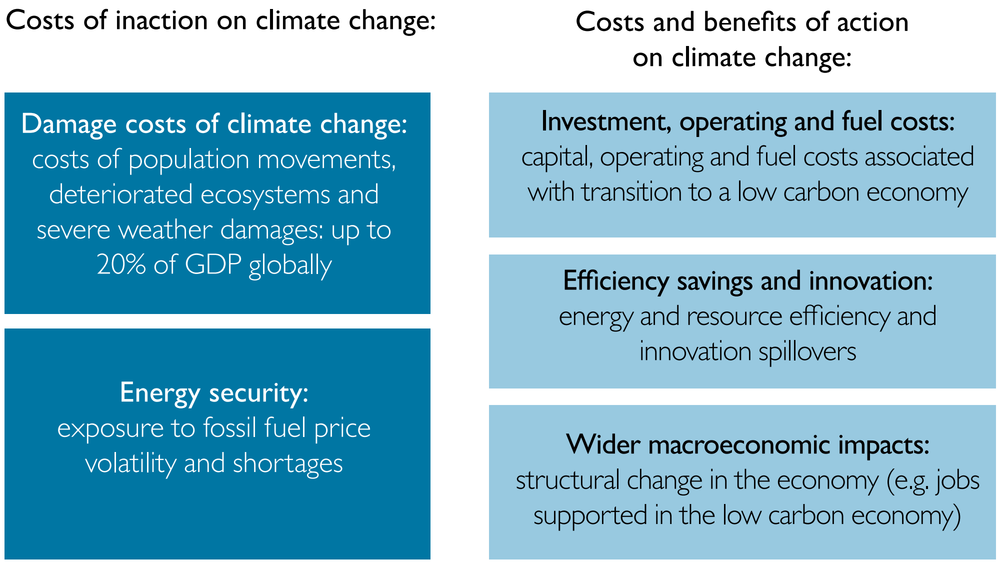
A45 In order to meet the demands of gas-fired CCS, natural gas imports play a bigger role in this scenario, with 215 TWh of imports being the largest of the three scenarios, though still approximately half of what the UK imported in 2010.

A46 Approximately 51,000 km^2 of land area in the UK and other countries is used to grow bioenergy. Heavy use of bioenergy could have a negative impact on local air quality. In particular, the damage to human health arising from air pollution, principally particulate matter, could be between 80% lower to 60% higher in 2050 compared with 2010. Given the scope for adverse implications for air quality, if the UK were to adopt this pathway, the Government would develop a policy framework that ensured that improved pollution abatement technology was fully deployed so that the health impacts of air pollution could be minimised.

Understanding the costs of 2050 futures

A47 The Stern Review *Report on the Economics of Climate Change*[5] concluded that tackling climate change is a rational and prudent macroeconomic strategy, with the benefits of strong, early action on climate change far outweighing the long-term costs of not acting. Figure A1 summarises the costs of action versus inaction on climate change.

Figure A1: Costs of action versus inaction on climate change



A48 History shows us that it is extremely difficult to forecast future costs with any degree of accuracy. To understand the costs of the 2050 futures we have used a range of models: MARKAL, ESME and the new 2050 Calculator, which includes costs data. The history and methodology of each of these models are set out below.

[5] Stern, N (2006) *Report on the Economics of Climate Change*. HM Treasury.

Box A1: MARKAL fact box	
History	MARKAL (MARKet ALlocation model) is an internationally peer-reviewed model that has been used in many countries over the last 30 years to model national energy system change over the long and medium term. UK MARKAL has been used extensively by the UK Government and the Committee on Climate Change (CCC) to estimate the costs of meeting the 80% GHG emissions reduction target in 2050. MARKAL results have been recently published in: • AEA (2011) *Pathways to 2050 – Key Results. MARKAL Model Review and Scenarios for DECC's 4th Carbon Budget Evidence Base. Final report*;[6] • Usher, W and Strachan, N (2010) *UK MARKAL Modelling – Examining Decarbonisation Pathways in the 2020s on the Way to Meeting the 2050 Emissions Target. Final Report for the Committee on Climate Change*. University College London;[7] • Department of Energy and Climate Change (2009) *Climate Change Act 2008 Impact Assessment*.[8]
Methodology	MARKAL is a **cost-optimising** model. Targets and assumptions are set in MARKAL (as described in the scenarios that the Government is exploring) to define an end point in 2050; the model then works backwards to construct a pathway to it in the least expensive (optimal) way. The model can be constrained in various ways to show optimal pathways under different conditions. Constraints can encompass variables ranging from technological choices to specific policies. MARKAL is also able to test these pathways against a range of factors that affect **energy security**. MARKAL calculates the **capital, operating expenditure and fuel costs** of the energy system. It can also calculate **welfare** costs (such as the loss of comfort associated with having a colder home or not being able to travel as far). Coverage of the model is limited to **fossil fuel** combustion and industrial processes; it does not cover international aviation and shipping, non-CO_2 greenhouse gases (GHGs) and land use, land use change and forestry (LULUCF). Data in the model takes the form of **point estimates** for technology costs rather than ranges. Learning curves are included and connected to prices, allowing **technology costs to be partially endogenous**, i.e. they are determined partly by learning due to factors within the model, and partly due to factors which are pre-set. MARKAL is a sophisticated model containing over 500,000 data elements. Even so, the model necessarily makes a number of important simplifying assumptions. **Perfect foresight** is assumed, as if knowledge of future technologies and prices were fully available. **Forward-looking and rational consumers** are assumed to apply this foresight in the context of **perfectly competitive markets**, meaning that price distortions do not raise costs.

6 www.decc.gov.uk/assets/decc/11/cutting-emissions/carbon-budgets/2290-pathways-to-2050-key-results.pdf

7 http://downloads.theccc.org.uk.s3.amazonaws.com/4th%20Budget/CCC%20MARKAL%20Final%20Report%20-%20UCL%20Nov10.pdf

8 www.decc.gov.uk/assets/decc/85_20090310164124_e_@@_climatechangeactia.pdf

Box A1: MARKAL fact box *(continued)*	
Methodology *(continued)*	MARKAL has a number of variants which cover gaps in its central analysis. For example, stochastic MARKAL introduces uncertainty, and in MARKAL Macro the model includes the interaction with UK economic growth to model the wider **macroeconomic** effects. For this exercise we have used the MARKAL Elastic Demand model, with model database version 3.26. This is the same version that was used in analysis supporting the *Impact Assessment of Fourth Carbon Budget Level* published in May 2011.[9]

Box A2: ESME fact box	
History	ESME (Energy System Modelling Environment) was developed by the Energy Technologies Institute (ETI) using technology assumptions supplied by businesses and industry. Completed in late 2010 and already used by the Department of Energy and Climate Change, the CCC and the ETI's industrial members, the key findings are due to be published in early 2012. The model aims to identify those technologies likely to be most important for an affordable, secure and sustainable energy system that meets the 2050 GHG Emissions Reduction Target of 80%.
Methodology	Like MARKAL, ESME back-casts and optimises to find least-cost solutions to meet energy targets. It **optimises technology costs** in the form of investment, operating, fuel and resource costs. It focuses on the **engineering system design for 2050**, characterising optimal outcomes at the energy system, sector and individual technology levels. It does not model specific government policies, and **learning rates are exogenously set**. Similarly, **demand for energy services is prescribed by input scenarios and is not responsive to prices**. Also like MARKAL, ESME includes the **capital, operating** and **fuel costs** of the energy system to 2050. Unlike MARKAL, ESME does not compute welfare costs. The ESME model has a wider coverage than MARKAL. In addition to sources of fossil fuel emissions, it also includes **international aviation and shipping** and a valuation for **housing stock**. But like MARKAL it does not include non-CO_2 GHGs or LULUCF. The model represents uncertainty of technology costs and other key assumptions by probability distributions. Perfect foresight is assumed in each run, with the costs being drawn from these probability distributions. A particular feature of ESME is the ability to define demands and resources at a UK regional level and show the **geographical location** of energy infrastructure solutions.

[9] www.decc.gov.uk/assets/decc/what%20we%20do/a%20low%20carbon%20uk/carbon%20budgets/1685-ia-fourth-carbon-budget-level.pdf

Box A3: 2050 Calculator fact box	
History	The new 2050 Calculator is **released alongside this report** as a **Call for Evidence**. Comments on the cost estimates and assumptions used are requested by **8 March 2012**. The new 2050 Calculator builds on the original **2050 Calculator** first released in **July 2010**. This tool enabled the public to join in an informed debate on the future of the UK's energy system, and to support policymakers in making the best choices for the long-term. The 2050 Calculator is an engineering model based on physical and technical potential which allows users to consider the implications of the pathway for energy security, land use, electricity demand and other wider impacts. Following a Call for Evidence, the Government decided to add costs to the 2050 Calculator to allow users to also compare pathways on this basis. The Government has been working to develop the analysis needed to update the Calculator, consulting with experts in industry and academia to develop the strongest evidence base available.
Methodology	The 2050 Calculator includes costs for **all activities associated with GHG emissions**. This includes fossil fuel combustion, international aviation and shipping, industrial processes, agriculture, waste and LULUCF.[10] Therefore, the coverage of the 2050 Calculator is wider than that of MARKAL and ESME. There are over 100 technologies in the 2050 Calculator and **capital**, **operating expenditure** and **fuel costs** are included for each of these to 2050. Unlike MARKAL, the 2050 Calculator excludes welfare costs. The 2050 Calculator shows the lower, higher and default point estimates for each technology and fuel in 2050. Since there is considerable uncertainty about costs in 40 years' time, the Calculator uses cost ranges that are intended to be sufficiently wide as to capture the views of all credible experts. In particular: • The **lower cost** estimate for 2050 is the most optimistic assessment of future technology costs published by a credible evidence source. It assumes both technological progress to drive costs down over time and sufficient availability of skilled staff and materials to build and operate the technology. • The **upper cost** estimate for 2050 is the most pessimistic view, assuming minimal technological progress[11] over the next 40 years. In practice this usually means assuming that technology costs remain frozen at today's prices.

[10] The 2050 Calculator includes all emissions which count towards the UK's 2050 target. The only exception is international aviation and shipping: the Government has yet to decide whether this will contribute towards the UK's 2050 target. However, for illustrative purposes this sector has been included in the Calculator in the meantime. The 2050 Calculator does not include embedded emissions because these do not count towards the UK's 2050 target.

[11] This assumes incremental improvements in energy efficiency only.

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<tr><th colspan="2">Box A3: 2050 Calculator fact box (continued)</th></tr>
<tr><td>Methodology
(continued)</td><td>

- The **default point estimate** is a point within the high–low range consistent with the latest cost assumptions from MARKAL.[12] The default fossil fuel price is the Department of Energy and Climate Change central fossil fuel price assumption and the default finance cost is 7% for all technologies.

The cost estimates in the 2050 Calculator are drawn from a **wide range of credible, published sources**. These include economic and energy models (MARKAL and ESME), sectoral analysis,[13] UK government departments, independent analytical bodies such as the Committee on Climate Change and, wherever possible, the real-world cost of technologies as reported by financial bodies or the media. The 2050 Calculator includes no new evidence about costs; it simply brings together existing published assumptions.

Critically, unlike MARKAL and ESME, the 2050 Calculator has no inbuilt **cost-optimisation** function; all choices are left up to the user.

Functionality

The 2050 Calculator is designed to be **easy to use**. Users can quickly design their own pathway (or select examples) and see a clear description of the cost implications. The user can compare the cost of their pathway with those from **experts** including Friends of the Earth, the ETI, Atkins, the Campaign to Protect Rural England and the National Grid. The user can see how costs are broken down **by sector and within sector**, and can choose to override the default cost assumptions and test the sensivity of the total cost of their pathway to alternative assumptions.

The 2050 Calculator is particularly well suited to answering questions such as:

- What is the cost of pathway X relative to pathway Y?
- What are the biggest component costs of pathway X?
- How could the cost of pathway X change if, say, nuclear costs are high and the cost of, say, renewables are as low as credible experts believe is possible?

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[12] MARKAL cost assumptions have been used for approximately half the technologies in the 2050 Calculator where the mapping between both models is fairly straightforward. This includes power sector technologies, road transport, heat insulation, bioenergy and hydrogen production costs. For those sectors where it is more problematic to map from MARKAL to the 2050 Calculator (aviation, shipping, heat and industry) and for sectors which MARKAL does not cover (agriculture and waste), we have used a 35th centile assumption. Finance costs are set at 7% default. Fossil fuel prices for 2050 will default to the DECC central projection for 2030 ($130/barrel).

[13] Including Parsons Brinckerhoff; Mott MacDonald; AEA; and NERA.

Box A3: 2050 Calculator fact box *(continued)*	
Methodology *(continued)*	**Caveats** There are a number of important caveats to bear in mind when interpreting results from the 2050 Calculator. **Does not represent an impact on energy bills.** Results from the 2050 Calculator are presented as £/person/year, but this should not be interpreted as the effect on energy bills. The impact on energy bills of, say, building more wind turbines will depend on how the policy is designed and implemented (e.g. via tax, subsidy, regulation, etc). Taxes and subsidies are not captured in the 2050 Calculator so we cannot use the tool to examine these effects. The Government uses other, more sophisticated models to examine the effect of specific policy interventions on electricity and energy prices. **Pathway costs should be understood relative to other pathways.** The total cost of pathways is presented in the 2050 Calculator but for these to be meaningful they should be compared with the costs of another pathway. This is because there is no 'zero cost' option (unless the UK were to stop using energy altogether). Not tackling climate change and remaining fossil fuel dependent would still entail an energy system and it would still have a cost. **The costs presented exclude energy security impacts, costs arising from the damaging impacts of climate change, welfare costs and wider macroeconomic impacts.** The damage costs of climate change could be particularly significant – up to 20% of GDP. Other welfare costs excluded from the analysis include costs associated with living in cooler buildings, travelling less, changes to landscape, and air and noise pollution. The 2050 Calculator does not take into account taxes or subsidies, R&D costs, administrative costs associated with delivering policies, or wider macroeconomic costs. **Long-term, not short-term analysis.** The 2050 Calculator is best suited to long-term analysis of the energy system in 2050 rather than policy implications over the 2010s and 2020s. **User-driven model, not market based.** The 2050 Calculator costs the combination of technologies chosen by the user. Consequently it does not take into account price interactions between supply and demand. For example, if the cost of electricity generation increases then the Calculator does not capture any elasticity of demand response from the electricity user. The cost optimising model MARKAL better handles such price responses. **Costs are exogenous.** Technology costs do not vary depending on the level of technology roll-out. However, if the user has beliefs about how they would expect the costs of particular technologies to change in their pathway, they can test the effect of varying these assumptions.

Costs of 2050 futures

A49 We have used MARKAL and ESME to calculate the **aggregate** costs of these 2050 futures. As the two models operate in slightly different ways, we have used different methodologies for mapping the futures created using the 2050 Calculator into the more complex cost-optimising models.

A50 For **MARKAL**, we used the same baseline assumptions as those described in the core MARKAL run. The key elements of each future are characterised in terms of imposed constraints on the model. For example, **'Higher renewables; more energy efficiency'** assumes large-scale deployment of wind power. In order to model this outcome, we introduced constraints to force a minimum or maximum amount of wind (both offshore and onshore), nuclear, CCS, solar and marine technologies onto the system to broadly match the capacity levels set in the 2050 futures. We imposed investment or capacity constraints on the technologies. As back-up gas plant is built to provide reserve capacity in the MARKAL model subject to the contributions of intermittent technologies, the model endogenously determines its capacity.

A51 On the demand side, we have adopted the revised estimates of the energy efficiency savings that can be achieved in the residential sector, taken from the analysis carried out for the Fourth Carbon Budget Impact Assessment.[14] We introduced constraints to replicate the figures used in the Calculator for uptake of heating technologies and ultra-low emission vehicles.

A52 For **ESME**, we took a different approach. Using version 1.2 of the ETI ESME assumption database, we made the minimum set of changes to reflect the spirit of the 2050 futures. Where possible, we changed the cost of different technologies to see how that influenced deployment rather than fixing deployment levels. Differences in behaviour change across the three scenarios were not modelled.

- For **'Higher renewables; more energy efficiency'** this meant making lowest cost assumptions for wind, electric vehicles and electric heating but upper end cost assumptions for CCS, nuclear and bioenergy. In each case 'lowest cost' means the technology cost was set at the bottom end of the ETI ESME 1.2 assumption database cost range while 'upper end' means it was set at the top.
- For **'Higher nuclear; less energy efficiency'** this meant prohibiting CCS; making lowest cost assumptions for nuclear and bioenergy; assuming that wind, electric heating and electric vehicles are at the upper end of predicted costs; and assuming that bioenergy is more abundant and nuclear power possible in more locations than the ESME default.
- For **'Higher CCS; more bioenergy'** this meant making lowest cost assumptions for CCS; but setting costs at the upper end for nuclear, wind power, electric heating and electric vehicles. It also assumes that bioenergy is more abundant than the ESME default.

A53 The technology and fuel cost assumptions used by MARKAL and ESME are towards the lower end of the range that credible experts believe possible by 2050. However, the use of these relatively optimistic cost assumptions in our analysis reflects confidence that the UK and other countries will successfully implement policies that are effective in stimulating businesses and industry to innovate to bring down costs down. Annex B sets out the policies the Government already has in place to stimulate innovation. If innovation does not drive technology costs down, the costs of the pathways would be higher than shown here. The results for the three 2050 futures are set out in table A1 overleaf.

14 HM Government (2011) *Impact Assessment of Fourth Carbon Budget Level*. Available at: www.decc.gov.uk/assets/decc/what%20we%20do/a%20low%20carbon%20uk/carbon%20budgets/1685-ia-fourth-carbon-budget-level.pdf

Table A1: Cost of pathways to 2050 compared with doing nothing on climate change (£bn in 2050)[15]

	MARKAL core run	Higher renewables; more energy efficiency	Higher nuclear; less energy efficiency	Higher CCS; more bioenergy
MARKAL	13	36	26	43
ESME	n/a	36	88	33

Sensitivity testing the three futures

A54 As set out above, we have represented the three 2050 futures in MARKAL by imposing the minimum number of constraints on the model.

A55 However, this simple representation does not capture the different energy demand profiles set out in the three futures pathways. For example, the 'Higher renewables; more energy efficiency' pathway assumes significant behaviour change: the average temperature of homes is one and a half degrees lower than it is today and travel behaviour is curbed (people travel the same distance as today and there is a significant shift to public transport).[16]

A56 We have deliberately not reflected different energy demand characteristics in the MARKAL modelling because we sought to maintain consistency with the MARKAL modelling practice of keeping demand assumptions the same in the baseline and the abatement pathway.[17]

A57 Relaxing this assumption reveals that the cost of achieving the 'Higher renewables; more energy efficiency' scenario could be significantly lower. Using a lower demand profile (compared with a baseline with central demand assumptions), this pathway actually saves the economy £8 billion in 2050 compared with taking no action on climate change.

A58 We have also sensitivity tested these results using the 2050 Costs Calculator to identify the major components of costs and where the most significant uncertainties are in the 2050 futures.

'Higher renewables; more energy efficiency' future

A59 Results from MARKAL and ESME suggest that the aggregate additional investment and operating cost of the **'Higher renewables; more energy efficiency'** scenario could be £36 billion[18] in 2050 compared with taking no action on climate change or energy security (see table A1). It is worth noting that all figures cited for 2050 costs are highly sensitive to methodological decisions.

'Higher nuclear; less energy efficiency' future

A60 The additional investment and operating cost of the **'Higher nuclear; less energy efficiency'** scenario could be perhaps £26–88 billion[19] in 2050 compared with taking no action on climate change or energy security (see table A1). There is a saving from less use of fossil fuels and an increase in costs in other sectors (in order of importance: finance costs, bioenergy and buildings).[20]

A61 Using the 2050 Calculator, we can see that, irrespective of the wider benefits of tackling climate change, the **'Higher nuclear; less energy efficiency'** future could be cheaper than the counterfactual if fossil fuel prices are high ($170/bbl for oil and 100p/therm for gas).

[15] This is the annual cost incurred in 2050 over and above doing nothing on climate change. Based on estimates of total undiscounted system costs in 2011 prices from MARKAL and ESME model runs

[16] In the 2050 Calculator this is characterised as effort level 4 for domestic transport behaviour and average temperature of homes.

[17] The MARKAL results set out in this annex are calculated using central demand assumptions in the baseline and abatement pathway unless stated otherwise.

[18] This is the annual cost incurred in 2050 over and above taking no action on climate change. Based on estimates of total undiscounted system costs in 2011 prices from MARKAL and ESME model runs.

[19] This is the annual cost incurred in 2050 over and above taking no action on climate change. Based on estimates of total undiscounted system costs in 2011 prices from MARKAL and ESME model runs.

[20] Analysis from the 2050 Calculator.

'Higher CCS; more bioenergy' future

A62 The additional investment and operating cost of the **'Higher CCS; more bioenergy'** scenario could be perhaps £33–43 billion[21] in 2050 compared with taking no action on climate change or energy security (see table A1). There is a saving from less use of fossil fuels and lower transport costs and an increase in costs in other sectors (in order of importance: buildings, finance costs and bioenergy).[22]

A63 Using the 2050 Calculator, we can see that, irrespective of the wider benefits of tackling climate change, the **'Higher CCS; more bioenergy'** future could be cheaper than the counterfactual if:

- fossil fuel prices are high ($170/bbl for oil and 100p/therm for gas);
- the cost of solid wall insulation on a house falls to around £2,000/household compared with £7,000 or more today;
- the cost of bioenergy falls (to £20/MWh for imported solid fuels); and
- cost of finance is 5%.

[21] This is the annual cost incurred in 2050 over and above taking no action on climate change. Based on estimates of total undiscounted system costs in 2011 prices from MARKAL and ESME model runs.

[22] Analysis from the 2050 Calculator.