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Pathways to a low-carbon economy for the UK with the macro-econometric E3MG model

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ABSTRACT

This paper examines different carbon pathways for achieving deep CO_2 reduction targets for the UK using a macro-econometric hybrid model E3MG, which stands for Energy–Economy–Environment Model at the Global level. The E3MG, with the UK as one of its regions, combines a top-down approach for modeling the global economy and for estimating the aggregate and disaggregate energy demand and a bottom-up approach (Energy Technology subModel, ETM) for simulating the power sector, which then provides feedback to the energy demand equations and the whole economy. The ETM submodel uses a probabilistic approach and historical data for estimating the penetration levels of the different technologies, considering their economic, technical and environmental characteristics. Three pathway scenarios (CFH, CLC and CAM) simulate the CO_2 reduction by 40%, 60% and 80% by 2050 compared to 1990 levels respectively and are compared with a reference scenario (REF), with no reduction target. The targets are modeled as the UK contribution to an international mitigation effort, such as achieving the G8 reduction targets, which is a more realistic political framework for the UK to move towards deep reductions rather than moving alone. This paper aims to provide modeling evidence that deep reduction targets can be met through different carbon pathways while also assessing the macroeconomic effects of the pathways on GDP and investment.

1. Introduction

Climate change, as a result of rising greenhouse gas emissions, threatens the stability of the world's climate, economy and population. The causes and consequences of climate change are global, and while national governments can and should take action, the ultimate solution must be a collective global effort. The latest scientific consensus (IPCC, 2007) has further strengthened the evidence base that it is very likely that anthropogenic GHG emissions at or above current rates would cause further warming and induce many changes in the global climate system during the 21st century. A major recent report on the economics of global climate change (Stern, 2006) supports the position that the benefits of stringent climate mitigation action outweighed the costs and risks of delayed action.

Although there is a global consideration of the climate change effects, individual countries have undertaken different steps in climate change mitigation, which is obvious given the extended negotiations towards the ratification of the Kyoto Protocol (e.g. Höhne et al., 2007). The EU and individual Member States have undertaken several commitments and directed several policies towards the reduction of their emissions. UK has been selected for this analysis as there is political will within the country, as described below from the commitments to tackle climate change. But this commitment can be examined in the context of negotiations at international level, such as the recent commitment of G8 to reduce their emissions by 80% by 2050.

1.1. The UK climate policy development

Climate change mitigation and energy security are the UK's core energy policy goals (BERR, 2007). In addition, the decline in domestic reserves and production of UK oil and natural gas, combined with increasing geopolitical instabilities in key gas and oil production and transmission countries have highlighted the need for a secure and resilient UK energy system (BERR, 2007). Other UK energy policy goals are reductions in vulnerable consumers' exposure to high energy prices (i.e. fuel poverty) and a continued emphasis on open and competitive energy markets.

The UK set itself a groundbreaking climate change mitigation policy with the publication of a long-term national CO_2 reduction target of 60% by 2050 (DTI, 2003). This target was established in response to the climate challenge set out by the Royal Commission on Environmental Pollution (RCEP, 2000). Climate

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change mitigation targets were reaffirmed in light of competing energy security issues via the 2007 Energy White paper (BERR, 2007). The 60% UK CO_2 reductions target is being established in the UK legislative process through the Climate Change Bill as the minimum CO_2 reduction target required by 2050 (DEFRA, 2008). This longer term target has been further analyzed by the new regulatory Committee on Climate Change (CCC, 2008), in light of new evidence concerning global stabilization targets (IPCC, 2007). This has led to the proposal for an 80% reduction target for greenhouse gases by 2050 compared to 1990 levels. This target has been adopted by the Brown Administration and the Energy and Climate Change Secretary of State Ed Miliband, becoming a law through the Climate Change Act (DECC, 2008). Additionally, the UK has been a leading proponent of global long-term CO_2 target setting within the G8, as the causes and consequences of climate change are global, and while national governments can and should take action, the ultimate solution must be a collective global effort. The G8 dialogue resulted in agreement at the 2009 G8 Italian summit for a robust response to climate change including the adoption of the goal to achieve at least 80% reduction of their emissions by 2050, and aiming to reach an agreement of a 50% reduction in global emissions with other countries.

The implementation of three deep CO_2 reduction targets (40%, 60% and 80%) for the G8 is examined using the macro-econometric E3MG model. Results are reported for the UK, which is selected as there is a political will to implement such reductions. These targets, examined within the UK Energy Research Centre's 2050 project (UKERC2050), are met through the implementation of a portfolio of policies in contrast to the neoclassical approach, where the targets are imposed and the marginal abatement cost for meeting those targets is estimated. The paper contributes by adopting a novel hybrid approach integrating simulation models of the economic system and energy technologies and therefore providing an alternative approach to the traditional economic equilibrium modeling. Moreover the paper aims to provide evidence that there exist pathways for meeting deep reduction targets and also helping the economy to grow. The need for such evidence has been noted by the IPCC (2007a) in its assessment of the literature on stringent mitigation targets. Such evidence can inform the international negotiations for a post-Kyoto global agreement.

2. Modeling framework

Long-term forecast of the economy and of the energy system expansion is subject to uncertainties on fossil fuel resources, prices, economic and technical characteristics of new technologies, behavioural change, political framework and regulatory environment. But the modeling approach implemented to simulate the energy system and the interaction with the global economy is crucial for the results. There are many modeling approaches used for examining energy and climate policies at global (van Vuuren Detlef et al., 2009; Dagoumas et al. 2006) or at national level (Cosmi et al., 2009; Anderson Kevin et al., 2008; Schulz Thorsten et al., 2008; Dagoumas et al. 2007) either through macro or energy system models. In the extensive literature on energy-economic modeling of energy and climate policies, there are two widespread modeling approaches: bottom-up vs. top-down models (van Vuuren Detlef et al. 2009). The two model classes differ mainly with respect to the emphasis placed on technological details of the energy system vis-à-vis the comprehensiveness of endogenous market adjustments (Bohringer and Rutherford, 2007). However, recent evaluations of the literature (IPCC, 2007) have shown the increasing convergence of these model categories as each group of modelers adopts the strengths of the alternate approach. There is a long track record of energy models underpinning major energy policy initiatives, producing a large and vibrant research community and a broad range of energy modeling approaches (Jebaraj and Iniyan (2006)). Particularly in recent years, energy models have been directly applied by policy makers for long-term decarbonisation scenarios (IEA, 2008; Das et al., 2007; European Commission, 2006), with further academic modeling collaborations directly feeding into the global policy debate on climate change mitigation (Weyant, 2004; Strachan Neil et al., 2009).

In terms of top-down modeling, a number of major international collaborations (Weyant 2004; van Vuuren et al. 2006) have assessed global scenarios of carbon dioxide (CO_2) and greenhouse gas (GHG) stabilization (and hence emission targets). Other modeling comparison exercises have focused on key model driver, notably innovation and technological change (Edenhofer et al. 2006). One innovative top-down model is Environment–Energy–Economy Model at the Global level (E3MG), a dynamic macro-econometric hybrid model based on a detailed input–output structure of regions and industries. This model allows implementation of internationally differentiated policy, sectoral representation of energy-economic interactions including innovation, and non-equilibrium behavioural change by industries and consumers (Barker et al., 2006). A further extension has been the adoption of a hybrid approach by the implementation of a detailed energy technology sub-model (Anderson and Winne (2007)).

E3MG is an econometric simulation model of the global energy–environment–economy system, estimated on annual data 1971–2002 and projecting annually to 2030 and every 10 years to 2100. It is a non-equilibrium model with an open structure such that labour, foreign exchange and public financial markets are not necessarily closed. It is very disaggregated, with 20 world regions (including the 13 nation states with the highest CO_2 emissions in 2000), 12 energy carriers, 19 energy users, 28 energy technologies, 14 atmospheric emissions and 42 industrial sectors, with comparable detail for the rest of the economy. The model represents a novel long-term economic modeling approach in the treatment of technological change, since it is based on cross-section and time-series data analysis of the global system 1970–2002 using formal econometric techniques, and thus provides a different perspective on stabilization costs. The methodology of the model can be described as post-Keynesian, following that of the European model E3ME developed by Cambridge Econometrics (E3ME), except that at the global level various markets are closed, e.g. total exports equal total imports at a sectoral level allowing for imbalances in the data. It is designed to address the issues of energy security and climate stabilization both in the medium and long terms, with particular emphasis on dynamics, uncertainty and the design and use of economic instruments, such as emission allowance trading schemes. The model is able to address the question of the costs of stabilizing atmospheric concentrations of greenhouse gases by projecting emissions up to 2100. At this stage, the model is not yet finalized and continues to represent work in progress. The model will be extended to include multi-gas abatement and Foreign Direct Investment and applied in a model comparison exercise.

2.1. *The long-term solution and effects of fiscal policies*

If we consider the theoretical properties of E3MG in the long-run and at a macro global level, as in the version used here, the crucial features determining the effects of fiscal policies can be identified.

Fiscal policies affect prices, incomes and expenditures in the model. The wage–price interaction has been simplified into price inflation being given exogenously and real wage rates rising according to labour productivity. Employment and investment are derived demands relating to real output by sector. Total demand and supply comes from industrial demand (the model uses input–output tables), private and public consumption and investment. At a regional level, e.g. for the UK, exports are added into demand and imports into supply of products.

The critical relationship affecting the global multiplier implicit in the model is that of the consumption function, i.e. how long-run consumption responds to changes in real disposable income. The ratio between consumption and real disposable income is calibrated at 0.8 for the UK, consistent with the estimate for 2001 made by Barrell and Davies (2007, Table 5 p. 263) in their study of consumption, wealth and liberalization of markets for seven OECD countries using quarterly data 1980Q1–2001Q4. Assumptions about fiscal policy can affect real disposable income through the price level, with carbon taxes and permit schemes affecting prices, through transfers such as income tax, affecting income and through employment affecting total wages, the main component of income in most regions. Government expenditure directly on investment or incentives for private investment will increase output and employment; and the extra employment will lead to extra consumption in the Keynesian multiplier process. At a regional level the size of the multiplier will also be affected by the extent to which the region is open to world trade.

Spilimbergo et al. (2009) provides a review of empirical estimates of fiscal multipliers and the implicit crowding out of government-induced increases in investment. They confirm a repeated finding of substantial differences in estimates of the fiscal multiplier both across countries, over time. It is particularly noticeable that different researchers for the same country and time period can estimate substantially different multipliers. The main reason for the substantial difference in long-run multipliers seems to be in the theoretical approach: new Keynesians and others assuming rational expectations in the modeling assume no long-run effect, i.e. full crowding out; those assuming adaptive expectation in a Keynesian framework, find multipliers above 1. The multipliers reviewed increase with the economic size of the region and are largest for globally co-ordinated policies, they increase over time and they vary according to the source of the fiscal stimulus. Our approach allows for long-term unemployed resources and a simplified form of the consumption function for long-term analysis. We assume adaptive expectations and a demand-side and technological determination of long-run economic growth. In the scenarios, fiscal balance is maintained through any extra government spending being covered by tax or auctioned permit revenues.

More information on the theory of the E3MG model can be found on several publications (Barker Terry et al., 2009; Barker, Scrieciu, 2009; Barker et al., 2007; Barker et al., 2006; Barker et al., 2005; Barker, 1999; Barker, 1996) and also on the description of the MDM-E3 (Barker and Peterson, 1987; http://www.camecon.com/suite_economic_models/mdme3.htm) and the E3ME (http://www.camecon.com/suite_economic_models/e3me.htm) models, as all three models share similar structure and theoretical approach.

2.2. Assumptions

For the purposes of this paper a range of data updates and technical adjustments have been made.

2.2.1. Fossil resource costs

E3MG, as a demand driven model, does not have fossil resources supply curves. Considering recent projections of global fossil fuel prices (IEA, 2007; BERR, 2008), fossil resources costs for coal, oil and natural gas has been shifted upward. These reflect long-term drivers in rising energy demands and constrained supplies. Base prices are shown in Table 1, and are converted into energy units (PJ) in gross calorific terms (GCV) and deflated into year 2000 prices.

2.2.2. Electricity technologies

E3MG has a sub-model for the treatment of the electric system expansion, as mentioned above. It includes 28 energy technologies, each of them is represented by 21 technology characteristics. These technologies and their characteristics have been recently updated in order to represent new options e.g. air capture. A comprehensive revision of economic and technical data on CCS, nuclear, wing, biomass and marine technologies has been undertaken (Winskel et al., 2009), including also updating the learning curves. CCS technologies are considered to account for capture efficiency (90%).

2.2.3. Transport technologies

E3MG does not have a detailed representation of the transport system. It has three fuel options (petrol, diesel and electricity), with biofuels not being considered. Recent technical developments from the auto manufacturers have been considered in the modeling by adopting a positive feedback approach. This means that once the electric vehicles start penetrating in the market, the alternative options (e.g. hydrogen vehicles) have to become much more competitive than the electric vehicles to penetrate in the market. Considering that hybrid vehicles are market available already and plug-in vehicles will enter the market in the next decade, the transport sector is moving towards electrification. The penetration of new technologies e.g. electric vehicles is assumed to be made through regulation which forces auto producers to develop advanced plug-in electric vehicles. Moreover the penetration of electric vehicles is modeled to work in favour of certain renewables. Wind and tidal plants are considered to increase their capacity factor by up to 10%, depending on the penetration level of plug-in electric vehicles. It is assumed that the electrification of the transport sector will be accompanied with tariff policies that

Table 1
Updated fossil resource costs.

Original units		2000	2005	2010	2015	2020	2025	2030	2035	2040	2045	2050
Crude oil	**2005$/bbl**	**31.38**	**50.62**	**57.50**	**55.00**	**55.00**	**57.50**	**60.00**	**65.00**	**70.00**	**70.00**	**70.00**
Gas	**2005$/MMBTU**	**4.77**	**7.46**	**6.75**	**6.75**	**7.00**	**7.32**	**7.64**	**8.27**	**8.91**	**8.91**	**8.91**
Coal	**2005$/tonne**	**35.89**	**60.48**	**55.00**	**55.00**	**57.04**	**59.63**	**62.22**	**67.41**	**72.59**	**72.59**	**72.59**
PJ (GCV)		**2000**	**2005**	**2010**	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Crude oil	**2000£/GJ**	**2.53**	**4.08**	**4.64**	**4.44**	**4.44**	**4.64**	**4.84**	**5.24**	**5.65**	**5.65**	**5.65**
Gas	**2000£/GJ**	**2.35**	**3.67**	**3.32**	**3.32**	**3.44**	**3.60**	**3.75**	**4.07**	**4.38**	**4.38**	**4.38**
Coal	**2000£/GJ**	**0.66**	**1.11**	**1.01**	**1.01**	**1.05**	**1.09**	**1.14**	**1.24**	**1.33**	**1.33**	**1.33**

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encourage cars to be charged during off-peak times. This can lead to a further use of specific renewables, which have the capability to operate at their maximum output during off-peak times (e.g. night), but for technical reasons (the base plants cannot be switched off), the renewables are otherwise underused.

2.2.4. EU-ETS

For the reference scenario the EU Emissions trading scheme is imposed with an EU-ETS price of €20/tCO_2 from 2010 onwards in the electricity and industrial sectors—broadly on EU-ETS Phase 2 coverage. This price level and coverage is maintained through 2050. The carbon price is exogenous in the model. Carbon pricing is considered as one of the policies that are applied for helping financing energy investments. So, the carbon price can be considered as a price signal required helping towards meeting deep emission reduction targets.

2.2.5. CO_2 constraint curve

In contrast with most energy system or general equilibrium models, emission reduction targets are not implemented by imposing this target exogenously in the model. A number of policies (described in the next session and the discussion of the results) are implemented at different strengths and in different timings so as to meet those targets.

2.2.6. Calibration

Base year 2005 CO_2, final energy and primary energy calibration has been fine-tuned to exactly match with calibration sources (IEA, 2008; DUKES, 2008).

2.3. Core model drivers

E3MG, as a macroeconomic model, estimates the interaction between the global economy and national/regional economies. As an energy–economy–environment model, it allows the interaction between these E3 systems. As it is based on historical data, its forecasts consider past trends. As a structural model, it enables detailed forecasts for the different sectors and regions. Although a top-down model, the treatment of the energy sector is quite detailed enabling the penetration of new technologies, depending on the use of economic instruments such as carbon pricing, subsidies, etc. E3MG has the advantage of a policy-oriented model, which means that it is estimated on historical data and policies (e.g. including regulations, and taxes) while its scenarios simulate the implementation of several policy packages.

The model provides future insights into the interaction of the whole economy and the energy system, considering that these systems are not independent. Policy measures, technology assumptions and behavioural changes are updated for various scenarios and constitute the core set of drivers for the results. In particular the key variables are:

- Technology costs (vintages and learning).
- Endogenous technology acceleration (learning by researching).
- Option of new energy technology chains.
- Regulation (e.g., transport shift to electric vehicles).
- Fiscal policies (taxes and subsidies in the demand/supply-side).
- Revenue recycling.

3. Scenarios

The E3MG model is run for a total of three carbon ambition pathways and a reference case (Table 2). These are designed for relevance to the UK policy process for the near and long-term targets of the Climate Change Committee. These pathways are designed to be comparable to those with the same names as in the UK Energy Research Centre's 2050 project (UKERC2050). The project used the energy technology model MARKAL to represent the scenarios and provide results for energy demand and supply, investment coats and carbon prices. This paper supplements the UKERC Report (Anandarajah et al., 2009) by simulating four of the scenarios, but using a hybrid approach which includes a macro-econometric model capable of providing effects on UK GDP and its components. However, in order to achieve the carbon reduction targets in E3MG, additional assumptions regarding regulation and incentives for energy saving and carbon reduction were required, which made the results less comparable to those from MARKAL.

Table 2
Carbon pathway scenarios run with the E3MG model.

Scenario	Scenario name	Annual targets below 1990 levels
REF	Reference	–
CFH	Faint heart	−40% by 2050
CLC	Low carbon	−60% by 2050
CAM	Ambition	−80% by 2050

An important advantage of the E3MG model is that it is an energy–economy–environment model of the global economy, allowing for the global reduction in costs of technologies if adopted by many countries. The cumulative investments on alternative technologies at global level, allow their faster penetration. Deep emission reduction targets, such as those examined at this paper, could be achievable at much lower costs if implemented internationally. For this reason, the emission reduction targets are examined as part of a global stabilization effort, representing a realistic political framework.

CO_2 reduction targets are achieved for the CFH, CLC and CAM scenarios through a number of policies implemented at different strengths and timing. This is in contrast with most energy system models or general/partial equilibrium models which impose a reduction target exogenously and the models estimate the marginal abatement cost for meeting this target. The policies considered in E3MG are:

- Carbon price (either through carbon trading for the emission trading system (ETS) sectors or Carbon Tax for the rest of the economy) is implemented. The revenues are recycled via the following policies.
- Incentives for electricity technologies through revenue recycling. These revenues are raised from the auctioning carbon permits. This subsidy is spread across new technologies i.e. renewables and CCS (excluding nuclear and hydro).
- Accelerated diffusion of electric plug-in vehicles is assumed through technological agreements and behavioural shifts in transport demand.
- Revenues raised from carbon permits auctioning are recycled to energy-intensive industries in order to incentivize the conversion to low-carbon production methods.
- Carbon tax revenues from households are recycled via investments in energy efficiency by providing incentives for improving the energy efficiency of domestic dwellings and appliances and for introducing new ones such as low-emission dwellings and solar appliances.
- Accelerated carbon price increase at an earlier year e.g. 2020

It should be mentioned that energy efficiency policies for electricity consumption are considered as no-regret options (IPCC, 2007), as they lead to reduction in electricity demand

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and so reduce the need for investment in new generation and infrastructure. These scenarios are assumed to be implemented first in the period 2010–2020 for all emission reduction scenarios. Based on the revenues from permit auctioning that are recycled via investments in energy efficiency at the consumption side, these measures can lead to significant demand reduction even in the medium term.

Moreover the rate at which plug-in vehicles replace conventional vehicles will affect the mix of electricity technologies in favour of some renewables e.g. wind. This comes from the fact that it is assumed that tariff policies are implemented that encourage plug-in vehicle users to charge their cars' batteries at night when the electric demand is at low levels. Such tariff policies combined with control systems allow the user to select when their cars' batteries will be charged so as to allow a new peak before midnight and lead to a more balanced load curve. Such policies reduce the need for investment in new capacity, and raise the load factors of the existing equipment. This works in favour of stochastic generation, such as wind farms, which normally have to operate at low levels during the night, although they could operate at higher output due to higher wind speeds at that time.

The above scenarios are implemented under the following main modeling assumptions:

- The discount rate is required only in the energy technology sub-model (10%), for estimating the net present value of the different technologies.
- Penetration of technologies in electro-production is based on Anderson and Winne (2007): the theory combines the estimation of net present value and a probabilistic approach for the diffusion of technologies compared to a marker technology.
- Reduction targets are implemented through a set of policies. These reduction targets are not set, but achieved via specially designed policy packages.
- International drivers are assumed.
- Macro effects are assumed e.g. in energy efficiency policies the direct plus macroeconomic rebound effect is considered.
- UK is considered as a region of the world. This means that emission reduction targets for UK e.g. 80%, is considered as part of global reduction efforts e.g. G8 80% reduction up to 2050.
- The economy is not treated as being in equilibrium.
- Full utilization of resources (e.g. full employment) is not assumed.

4. Results

4.1. Decarbonisation Pathways

E3MG focuses on the implementation of policies rather than on the reduction targets. The three emission reduction scenarios (CFH, CLC and CAM) are characterized by a set of policies and measures, with analysis to check the influence of those policies when implemented alone or together. Firstly the CLC scenario is examined, where all the above described policies (carbon price, incentives in end-use sectors, regulation for the penetration of electric vehicles and incentives for new energy technologies) until the 60% reduction target is achieved. Then these policies are being extended aiming for the 80% reduction target of the CAM scenario. The CFH scenario is modeled slightly differently, as its starting point is the CAM scenario rather than the REF scenario. This means that from the set of policies implemented to have the 80% reduction target of the CAM scenario, the carbon price is steadily decreased so as to finally get the 40% reduction. This finally leads to a low-carbon price, as there is space for removing the energy inefficiencies in the system and adopting new behavioural patterns. This finding shows that the achievement of reduction targets at low-carbon prices requires the use of several policies. This means that there exist many alternative pathways towards low-carbon societies, where the different policies interact in a complex way, which can be analyzed through the non-linear nature of the E3MG model.

4.1.1. CO_2 emissions

Figs. 1 and 2 provide the CO_2 emission levels for the four scenarios over the projection period. CO_2 emissions for the REF scenario are estimated to be increased to 628 Mt from 587 Mt in 1990, thus an increase of 7%. The increase is observed in the last decade 2040–2050 and is attributed mainly to an increase in energy demand which is covered mainly from natural gas either for electric production or for heating purposes. The energy demand is estimated to fall in the period 2010–2020 due to current directed energy efficiency measures. Then the economic activity forces the energy demand to be increased, as the demand and the economic activity are positively correlated.

The energy demand and emissions level in the REF scenario is reduced in the medium term, resulting from the effect of the global recession. This scenario develops earlier work (Dagoumas et al. 2009) examining the financial crisis, which outlines some of the causes of the current crisis and suggests a global co-ordinated policy response focused on investment. The financial crisis affects the economic activity, the saving rates, the consumption, the access to the credit and so the investments leading to a lower

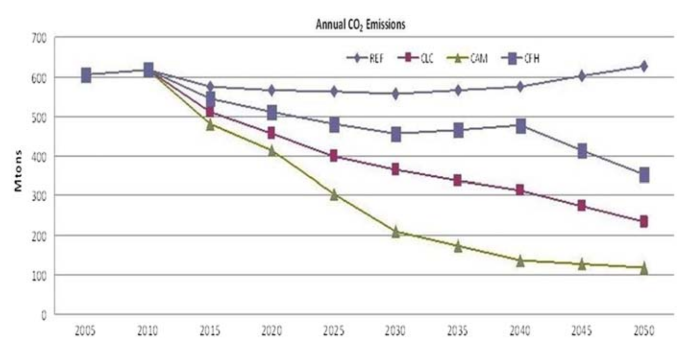

Fig. 1. Emissions evolution (Mt-CO_2) for the different scenarios over the projected period 2005–2050.

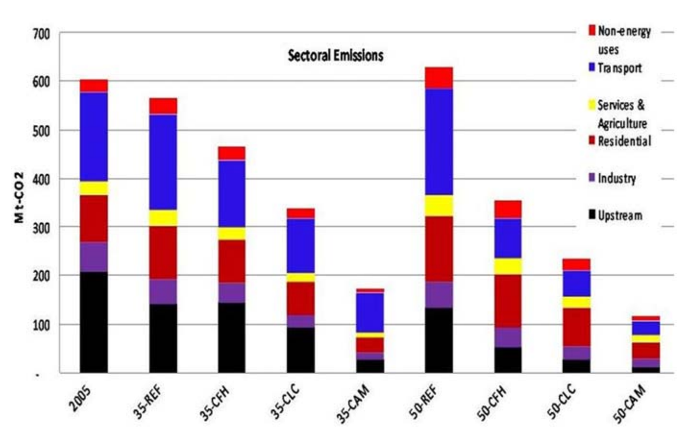

Fig. 2. Sectoral Emissions (Mt-CO_2) for the different scenarios for years 2005, 2035 and 2050.

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economic growth for the medium term, after the recovery of the global economy. But in the long-term (beyond 2020) the impact of the recession is partly offset from the policies that have been directed. The REF scenario considers all structural changes and investments directed until the mid-2009, when the scenarios were constructed. The investments are treated as green energy investments that lead to tackling the climate change and also boosting the economy, (Dagoumas et al. 2009). However, the REF scenario does not consider additional long-term policies or the implementation of further energy investments, reported in several official publications in the medium term (IEA WEO (2008); IEA (2008)). Such policies are considered in the CO_2 reduction scenarios.

The emissions reductions for the other three scenarios are not linear, a feature that is attributed to the character of the model and the way these scenarios are being implemented. We do not adopt a neoclassical approach, looking for the marginal abatement cost of achieving an emission reduction target. Instead, different policies are being implemented at different strengths and timing, aimed at meeting the targets without affecting significantly economic growth, although we find that the economy is stimulated which leads to an increase in employment. This approach is consistent with the current economic situation of the global recession if most governments assume adaptive expectations and pursue Keynesian policies on consumption and green investments to boost their economies and employment levels.

At sectoral level, the consumption sectors (buildings, industry) decrease emissions in the first decade and later stabilize their emissions due to the implementation of energy efficiency measures, while the power sector is the first to reduce significantly its emissions up to 2035 even for the REF scenario. Alternative technologies prove to be competitive to the traditional ones and dominate almost the whole system in the carbon reduction scenarios. Crucial to the results is the emission reduction of the transport sector, due to the penetration of electric vehicles and behavioural shifts. As described above, the shift to electricity in the transport sector works in favour of some renewables, such as the wind, the availability of which is significant in the UK. The transport sector leads to an important reduction in overall emissions, resulting also from a behavioural shift that locks in the energy and emissions reduction resulting from the higher prices and the regulation. The rebound effect (Brannlund et al., 2007; Sorrell, 2007), i.e. the increase in energy use arising from the implicit reduction in costs of energy as a result of energy-efficiency improvements, is offset by the increase in energy prices due to the emission trading scheme and the carbon tax. A recent paper (Barker Terry et al., 2009) analyzes the rebound effect using the E3MG model, where it is estimated that the total rebound effect can be at levels of 50%, therefore offsetting half of the targeted energy demand reductions. Considering that all the end-use sectors (transportation, residential, services and industry) are covered by policies that decrease their energy demand and emissions sharply, especially for very strict targets such as the 80% reduction, it is becoming crucial to consider policies with neutral rebound effect e.g. behavioural shift.

4.1.2. Energy demand

E3MG uses a two-level hierarchy for estimating the energy demand for 12 fuel types and 19 fuel users. This is done by estimating the aggregate and disaggregate energy demands, through five stochastic econometric functions. Aggregate energy demand is affected by industrial output of user industry, household spending in total, relative prices, investments by fuel users and R&D investments. The measures of research and development expenditure and investment capture the effect of new ways decreasing the energy demand and the elimination of inefficient technologies. The equations for disaggregate energy demand have been specified for four fuels: coal, heavy fuel oil, natural gas and electricity. The specifications of the equations follow similar lines to the aggregate energy equations.

The above described energy demand functions predict that the final and primary energy demand (Figs. 3–5) will fall in the first decade, remain stable in the period 2020–2030 and then be increased up to 2050 for the REF scenario, affected mainly from the economic activity and from the fact that energy efficiency investments are considered for the first decade of the examined period. The emission reduction scenarios are implemented through increased investments in energy efficiency measures and also through behavioural shifts with neutral rebound effect. Such measures lead to a significant decrease in energy demand by about 20–30% and 50-60% for the CLC and CAM scenarios respectively compared to base year (2005) demand and even more compared to the REF demand in 2050. The same figures are not decreased significantly for the CFH scenario, as the price response does not lead to high demand reductions due to the small carbon price.

As mentioned above, CFH considers the same portfolio of policies with the CAM scenario, but implemented at different strengths and timing. The CAM scenario is characterized by a considerable reduction in energy demand, leading to the need of investments in energy efficiency measures, the CFH scenario (with modest energy demand reduction) allocates extra investment in the electro-production and the electrification of the transport sector. Moreover the introduction of regulation in both scenarios leads to a shift in technologies forcing investment across both consumption and production. Starting from the CAM scenario price levels, the carbon price is steadily decreased for the CFH scenario, at low levels as shown in Fig. 9, so as to get the required emission reduction. One result is that in the CFH scenario, investment and GDP growth are very slightly higher than in the CAM scenario (Fig. 10). This result is attributed to the extra CFH investment being focused mainly on the further electrification of the transport sector (Figs. 4 and 5) and on the support of new technologies in the power sector (Figs. 7 and 8) such as wind, nuclear and gas CCS rather than on energy efficiency in consumption. The results for the CAM scenario are affected by the much higher carbon prices leading to a decrease of the rebound effect. Although the amount of investment is the same for CAM and CFH scenarios, the CAM portfolio (with higher energy prices) leads to a significant decrease of energy demand but the CFH portfolio (with more supply-side investment) leads to a more

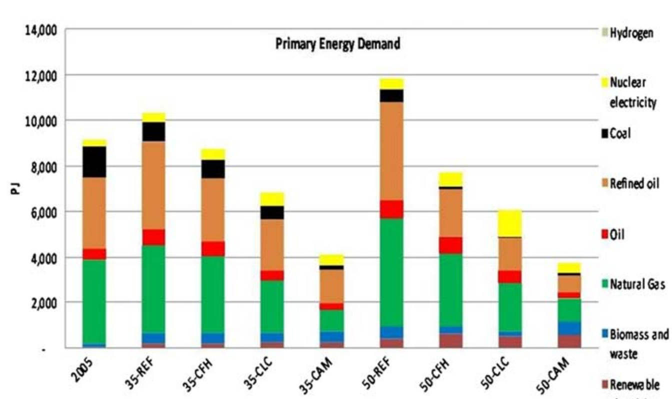

Fig. 3. Primary energy demand by fuel type (PJ) for the different scenarios for years 2005, 2035 and 2050.

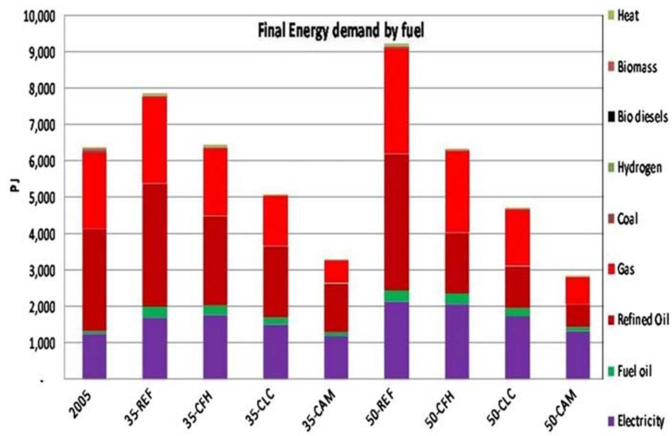

Fig. 4. Final energy demand by fuel type (PJ) for the different scenarios for years 2005, 2035 and 2050.

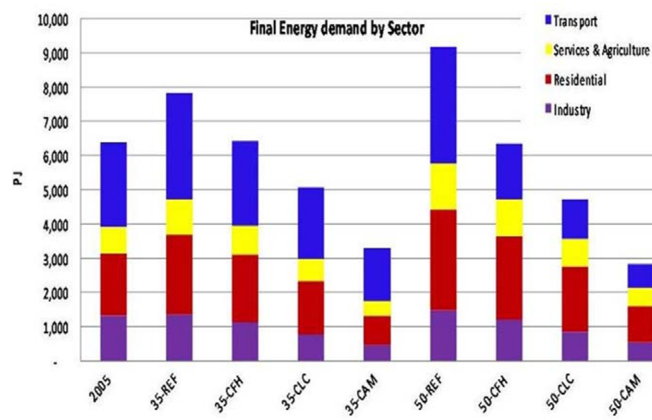

Fig. 5. Final energy demand by sector (PJ) for the different scenarios for years 2005, 2035 and 2050.

modest decrease in energy demand but higher GDP growth for the economy.

Transport demand (Fig. 5) is decreased more compared to other sectors. This is attributed to behavioural changes (especially for the CLC and CAM scenarios) and to a shift to electric vehicles through the implementation of relevant regulation. Electric vehicles are more efficient compared to conventional fuel vehicles and their penetration works in favour of renewables such as wind resources as they increase their capacity factor (Figs. 7 and 8). This is shown in case of the CFH scenario, where as mentioned above the further electrification of the transport sector is crucial for reducing the emissions and for boosting the economy. It has to be mentioned that the biofuels option is not considered in modeling the transport sector in E3MG. But this would be implemented through a regulation leading to penetration of biofuels at certain levels, but also requires a detailed modeling of land-use changes and the consideration of their effects on other factors such as food prices.

The significant decrease in the transport demand especially in the CLC and CAM scenarios are attributed to changes in citizens' behaviour in two directions. The first is a positive feedback in the adoption of the new technologies by the consumers. This means that once the electric vehicle becomes the dominant technology, alternative options such as the hydrogen cars have to be cheap enough and not just competitive, so as to gain percentage of the market. The second change is a behavioural shift of citizens to a different lifestyle by preferring cycling and public transport, which is considered as a policy with neutral rebound effect. But for the time being such policies are not modeled in great detail within the E3MG model.

Finally Figs. 4 and 6 show that the electric demand is decreased less than the other fuel types or even increased for the CFH scenario, due to the higher penetration of plug-in electric vehicles. But even in case of the plug-in vehicles, the penetration of electric vehicles may be proved conservative. Recent developments in auto manufacturing industries, and recent decisions from governments (Israel, Denmark and Portugal) to invest in new infrastructure for electric cars, may further boost their faster penetration. In a case where the whole stock of cars is electric, at least for the developed countries by 2050, we expect a higher growth of the whole economy.

4.1.3. Power sector

Renewables (Figs. 7 and 8) are introduced significantly in the electro-production mix for all three CFH–CLC–CAM scenarios. Nuclear and CCS are also increased. The results show that the electric mix can be diverse which, considering the significant penetration of renewables, increases the energy security of the country. This diversity comes from the fact that the electric system expansion is not modeled as a classic cost optimization problem, where once one technology is slightly cheaper than the others dominates the system. The different candidate technologies can penetrate into the system, by increasing their cost effectiveness through incentives, learning by doing and

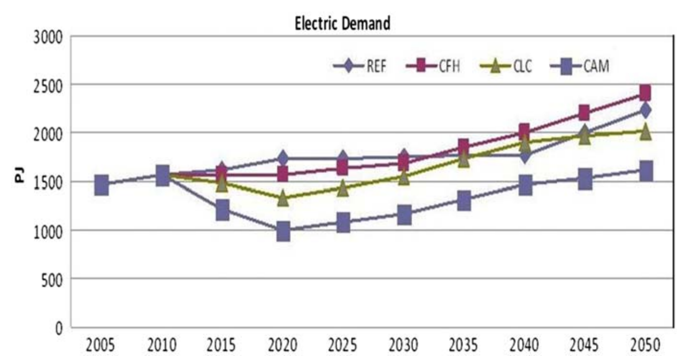

Fig. 6. Electric energy demand mix (PJ) for the different scenarios over the projected period 2005–2050.

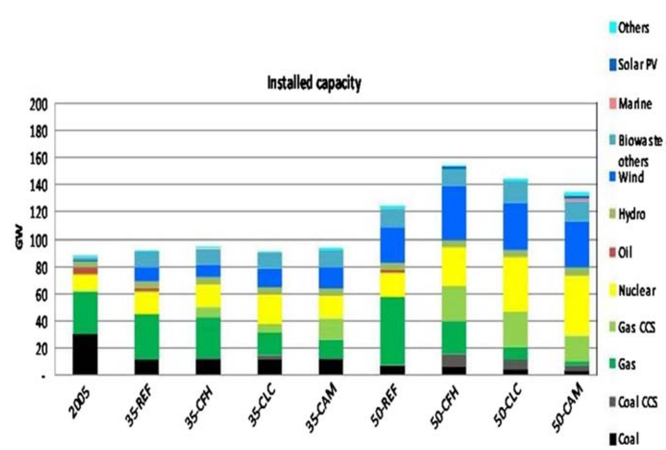

Fig. 7. Installed electric capacity (GW) for the different scenarios for years 2005, 2035 and 2050.

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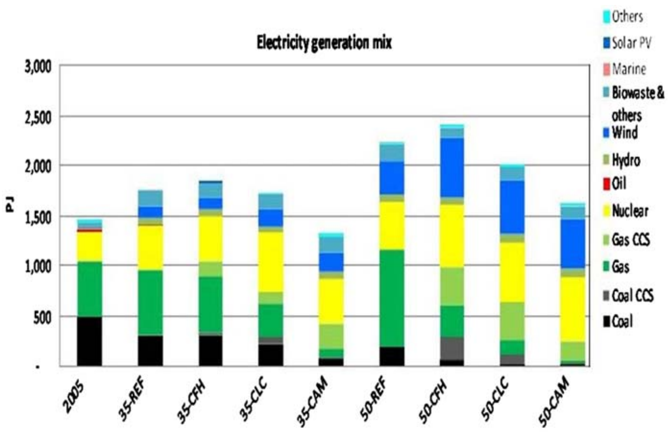

Fig. 8. Electricity generation mix (PJ) for the different scenarios for years 2005, 2035 and 2050.

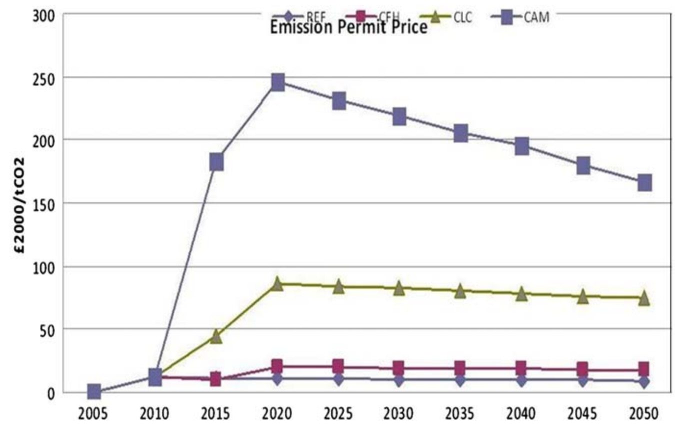

Fig. 9. Emission permit price (2000£/tCO_2) for the different scenarios over the projected period 2005–2050.

learning by R&D, based on a probabilistic approach (Anderson and Winne, 2004). This approach considers the market penetration of the different technologies in the history and estimates acceleration factors for them, allowing them to penetrate at a small or higher extent depending on their net present value.

By examining Figs. 7 and 8 it can be deduced that there is competition between two technologies, nuclear and CCS to replace conventional units. Those technologies can act as complementary if it is the case that countries or entities such as the EU are looking for energy diversity and so for energy security. If they are competitive, e.g. if the aim of a country is to gain a technological advantage against other countries so as to export technology in order to help it satisfy the obligations of a possible international agreement on climate change, then more R&D investments are expected in CCS technology. Under such a case, which requires political decisions and relevant regulation, CCS can become a mature and competitive technology sooner and penetrate more. But in contrast to neoclassical modeling approaches, the probabilistic approach implemented in ETM sub-model within E3MG is expected to provide a diverse electric mix with a major but not dominant technology e.g. CCS. The role also of renewables is crucial because they appear to become the dominant set of technologies over the next few decades. The penetration of renewables can be increased via the developments in the transport system, which helps in two ways: by increasing their capacity factor with the implementation of appropriate tariffs as mentioned above and by increasing the storage capacity and so moving on small decentralized systems that can operate on island mode, based on the batteries for electric vehicles.

4.1.4. Economic results

Carbon permit price (Fig. 9) is increased for CLC and CAM scenarios. CLC scenario is modeled as ‘‘light’’ version of CAM scenario, where the same policies are applied at lower scale with the difference that CAM invests mainly on CCS while CLC on nuclear technology. The most important difference is that the carbon price had to be increased at very high levels in the medium term (by 2020) for the CAM scenario so as to get the 80% emission reduction target. The carbon price remains at low levels for the CLC scenario and especially for the CFH scenario due to the way this scenario is modeled e.g. all policies mentioned above were applied so as to follow the CAM scenario, including increasing the carbon price, but at a lower rate.

The investment budget applied for the CAM scenario was the starting point for implementing the CFH scenario. The portfolio of policies remained the same with differences on the extent and the timing of each policy, except that the carbon price which was steadily increased at a lower rate so as to get a 40% (from 80%) reduction. The results show that the carbon price is not very high, when accompanied with several policies. It is very high in case of a very deep reduction target (80%), but as discussed above if the portfolio of policies were implemented with other priorities e.g. further electrification of the transport sector and further support on renewables, then the economic growth would be higher and the required carbon price lower. It has to be mentioned that in all scenarios, carbon price is implemented as a carbon tax or by auctioning emission permits, which both lead to extra revenues for the government. These revenues were recycled to subsidise energy sector investments. The current Emission Trading System in EU, where the emissions producers get free permits, has lead to increase in consumers' prices for electricity but not to significant investments in alternative technologies for most countries.

Probably the most important conclusion arising from this paper is that there exist different pathways implementing deep reduction targets that also lead to an increase in economic growth. GDP (Fig. 10) is slightly increased for all CFH, CLC and CAM scenarios, compared to the REF scenario. This shows that there exist pathways towards low-carbon societies without leading to a decrease in the economic growth. But this requires that there exist policies to guarantee that the revenues from the energy sector or other policies e.g. green fiscal measures will be recycled to energy efficiency investments and low-carbon technologies. Once this is ensured, it can be more certain that revenue recycling can lead to a rise in economic growth.

Fig. 10 shows that consumers' expenditure and investment are at much the same levels for all three emission reduction scenarios. Total investment spending is higher for all three scenarios compared to the REF scenario by less than 5% each year in the examined period. The consumers' expenditure divergence of the three scenarios from the REF scenario is less than 2.5% each year in the examined period. The highest difference of the investment and consumers' spending between the three emissions reduction and the reference scenarios is mentioned in year 2050 is 50 and 25 billion £ (2000 prices), showing the extent of the spending on the production and consumption side. The CAM scenario is implemented by investing more money in the consumption side, which leads to a significant decrease in energy demand, but not to the highest growth of the whole economy in the scenarios. On the other hand, a different allocation of the spending implemented for the CFH scenario, can lead to higher economic growth.

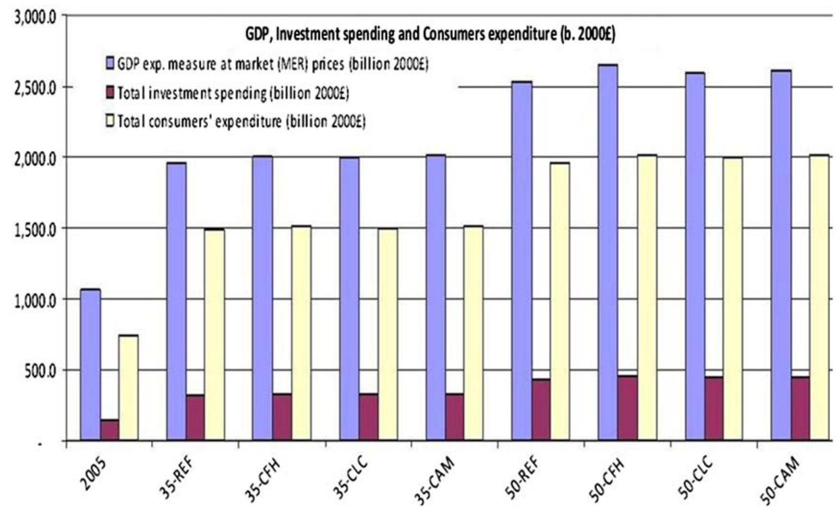

Fig. 10. GDP, investment spending and consumers expenditure (2000bn£) for the different scenarios for years 2005, 2035 and 2050.

5. Conclusions

Before deriving any particular conclusion from the scenarios presented in this paper, it is important to consider the modeling approach and the way the scenarios have been implemented with E3MG. E3MG being a macro-econometric model of the global economy has the advantage of examining policies at global and at national level, which is more important in cases of international efforts. The 40%, 60% and 80% reduction targets are not realistic options if implemented only by UK because they would not lead to a significant reduction in climate change and because no single country would easily take a decision moving towards such policies on its own. For these reasons we assume that the emissions reduction targets for the UK are implemented as part of international reduction targets. Based on the facts that the Obama USA Administration is committed to finding solution to climate change issue and the major developing countries are reluctant to adopt such policies in the medium term, a G8 reduction target of 40%, 60% and 80% by 2050 compared to 1990 levels seems to be a more realistic framework.

The E3MG model adopts a hybrid approach. The aggregate and disaggregate energy demand is estimated using econometric techniques, allowing for fuel switching for the 12 different fuel types and for the 19 fuel users, while the power sector is simulated using a probabilistic approach which considers the economic, technical, environmental characteristics of the power units but considers also the history. The electric system expansion is modeled by using parameters for the different technologies based on historical data on learning rates, which allows new technologies to gain a share in the market even when their cost is higher than conventional technologies. Moreover the dispatch of the different technologies to meet the electric demand, although using the cost optimization approach comparing the penetration of the different technologies, takes historical data as its starting point. Both the energy demand system and the energy technology options are implemented so as to model market imperfections which exist in all markets and are not usually considered in the classical cost optimization techniques. These market imperfections, resulting either from socio-political factors or from the presence of oligopolies that speculate on the electricity price, cause differentiation in the electricity mix across countries, and lead in many cases to significantly different profiles from those projected from models assuming perfect market conditions.

The scenarios are implemented in this framework, allowing the cumulative investment at global level for alternative technologies so their faster penetration provides solutions with a more diverse electric mix. It is also important to mention that the emission reduction scenarios are modeled not by imposing a reduction target and estimating the marginal abatement cost for meeting this target, but by applying different policies at different strengths and different timing, which is consistent with the theoretical background of the space–time economics adopted in the E3MG model. The strength and timing of a policy can trigger (or not) the penetration of a new technology. For example, large investments in electric cars in the medium term can lead to their fast penetration, while large investments in hydrogen cars take longer to have effect and so cannot have similar results. The different scenarios have been implemented by applying in different strengths and timing the policies of carbon pricing, direct investment and revenue recycling in the form of investments in the power sector, investments in the transport and other consumption sectors. The aim was all of them to have a positive effect, by reducing emissions whilst maintaining economic growth. This proves to be the most important conclusion of this paper, that there exist several portfolios of policies that can have large emissions reductions and also help the economy to grow. This finding is in contrast with those from many models predicting that energy investments will have an important negative effect on the economic growth, deriving from the assumptions in the neoclassical approach of full employment (so that there are no extra resources available to produce extra output) and of optimization of the baseline economy by a central planner (so that any shift away from the optimal solution will reduce GDP). But it is consistent with recent political decisions at EU, USA and Japan to invest on green technologies and infrastructure so as to boost their economies out of the global recession.

5.1. The UK energy system under decarbonisation pathways

The set of Carbon Ambition scenarios (40%, 60% and 80% CO_2 reductions from 1990 levels by 2050) offer insights on decarbonisation pathways and energy–economy–environment trade offs.

The reference scenario shows that a small reduction in energy demand and emissions is expected in the medium term (up to 2020) due to the number of energy efficiency policies already implemented (Barker et al. 2007). This reduction would be higher if the financial crisis at the end of year 2008 was considered, as a previous version of the model has been used. In the long run the model estimates that economic growth will lead to an increase of energy demand and emissions by 7% by 2050 compared to 1990 levels. The approach selected to implement the scenarios is consistent with the political will of major developed countries (USA and EU) to incentivise investments in green technologies so as to boost their economies. In the reference scenario such as investment plans are not considered and this leads to an electric mix with 50% gas and coal and 20% nuclear plants units by 2050. Transport sector is not expected to shift to electric vehicles and it is the dominant sector concerning emissions followed by the power and the building sectors.

Under the decarbonisation pathways, the power and the transport sector show the highest decrease in emissions and so constitute the most critical sectors for meeting deep reduction targets. The decarbonisation of the power sector happens in two directions: in the replacement of conventional units with nuclear or CCS plants and in the further penetration of renewables. The extent and the timing of the incentives for these technologies are critical. Renewables penetrate at levels lower than 50%, based on the assumptions on technical restrictions. Recent research work under the IEA on the penetration rates of renewables suggests levels up to 40% for the UK (Holttinen et al. 2006) due to stability and power quality issues. But the electrification of the transport sector allows an increase of the capacity factor of stochastic renewables such as wind, if accompanied by the proper tariff policies. So their penetration level in the electricity production has been allowed up to 50%, generated mainly from wind farms and secondly from biomass, marine and solar plants. In all scenarios the model produces solutions with higher energy diversity than expected from a cost-optimization solution. In that way the model's probabilistic approach resolves the problem of energy security. There is only one case where one technology (nuclear) penetrates more than 50% by 2050 in the electric mix, thus violating a possible indicator of resilience.

The decarbonisation of the electric and transport sectors leads to significant emission reductions and also maintains economic growth. In case where more incentives are provided on the consumption side (building and industry) for energy efficiency projects, the energy demand reduction helps towards emission reduction but the effect on the growth of the economy is smaller. The overall gains of the economy are in the range £55–130bn (2000 prices) in year 2050 depending on the scenario. There is no simple trade-off in emission reduction and economic growth: all the scenarios show higher GDP compared to the reference case (REF); the 40% reduction scenario (CFH) leads to higher GDP compared to the other scenarios, but the 80% reduction (CAM) leads to higher GDP compared to the 60% reduction (CLC) scenario. These results are attributed to the strength and timing of the policies implemented. CFH has a lower reduction target but has also, through regulation, a higher shift of transport into electric vehicles and a higher penetration of wind. The ambitious scenario, CAM, has more positive effect on GDP compared to CLC, because the more stringent target can only be achieved through stronger regulation, encouraging faster adoption of new carbon-reducing technologies and higher investment. The CAM scenario implies a global technological revolution in favour of low-carbon products and processes, achieving lower costs through economies of specialization and scale.

Decarbonising the global energy system is a timing and well as a political problem with the different portfolios of policies becoming preferable depending on the final and intermediate targets. Achieving the stringent 80% target for the UK by 2050 appears feasible, while maintaining economic growth, but implies adoption of a portfolio of policies including strong regulation and high carbon prices.

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