UCL ENERGY INSTITUTE

INTERTEMPORAL ISSUES AND MARGINAL ABATEMENT COSTS IN THE UK TRANSPORT SECTOR*

Fabian Kesicki

Energy Institute
University College London
14 Upper Woburn Place
London WC1H 0NN, United Kingdom
E-mail: fabian.kesicki.09@ucl.ac.uk

Abstract

Many G20 countries, including the United Kingdom (UK), have committed themselves to stringent emissions reductions with envisioned abatement paths through to 2050. To illustrate the costs associated with the decarbonisation of the energy system, marginal abatement cost (MAC) curves have been frequently used by policy makers. Although MAC curves are subject to intertemporal interactions, they are generally presented as a static snapshot of one year. Therefore, the robustness of such a curve is tested for two important parameters: path dependency and discount rate. A sensitivity analysis concerning a MAC curve for the UK transport sector is carried out. Path dependency, is found to be a significant, yet not substantial, influencing factor on the shape and the structure of the MAC curve. Doubling the discount rate from 5% to 10% showed that emission abatement would be much more expensive, while a switch to a societal perspective did not have a significant effect. This can be explained by the reduced annual investment costs and the reduced fuel savings evening out. The results suggest that assumptions concerning the CO2 tax path should be clearly stated and that the level of the discount rate has a major influence and should be carefully chosen.

Keywords

Emissions reduction, MAC curve, path dependency, discounting, transport, energy system modelling, decomposition analysis

* The support of a German Academic Exchange Service (DAAD) scholarship is gratefully acknowledged.

1 INTRODUCTION

The United Kingdom (UK), along with many other developed countries, has committed itself to deep CO_2 emission cuts of 80% in 2050 compared with 1990 levels. This implies that all sectors of the economy will have to reduce emissions substantially during the first half of the 21st century. The Committee on Climate Change (2010), an independent body set up to advise the UK government on reducing greenhouse gas emissions, recommends in its fourth carbon budget report that emissions should be reduced by 60% in 2030 compared to 1990 in order to achieve the emission target in 2050. In this context, it is an open question of how to reduce emissions cost-efficiently.

Marginal abatement cost (MAC) curves, which quantify the abatement costs and potentials, are used to assist answering this question. MAC curves have become a standard tool to illustrate the economics of climate change mitigation. They are increasingly used by environmental economists in many countries as a tool for policy analysis. In most cases, policy-orientated MAC curves are based on the individual assessment of abatement measures and subsequently ranked from cheapest to most expensive (HM Government 2009; Nauclér and Enkvist 2009; Kennedy 2010). This causes several problems in the form of negligence of technical, behavioural, intertemporal and economic interactions, possible double counting and a limited treatment of uncertainty (see e.g. Stoft 1995; Fleiter et al. 2009; Kesicki 2010a). To address these problems, bottom-up and top-down energy models have been used to generate MAC curves (Ellerman and Decaux 1998; Criqui et al. 1999; van Vuuren et al. 2004). A systems approach is used for this study based on an energy system model, UK MARKAL, in combination with decomposition analysis. This paper focuses on sectoral MAC curves and does not consider MAC curves as the marginal profit of one more unit of emissions of a single firm (see e.g. McKitrick 1999; Bauman et al. 2008).

Many factors have been studied for their influence concerning the shape and structure of a MAC curve: fossil fuel prices (AEA Energy & Environment et al. 2008; Nauclér and Enkvist 2009), technological learning/innovation (Barker et al. 2006; Baker and Shittu 2007; Amir et al. 2008; Bauman et al. 2008; Hazeldine et al. 2009; Nauclér and Enkvist 2009), model choice (Fischer and Morgenstern 2006; Kuik et al. 2009), the inclusion of further greenhouse gases beside CO_2 (Morris et al. 2008; Kuik et al. 2009), carbon capture and storage (Kuik et al. 2009) and carbon trading (Ellerman and Decaux 1998; Criqui et al. 1999; Klepper and Peterson 2003).

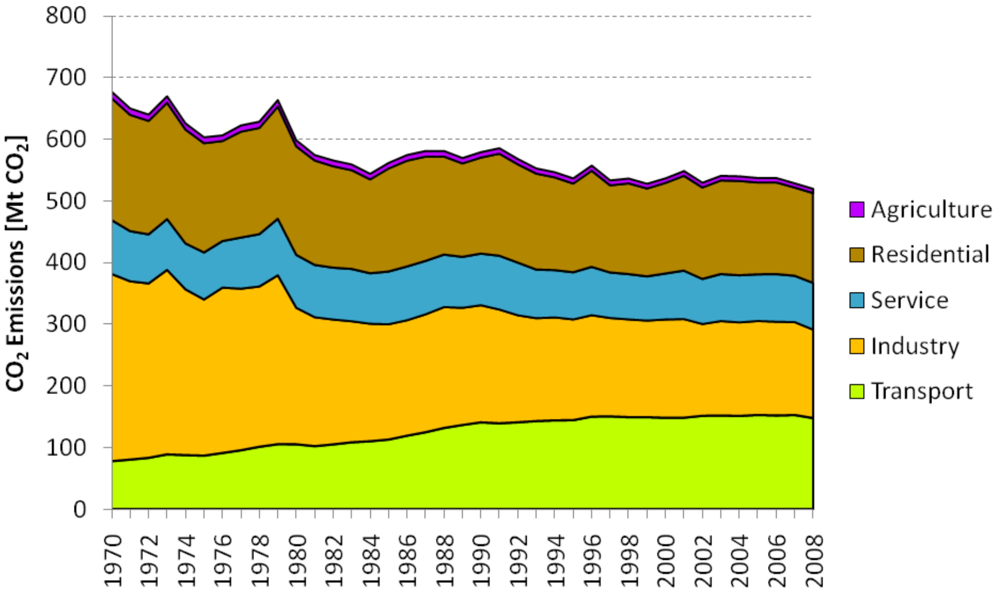
Since MAC curves are a static snapshot of one year's emission reduction, a major and potentially important weakness is the negligence of intertemporal aspects that have not been intensively studied. In some cases static MAC curves are even taken as an input for other models to calculate potential carbon trade flows. In a broader context, the appropriate choice of discounting costs in the context of climate change mitigation over a long time horizon has been discussed in the past (Manne et al. 1995; Azar and Sterner 1996; Nordhaus 1999; Newell and Pizer 2003). This debate intensified with the publication of the Stern report (Stern 2007; Tol and Yohe 2009). Path dependency, i.e. the phenomenon that abatement costs and potentials depend on previous efforts, has not aroused the same amount of interest (see e.g. Webster 2008). In order to address these gaps in research, this paper looks at intertemporal issues in the context of MAC curves.

As the employed model is a perfect foresight model, not only past actions determine abatement costs and potentials in one period, but also expectations about future carbon policies. So far the only study that has dealt with path dependency issues concerning MAC curves is Morris et al. (2008). Using a general equilibrium model the authors found the influence of path dependency to be substantial for MAC curves in 2050. This paper looks specifically at the year 2030, an important medium-term target for emission reduction, and so the influence of path dependency is expected to be more limited compared with 2050.

The influence of discount rates on MAC curves have been studied in several studies. Discount rates are used in order to compare costs and benefits in different time periods. While Blok et al. (1993) studied the influence of different discount levels on energy conservation techniques and did not find a significant influence, AEA et al. (2008) applied a social and private discount rate for the UK transport sector. The authors find that moving from a private discount rate to a social one significantly increases the marginal abatement costs as fuel duties are not considered. However, this study looks only at the transport sector and therefore neglects any interactions with other sectors, in particular power production. Nauclér and Enkvist (2009) generate a global expert-based MAC curve and find that the discount rate has only a limited influence on abatement costs in 2030.

In the UK, the overwhelming majority of all CO_2 emissions originate in the energy system (97.5% in 2008). This paper specifically looks at the situation in the transport sector as transport-related emissions accounted for 28% of all energy-related CO_2 emissions in the UK in 2008. Of all energy end-use sectors, transport-related emissions now account for the highest share and it is the only sector where emissions have continuously increased over the last four decades (see Fig. 1). One reason is the increasing demand for transport services, which is not expected to change in the near future. Furthermore, the transport sector is at the moment almost completely dependent on refined products based on crude oil and different transport modes with millions of vehicles that render abatement actions difficult.

Fig. 1: CO_2 emission by final user in the United Kingdom from 1970 to 2008



Source: Department of Energy and Climate Change (2010)

The aim of this paper is to contribute to the debate on the timing of emission reduction and intertemporal issues surrounding costs of emission reduction. More specifically, uncertainties related to path dependency and the choice of the discount rate on abatement costs and abatement potentials in the UK transport sector are quantified. First, the technology-specific abatement potential and associated abatement costs are assessed, taking into account interactions in the whole energy system. Secondly, a sensitivity analysis helps to single out the influence of path dependency and the discount rate on the MAC curve.

The next section briefly presents the general approach to generate MAC curves via the use of an energy system model and decomposition analysis. Section 3 presents the scenarios that have been performed and section 4 presents the results for the UK transport sector. Finally, the paper is concluded with section 5, which argues that a reduction in the carbon intensity of electricity and structural changes are important sources of emission reduction in the UK transport sector.

2 METHODOLOGY

In order to overcome the shortcomings in present approaches to generate MAC curves, the approach outlined in this paper combines energy system modelling with decomposition and sensitivity analysis. For a detailed discussion of the approach, see Kesicki (2010b).

2.1 ENERGY SYSTEM MODELLING

For the calculation of MAC curves, an energy-economic model-based approach provides a solid theoretical basis, through a technologically explicit, partial equilibrium, consistent optimisation framework. A systems approach serves as a base to calculate abatement cost curves taking into account interactions between mitigation measures. The MARKAL (MARKet ALlocation) energy model generator, developed within the International Energy Agency's ETSAP consortium, is used within this context.

MARKAL is a dynamic, technology-rich linear programming (LP) energy system optimisation model. In its elastic demand formulation, accounting for the response of energy service demands to prices, its objective function maximises producer and consumer surplus under conditions of perfect foresight. The bottom-up model, MARKAL, portrays the entire energy system from imports and domestic production of energy carriers through to fuel processing and supply, explicit representation of infrastructures, conversion of fuels to secondary energy carriers, end-use technologies and energy service demands of the entire economy. Full details of the optimisation methodology is given in Loulou et al. (2004). A comprehensive description of the UK model, its applications and core insights can be found in Strachan et al. (2008), and in the model documentation (Kannan et al. 2007). The UK MARKAL model, which is calibrated to the UK context concerning technologies, costs and the policy context, has been used in many different research studies (Strachan et al. 2009; Anandarajah and Strachan 2010). All existing UK or EU climate policies were excluded from the UK MARKAL model in order not to dilute the calculation of marginal abatement costs.

In the transport sector of the UK MARKAL model, the energy service demands, measured in billion vehicle kilometres, are included for various modes of transport: air travel, car travel, bus travel, heavy goods vehicles (HGV), light goods vehicle (LGV), rail transport and two-wheeler. In addition, it has a number of fuel distribution networks to track fuel use by mode of transport. To meet the different transport energy service demands, a number of vehicle technologies are integrated in the model. Those include internal combustion engine (ICE) vehicles, hybrid vehicles, plug-in vehicles, battery vehicles, E85 vehicles (flexible-fuel vehicles that can run on as much as 85% of ethanol in the fuel mix), methanol vehicles and hydrogen vehicles. A number of key data parameters that are required to characterise the transport vehicle technologies, such as technical efficiency of a vehicle, capital cost, vehicle lifetime or annual kilometres usages, are defined in the model.

2.2 DECOMPOSITION ANALYSIS

Decomposition analysis (in this paper used as a synonym for index decomposition analysis) helps to bring technological detail in the representation of the MAC curve. This technique is a well established research methodology to decompose an aggregated indicator, usually either energy use or CO_2 emission, into its drivers (see Ang and Zhang 2000).

In this study, the resulting CO_2 emission in the transport sector are decomposed into four different effects: activity effect, structure effect, fuel intensity effect and carbon intensity effect:

$$CO_{2,Transport} = \sum_{i=vehicle\ type} activity_i * \left(\sum_{j=technology} \frac{activity_{i,j}}{activity_i} * \frac{fuel_{i,j}}{activity_{i,j}} * \frac{CO_{2,Transport,i,j}}{fuel_{i,j}} \right) \quad (1)$$

The activity is the energy service demand in billion vehicle kilometres, $fuel_{i,j}$ describes the amount of fuel that is necessary to satisfy demand *i* with technology *j*. $CO_{2,Transport,i,j}$ represents the amount of CO_2 released by the use of technology *j* to satisfy demand *i*.

The emphasis is not on an absolute number but on what influences the change in CO_2 emissions in the transport sector, so that Equation (1) can be expressed in the following way:

$$\Delta CO_{2,Transport} = \Delta activity\ effect + \Delta structure\ effect + \Delta fuel\ intensity\ effect + \Delta carbon\ intensity\ effect + residual \quad (2)$$

In the past there have been many approaches to distribute the residual terms to the other variables in order to achieve a so-called perfect decomposition (Ang 2004). This is regarded as easier to interpret as it does not include a residual term. In this study the Logarithmic Mean Divisia Index (LMDI) is used (Ang et al. 1998). The LMDI is used because it leaves no residual and therefore gives a perfect decomposition. Furthermore, it does not differ significantly from other perfect decomposition methods and its calculation is comparably easy.

3 SCENARIOS

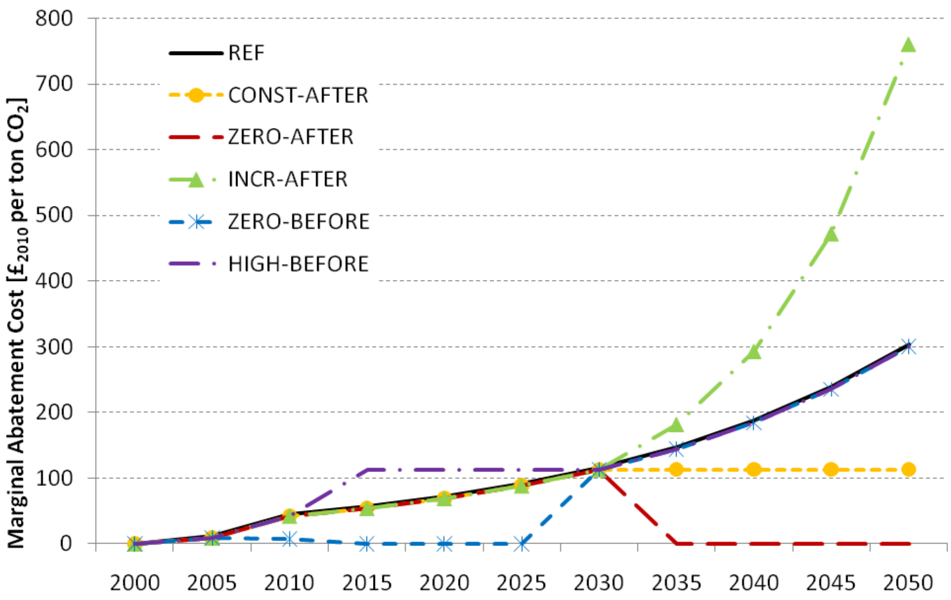
This paper looks specifically at the influence of path dependency and the choice of the discount rate on the shape and structure of a MAC curve that covers direct and indirect emissions in the transport sector. Indirect emissions are emissions that occur in other sectors due to energy consumption in the transport sector, e.g. electric vehicles consume electricity, which is to some extent produced by burning fossil fuels and thereby emits CO_2. The consideration of uncertainty in the form of sensitivity analysis can help to draw conclusions about the robustness of a MAC curve. In total, eight scenarios are considered: one reference scenario, five path dependency scenarios, and two discount rate scenarios (see also Table 1).

Table 1: Overview of scenarios

Scenario	Category	Descritpion
REF	*Reference*	Carbon tax increases with 5% p.a. from 2010
ZERO-BEFORE	*Path dependency*	Carbon tax is zero before 2030
CONST-AFTER	*Path dependency*	Carbon tax is constant after 2030
INCR-AFTER	*Path dependency*	Carbon tax increases with 10% p.a. from 2030
ZERO-AFTER	*Path dependency*	Carbon tax is zero after 2030
HIGH-BEFORE	*Path dependency*	Carbon tax is kept constant at the 2030 level used in the BASE scenario for the period 2015-2030
PDR10	*Discount rate*	Discount rate increased to 10%, hurdle rates doubled
SDR	*Discount rate*	Discount rate lowered to 3.5%, all hurdle rates, taxes and subsidies removed

To illustrate the different path dependency scenarios, Fig. 2 presents the different CO_2 tax pathways for one exemplary model run (£113/t CO_2 in 2030), where three consider different pathways after 2030, CONST-AFTER, ZERO-AFTER, INCR-AFTER, and two regard different pathways before 2030, ZERO-BEFORE, HIGH-BEFORE.

Fig. 2: CO_2 tax trajectory for different path dependency scenarios for a model run with a CO_2 tax of £113/ t CO_2 in 2030



In order to generate a MAC curve for a scenario, 46 model runs with different model-wide CO_2 tax levels are generated. In the REF scenario, the CO_2 tax increases over time from 2010 to 2050 at a discount rate inherent to the model of 5% p.a. As an example, a CO_2 tax of £98/t CO_2 in 2030 corresponds to £50/t CO_2 in 2020, £160/t CO_2 in 2040, and £260/t CO_2 in 2050. In the 46 different model runs, the CO_2 tax is varied between $£_{2010}$ 0 per ton CO_2 to $£_{2010}$ 294 per ton CO_2 in the year

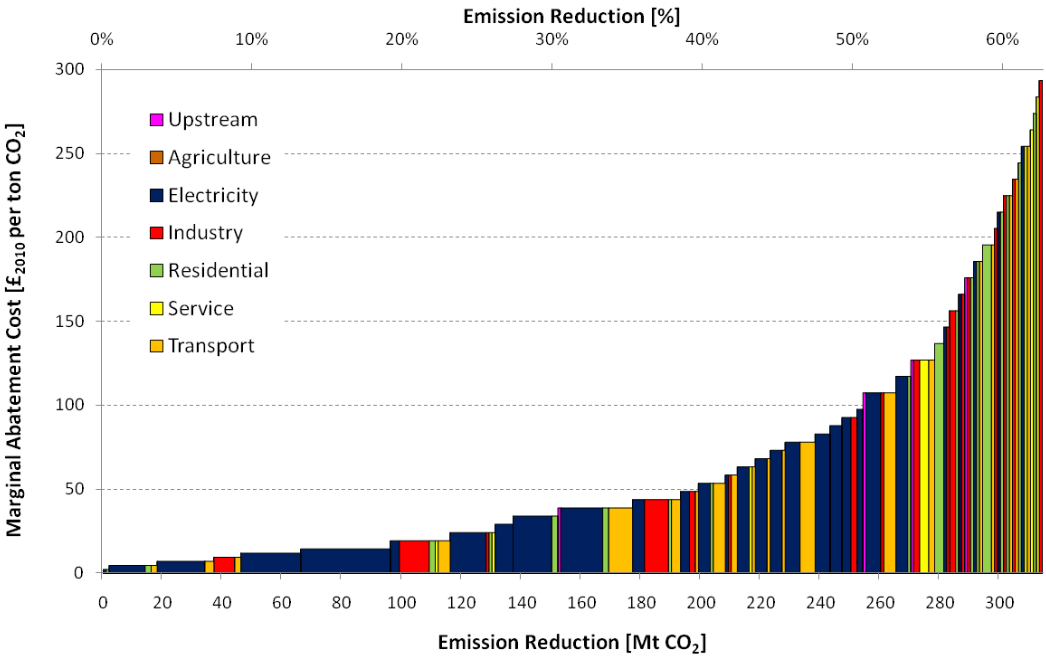
2030, i.e. the first run is £0/t CO_2, the second is £0.5/t CO_2, the third is £1/t CO_2, the 20th is £64/t CO_2 and the last is £294/t CO_2. A CO_2 price of £100/t CO_2 corresponds to an increase of about £31 for a barrel of crude oil. All the 46 model runs with different CO_2 taxes are calculated and later on consolidated to a MAC curve for one scenario. All costs are given in £ of the year 2010 (long-term exchange rate £=1.4€ and £=1.8$).

4 RESULTS

4.1 SYSTEM-WIDE MAC CURVE

Before turning towards the results for the transport, a MAC curve in the REF scenario for the whole energy sector showing the contribution of each sector gives insights into the wider abatement structure (Fig. 3). The height of each bar represents the marginal abatement cost, while the width represents the emission abatement and the colour indicates the sector.

Fig. 3: Marginal Abatement Cost Curve for the UK Energy Sector in 2030 in the REF scenario

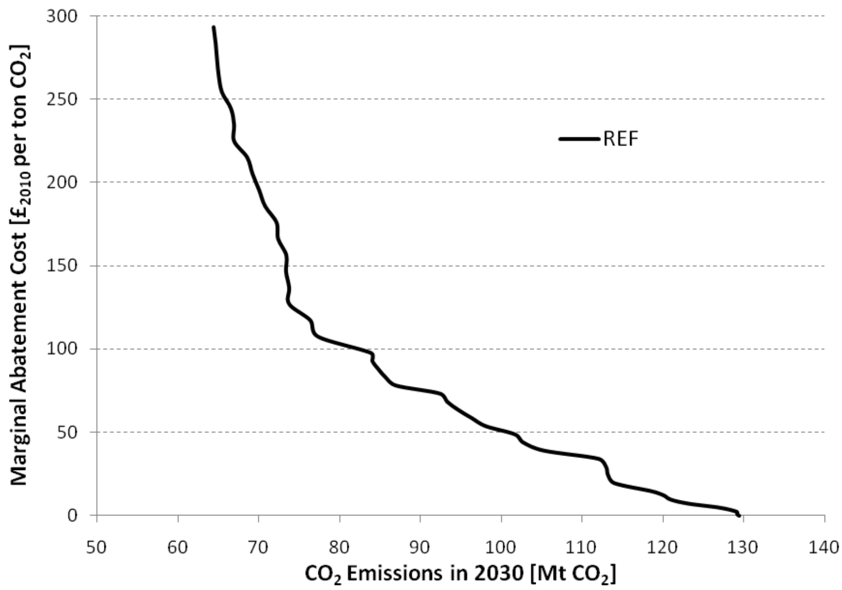


Model results indicate that total energy-related CO_2 emissions in 2030 are 502 Mt CO_2 without any CO_2 policy. In the model run with the highest implemented CO_2 tax of £294/t CO_2, emissions are reduced to 187 Mt CO_2. This corresponds to an emission reduction of 63% compared to the no-tax model run and to a 68% emission reduction compared to 1990 levels. Most of the low-cost abatement potential can be found in the electricity sector, which accounts for almost 44% of all CO_2 emissions by source, followed by the transport sector with 24%, industry with 9% and the residential sector with 7%. It is apparent that there are some low-cost abatement options in industry, transport and the residential sector, but the contribution of end-use sectors is only dominant from around £100/t CO_2 on.

4.2 REFERENCE SCENARIO

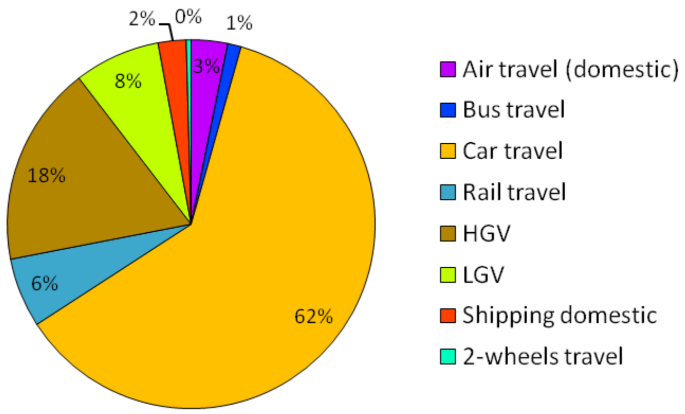
While Fig. 3 shows the contribution of each sector, in the following analysis of the transport sector, emissions have been attributed from an end-use perspective, i.e. emissions resulting from the generation of electricity that is consumed in the transport sector are assigned to the transport sector. Thus, this analysis comprises direct, as well as indirect emissions in the transport sector. According to the model results, transport emissions from an end-use perspective are 130 Mt CO_2 in 2030 in £0/t CO_2 tax run, which compares to 134 Mt CO_2 in 1990. Fig. 4 shows an emission curve for the transport sector from an end-use perspective. At a price of £100/t CO_2 emissions are reduced by 50 Mt CO_2 to a level of 80 Mt CO_2 and from then on more gradually to 65 Mt CO_2. This representation does not only allow insights on the emission reduction from a baseline, but also to put the absolute emissions into perspective.

Fig. 4: End-use emission curve for the transport sector (REF scenario) in the United Kingdom in 2030



130 Mt of CO_2 emissions at no CO_2 tax originate from different transport modes (see Fig. 5). As the majority of all travel is done via cars, this transport mode is responsible for 62% of all end-use transport emissions in 2030. The second most important source of CO_2 emissions are heavy goods vehicles (HGVs) with 18%, followed by light goods vehicles (LGVs) with 8% and rail travel with 6% of all transport emissions. Minor contributions come from airplanes (3%), shipping (2%), bus (1%) and two-wheelers (<1%). Correspondingly, one can expect to see emission reduction measures predominantly associated with those transport modes that emit the most CO_2, i.e. cars, HGVs and LGVs.

Fig. 5: CO_2 emissions from different transport modes in United Kingdom in 2030



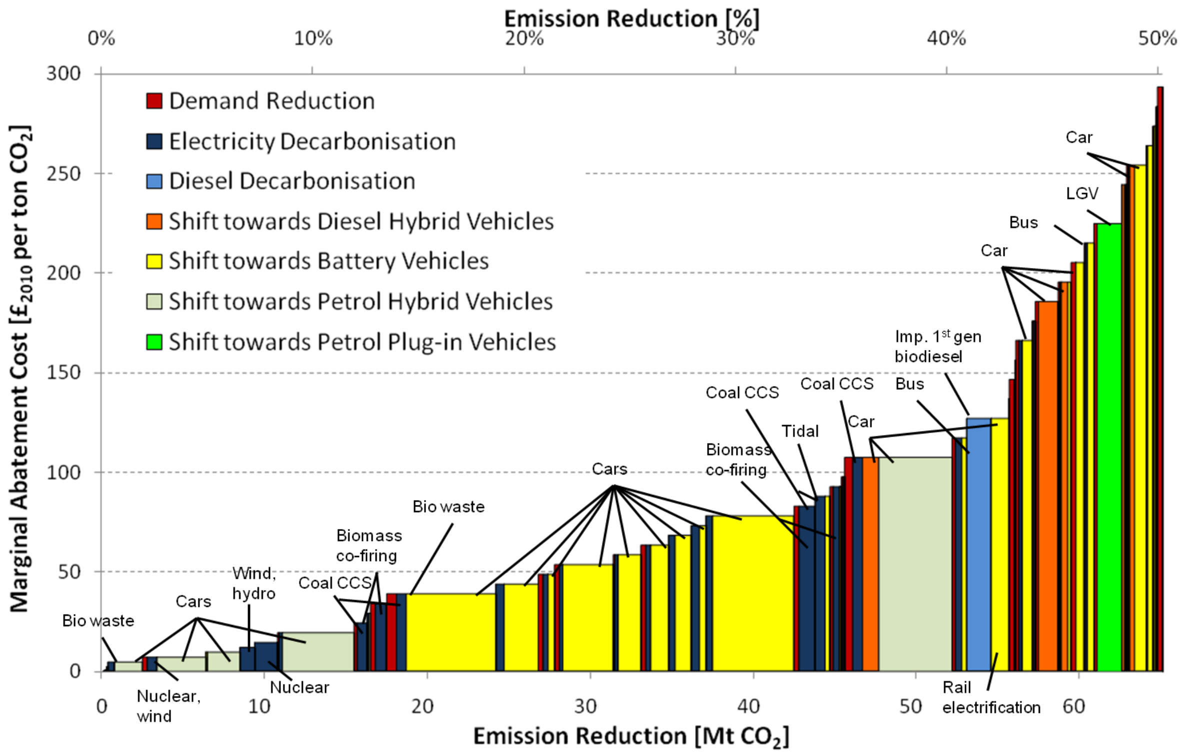
In order to judge the technological structure of the MAC curve it is important to know what propulsion systems are used for the different transport modes in the REF case. Without any CO_2 price, the transport sector is characterised by cars that rely on petrol/diesel ICE vehicles and petrol hybrids (46%) and buses with diesel hybrid engines. A small proportion of buses (12%) are vehicles equipped with a battery. The large majority of light goods vehicles as well as heavy goods vehicles are also propelled by diesel hybrid engines. 7% of all rail travel does not use electricity, but relies on diesel as a fuel.

Fig. 6 shows that structural shifts and the decarbonisation of fuels are responsible for the majority of emissions reductions in the REF scenario. Demand reduction due to higher costs for energy service demands represent a constant but minor contribution. The demand contribution is limited due to structural changes that keep the price for energy service demand relatively constant, especially for cars. Nevertheless, alternative technologies are limited for aviation, shipping and HGV, so that these transport modes show a disproportionately high demand reduction. In addition, one can distinguish two major trends in the MAC curve.

Firstly, the predominant trend in the transport sector is the electrification of most of the transport modes. The cheapest option to reduce transport emissions is the switch from conventional petrol cars towards petrol hybrid cars as they are more efficient and consume less fuel. Mainly in a range from £40/t CO_2 and £80/t CO_2, battery cars become cost-efficient and make up 43% of all cars. This trend is accompanied by a decarbonisation of electricity. It is an important condition since electricity is used as an energy input for almost all trains, for slightly more than 10% of all buses and from £40/t CO_2 a significant proportion of cars. Major structural changes away from coal-fired power plants to nuclear power, biomass co-firing, coal CCS plants, wind power and tidal power are responsible for this development. This plays a major role up to £40/t CO_2, where electricity is decarbonised by 80% compared to £0/t CO_2 in 2030. At a higher tax of around £225/t CO_2, LGVs partly shift to petrol plug-in vehicles and thereby reduce CO_2 emissions via a higher consumption of electricity instead of petrol.

A second minor trend concerns cars and light goods vehicles consuming diesel. Diesel begins to be slightly decarbonised (by 5%) around £125/t CO_2 due to a higher share of imported first generation biodiesel in the diesel mix. The decarbonisation of this secondary energy carrier via the increase of the share of biodiesel reduces the CO_2 emissions from transport modes relying on diesel, i.e. bus, car, LGV and HGV.

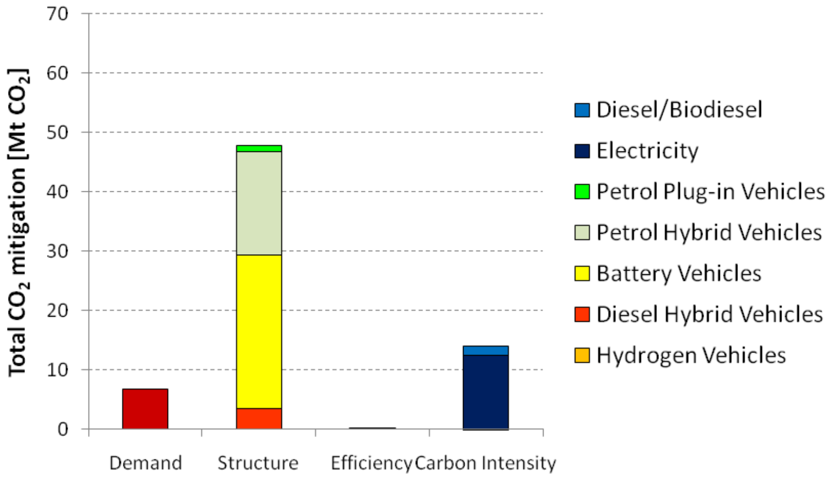
Fig. 6: MAC curve for the REF scenario in 2030



At the upper end of the MAC curve, conventional diesel cars are displaced by diesel hybrid cars in a range from £100 to £250. Diesel hybrid cars are at a higher cost level in the MAC curve because the additional investment cost of diesel hybrids compared with diesel ICE cars is higher than the additional cost of petrol hybrids compared with petrol ICE cars. In 2030, the investment cost premium for an average car is assumed to be £1556 for petrol hybrid cars, but £2054 for diesel hybrid cars. This is based on the reasoning that nowadays most hybrid vehicles are petrol vehicles, so that technology costs can be reduced more quickly for petrol hybrids than for diesel hybrids. Even this small difference in investment cost premia is important as the reduced fuel costs of hybrids compensate for the higher investment costs only gradually with higher CO_2 taxes due to the fact that most of the diesel and petrol price consists of fuel taxes and the oil price makes up only a relatively small part. Consequently, the mitigation cost of hybrid vehicles are very sensitive to the assumptions, not only investment costs, but also hurdle rates and efficiency advantage.

An idea of the overall contribution of different technologies and effects for the emissions reductions up to the highest CO_2 price of £294/t CO_2 in 2030 is given in Fig. 7, which summarises the results for CO_2 emissions reduction due to demand changes, structural shifts, efficiency improvements, and carbon intensity reductions. The reduction in the demand for energy services caused by higher prices, has a minor (10%), but constant, contribution. This finding, though, is dependent on the specified price elasticity of energy service demands.

Fig. 7: Total decomposition of transport MAC (REF scenario) for the UK in 2030



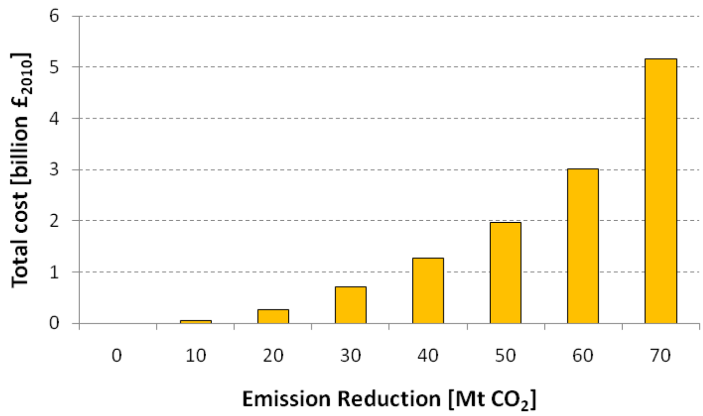
A reduction in fuel intensity (equivalent to efficiency improvement) does not contribute to emissions reductions in the transport sector. This means that carbon prices do not present an incentive for efficiency gains in addition to those present in the base case. Significant efficiency improvements are already incorporated in the base case as they are assumed to be cost-efficient even without a CO_2 tax. Possible efficiency gains are relatively small (in the order of a few percent) and affect only a limited portion of the entire vehicle fleet. More importantly, since structural changes dominate the transport sector and since road vehicles have an average life time of 7 to 15 years, investments into more efficient vehicles will not be realised given an anticipated switch to a different technology. Another reason is the poor treatment of efficiency options in the model so that the fuel intensity effect could possibly change under an alternate model type.

The most important effects for carbon reduction are structural changes and the decarbonisation of electricity and diesel. 70% of total carbon reduction originates from structural changes. This is shared between battery vehicles (38%), petrol hybrid vehicles (25%), diesel hybrid vehicles (5%), and petrol hybrid vehicles (2%). The decarbonisation of fuels contributes 20% towards CO_2 emission reduction. Only a small proportion (2%) comes from a higher share of biodiesel due to the fact that it is more efficient to use the available biomass resources in the power sector and in buildings for space and water heating.

This stresses the importance of the supply sectors and the corresponding decarbonisation of secondary energy carriers in order to achieve mitigation targets for the transport sector. Structural changes and a reduction of carbon intensive electricity are pivotal for emission reduction in the transport sector, where structural changes are in general preceded by a decarbonisation of the concerned energy carrier.

Taking the integral under the curve in Fig. 6 gives information about the total cost associated with emissions reduction in 2030. This does, however, not consider costs associated with carbon abatement in earlier and later time periods. Fig. 8 indicates that total costs increase exponentially with an increasing emission reduction target. Total cost in 2030 are £1.96 billion for an emission reduction of 50 Mt of transport-related CO_2 emissions and £5.17 billion for a reduction of 70 Mt CO_2, this corresponds to an average abatement cost of £39/ t CO_2 and £74/t CO_2 respectively.

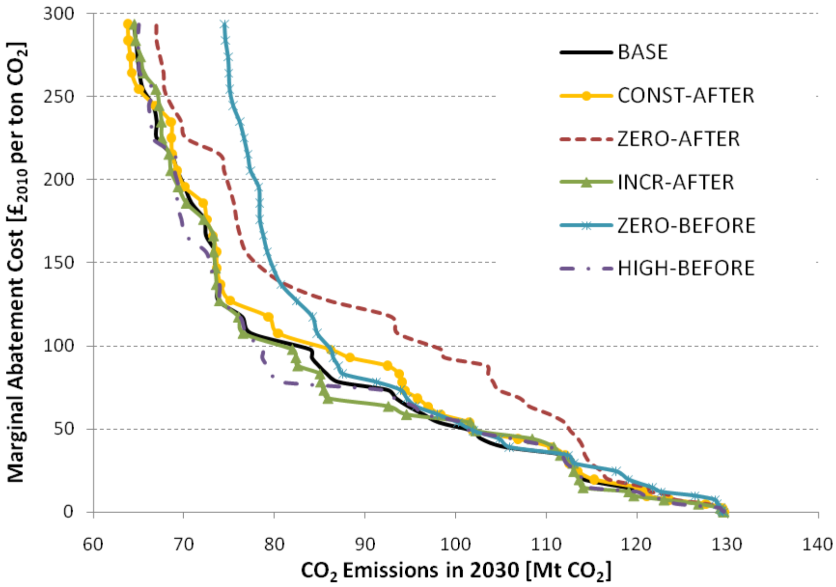
Fig. 8: Total cost for the transport sector in United Kingdom in 2030 in the REF scenario



4.3 PATH DEPENDENCY

MAC curves are merely a static snapshot of one year, in this case of the year 2030. Nevertheless, the abatement cost and the corresponding abatement potential of all abatement measures depend on previous abatement efforts and on uncertain expectations of future developments. As the model underlying the MAC curves is a perfect foresight model, the MAC curve is influenced by future climate change policies. In order to quantify how sensitive the MAC curve reacts to different CO_2 tax trajectories the CO_2 tax path of an annual 5% increase has been altered in five scenarios (see Fig. 2). Although all six scenarios have the same CO_2 tax in 2030, they result in different MAC curves, especially for higher abatement costs (see Fig. 9). Those scenarios with a higher CO_2 tax compared with the REF scenario, i.e. INCR-AFTER and HIGH-BEFORE show for the same carbon price generally a slightly higher abatement level. The CONST-AFTER scenario, which keeps the CO_2 tax constant after 2030, shows only a very limited divergence from the REF scenario.

Fig. 9: End-use emission curve for different path dependency scenarios



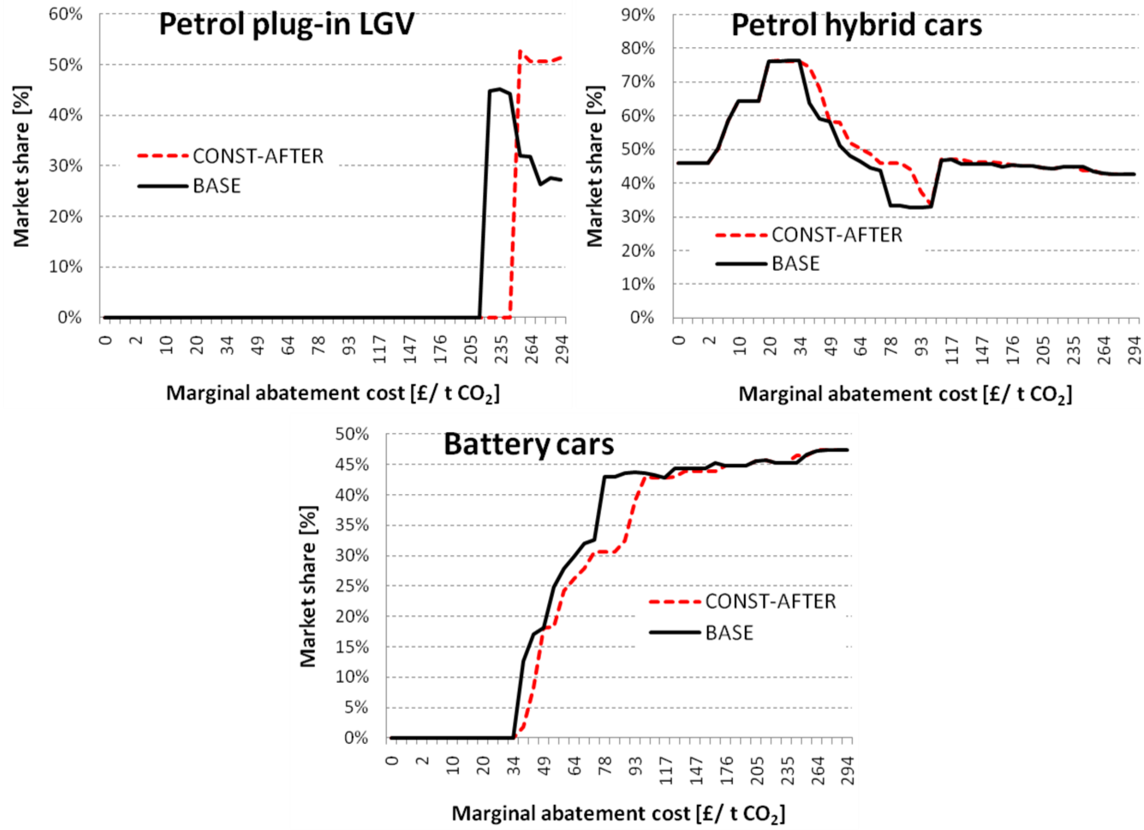
The emission curves for all three mentioned scenarios look very similar to the REF emission curve, where, for a given CO_2 tax, the biggest difference in the abatement potential is 9%. The picture looks different for the scenarios where the CO_2 tax is kept at zero before or after 2030, which significantly increases the marginal abatement costs. While the abatement potential is significantly lower for a given CO_2 tax up to £150/t CO_2 in the ZERO-AFTER scenario, it is the inverse case for the ZERO-BEFORE scenario where the abatement potential is less from around £100/t CO_2 on.

4.3.1 CONSTANT CO_2 TAX AFTER 2030

The CONST-AFTER scenario differs from the REF scenario in the way that the CO_2 tax does no longer increase with the model inherent global discount rate of 5% p.a. after 2030, but instead stays constant at the same level as it is in 2030. The incentive for CO_2 abatement is therefore less than in the REF scenario. Consequently the MAC curve can be expected to be steeper.

It turns out that the MAC curve looks very similar and that the constant CO_2 tax after 2030 has only a small cost-increasing effect. Fig. 10 reveals that the abatement cost is slightly higher for certain technologies in the CONST-AFTER scenario, i.e. £5-25/t CO_2 more for battery cars, £15/t CO_2 more for diesel hybrid cars and £29/t CO_2 more for LGVs.

Fig. 10:: Market share for different technologies in the CONST-AFTER scenario in 2030



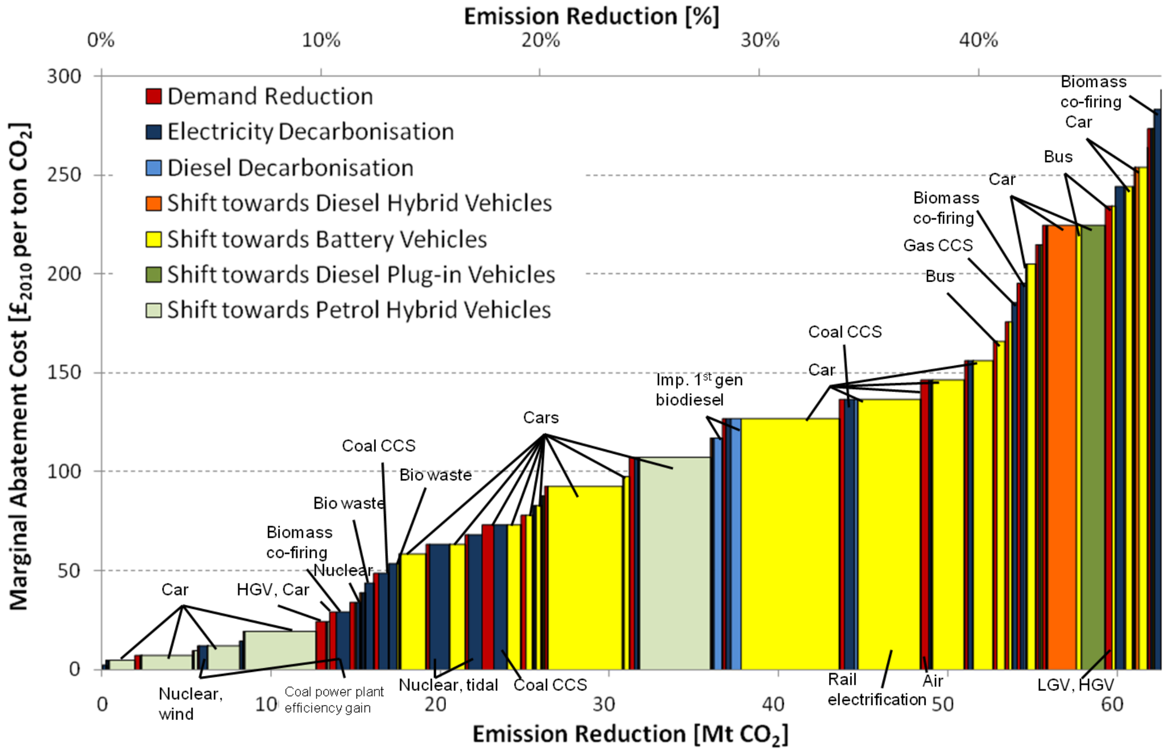
Petrol plug-in LGVs become cost-efficient in the CONST-AFTER scenario at a higher cost level of £254/t CO_2 because petrol plug-in LGVs are used during the whole model horizon after 2030 and only partially replaced by diesel plug-in LGVs in 2050. In contrast to this, hydrogen becomes an important fuel for LGVs in the REF scenario after 2030 from around £250/t CO_2 on, so that petrol plug-in LGVs are earlier introduced, but to a smaller extent compared to the CONST-AFTER scenario as the technology replacement is anticipated. Furthermore, the market share of petrol plug-in LGVs is not reduced with rising marginal abatement cost as no hydrogen vehicles become cost-efficient in later periods.

Petrol hybrid cars are the cheapest abatement option and up to £34/t CO_2 their market share increases to 76% in compensation for petrol internal combustion engine (ICE) cars (see Fig. 10). From this CO_2 tax level upwards, the market share declines steadily up to £98/t CO_2 as battery cars take over the market share. This decline is slower in the CONST-AFTER scenario due to the fact that the introduction of battery cars happens at higher cost levels. A last increase in market share can be observed at £108/t CO_2, where all remaining petrol ICE cars are replaced by petrol hybrid cars. A reason for the later introduction of battery cars is that the CO_2 tax does not increase as rapidly as in the REF scenario after 2030, which leads to a situation where electricity is not as quickly decarbonised.

4.3.2 ZERO CO_2 TAX AFTER 2030

This path dependency scenario assumes a CO_2 tax that drops back to zero for all model runs after 2030. This means that there is less of an incentive to shift the energy system to low carbon technologies because there is no penalty for emitting CO_2 after 2030. Correspondingly, one should expect less emission reduction for the same CO_2 tax level. A look at Fig. 9 and Fig. 11 reveals that the ZERO-AFTER scenario is up to £50/t CO_2 more expensive compared with the REF scenario and in total it results in 2.5 Mt CO_2 less abatement.

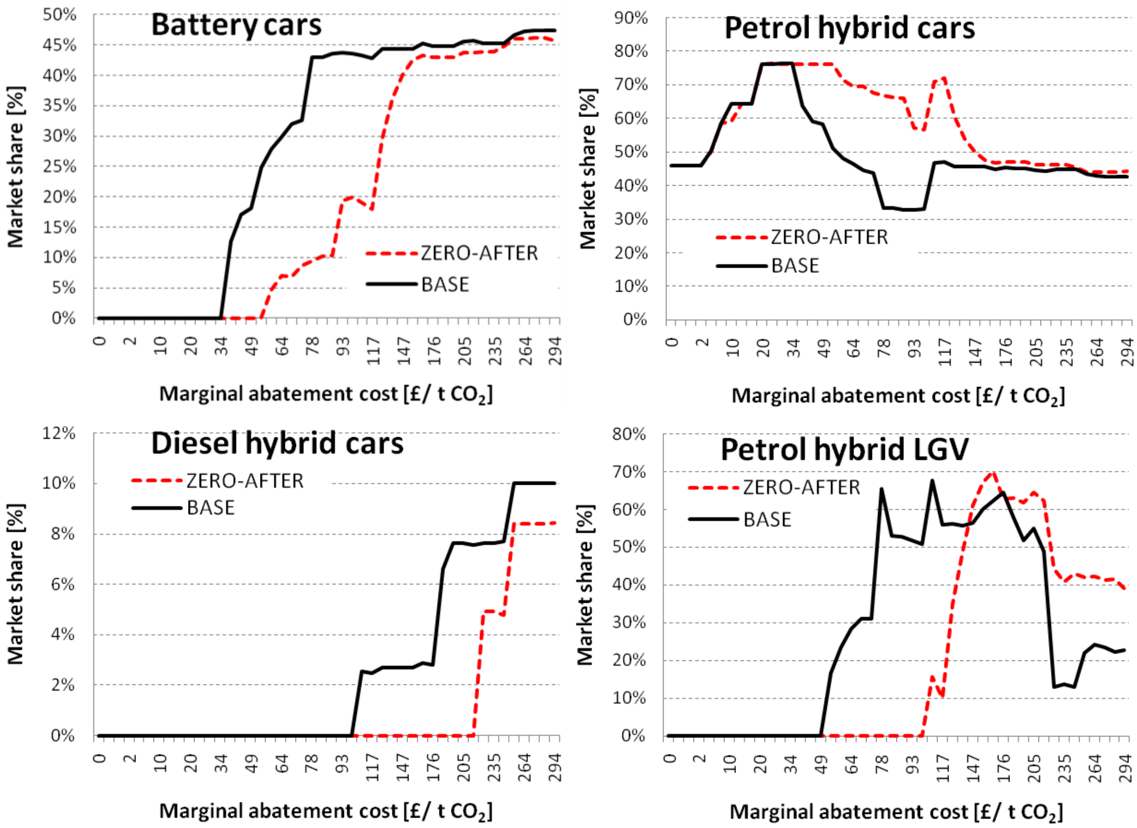
Fig. 11: MAC curve for the ZERO-AFTER scenario in 2030



The MAC curve indicates that mitigation technologies, such as petrol and diesel hybrid cars, and battery cars are introduced to the market at higher marginal abatement costs. It is also interesting to note that the whole MAC curve only includes technological mitigation measures relating to cars and buses, i.e. there are no structural changes within LGVs. Petrol plug-in LGVs do not become cost-efficient up to £294/t CO_2, while petrol hybrid LGVs need a carbon tax that is £54/t CO_2 higher than in the REF scenario to enter the market. This is not reflected in the MAC curve because the reference technology is diesel hybrids, so that a switch does not result in an emission reduction. In anticipation of the CO_2 tax disappearing after 2030, the model does not choose petrol plug-in LGVs. The abatement potential from diesel hybrid cars is less compared with the REF scenario because diesel plug-in cars become cost-efficient at £225/t CO_2 (see Fig. 12). Thus, this additional abatement technology is introduced in 2030 as a consequence of the situation that no other low-carbon technologies are needed after 2030.

From Fig. 12 it can be seen that abatement options need a higher CO_2 tax than in the CONST-AFTER scenario to become cost-efficient. Battery cars, for example, reach their full potential at £157/t CO_2, which is £78/ t CO_2 more than in the REF scenario and is influenced by the higher carbon intensity of electricity. As battery cars are later introduced into the market, the decrease of the share of petrol hybrid cars is less pronounced in the CONST-AFTER scenario.

Fig. 12: Market share for different technologies in the CONST-AFTER scenario in 2030



4.3.3 STEEP INCREASE IN CO_2 TAX AFTER 2030

In the INCR-AFTER scenario the CO_2 tax increases after 2030 by 10% annually, thus with a rate that is double as high as in the REF scenario. The shape of the MAC curve looks very similar to the REF scenario as Fig. 9 shows. Since the CO_2 tax is higher in the years after 2030, there is an additional incentive for the model to choose low carbon technologies already in 2030 in order to anticipate the future additional penalty for emitting CO_2. Therefore, mitigation technologies figure at lower cost levels on the MAC curve, e.g. battery cars reach their highest market share of 43% at £10/t CO_2 less, battery buses significantly increase their market penetration at £29/t CO_2 less and plug-in LGVs enter the market as well at £29/t CO_2 less.

The steep increase of the CO_2 tax of 10% p.a. after 2030 does not present a big, additional incentive to invest in low carbon technologies already in 2030 compared to the REF scenario. Overall, the influence of this additional increase of the later CO_2 tax is limited.

4.3.4 ZERO CO_2 TAX BEFORE 2030

In contrast to the REF scenario, there is no CO_2 tax before 2030 in the ZERO-BEFORE scenario. There is no incentive to shift to any low-carbon technologies before 2030. This is important since road vehicles have a lifetime of 7 to 15 years, while aircrafts, ships and trains have a lifetime of up to 40 years. Even if investments are taken into low-carbon technologies in 2030, there will be still conventional technologies present in 2030 due to investments in earlier years.

Fig. 13:: MAC curve for the ZERO-BEFORE scenario in 2030

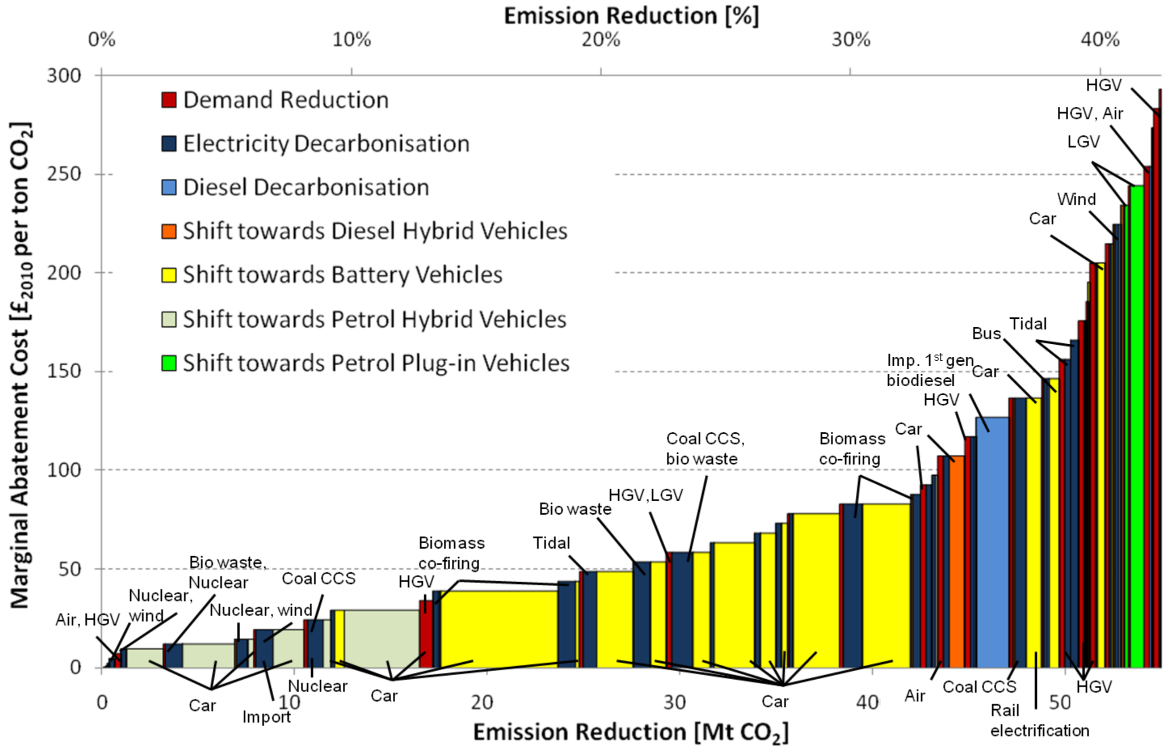
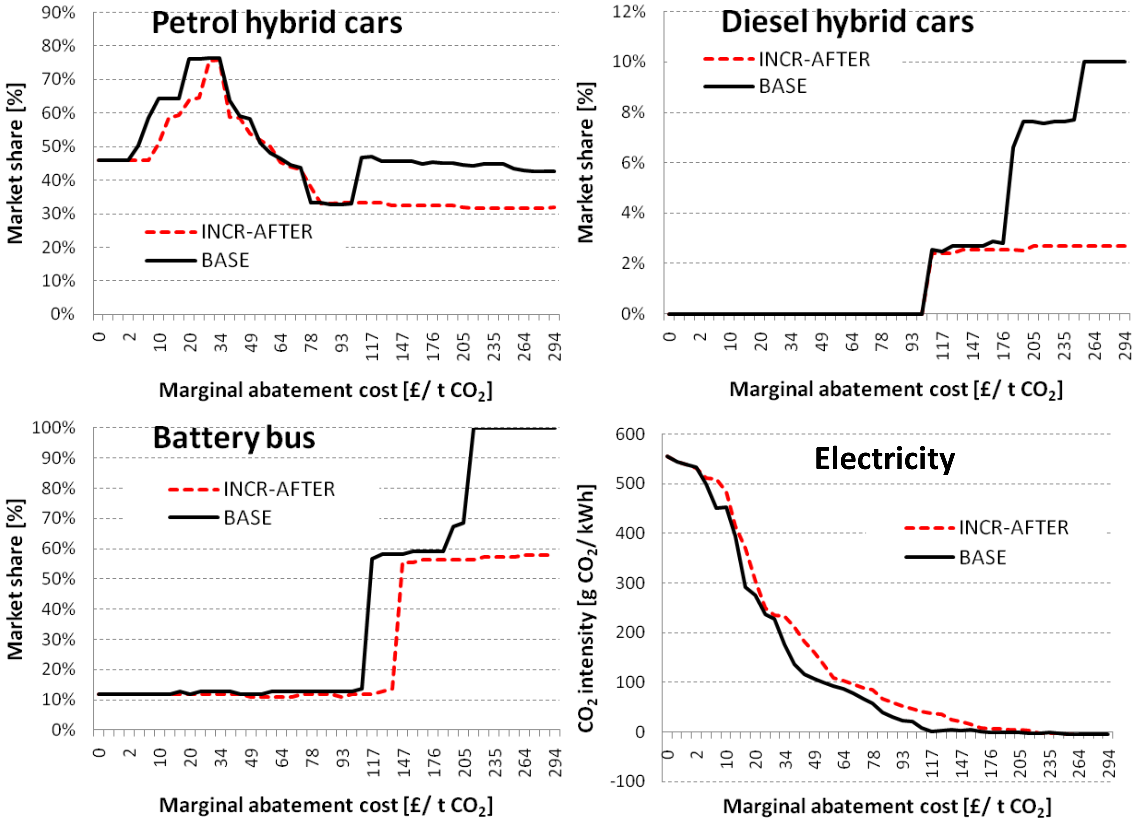


Fig. 9 and Fig. 13 show that the overall MAC curve for the transport sector looks very similar to the REF scenario up to £70/t CO_2, but then starts to diverge in the sense that less CO_2 is reduced so that in the end at £294/t CO_2 10 Mt CO_2 are unabated compared to the REF scenario. The contribution of electricity decarbonisation is higher with a share of 26% compared to 18% in the cars happens at approximately the same cost level, but electricity is decarbonised at slightly higher cost levels (see Fig. 14).

The abatement potential is lower in the ZERO-BEFORE scenario compared with the REF scenario due to the fact that several low-carbon technologies remain significantly behind their market penetration in the REF scenario. This is particularly the case for petrol hybrid cars, diesel hybrid cars and battery buses (see Fig. 14). A reason for the lower market share of diesel hybrid vehicles is that no investments are realised for this vehicle type before 2030 in the model so that there is still a part of the vehicle pool made up of diesel ICE cars. Similarly, the model does not invest into petrol hybrid cars until 2025, while this is already the case in 2020 for the REF scenario. Equally, the first electric buses drive on the roads in 2025 compared to 2020 in the REF scenario.

In summary, the fact that there is no CO_2 tax prior to 2030 represents a significant disincentive for the investment in low-carbon technologies prior to 2030 so that the investment level is lower in comparison to the REF scenario despite a CO_2 tax in 2030 and in the following years.

Fig. 14: Market share for different technologies and carbon intensity of electricity (bottom right) in the ZERO-BEFORE scenario in 2030



4.3.5 HIGH CO_2 TAX FROM 2015

The HIGH-BEFORE scenario assumes that the CO_2 tax stays on a constant level from 2015 to 2030, which is the same as the CO_2 tax in the REF scenario in 2030. This means that for the period from 2015 to 2025 the CO_2 tax is higher than in the REF scenario and should present an additional incentive to decarbonise the energy system.

The shape of the emission curve (see Fig. 9) as well as the MAC curve look very similar to the REF scenario. The overall abatement is also almost the same as in the scenario with a constantly rising CO_2 tax. Looking specifically at mitigation strategies, reveals that petrol ICE cars are completely replaced by petrol hybrid and battery cars already at a cost level of £78/t CO_2, thus at £30/t CO_2 less. Similarly, electric buses become cost efficient at £50/t CO_2 less compared with the REF scenario. For other mitigation options the abatement potential and the marginal abatement cost level is comparable.

Consequently, a high CO_2 tax that is higher for two periods can lead in specific cases to a reduction of marginal abatement costs, but does not alter the overall MAC curve substantially.

4.4 DISCOUNT RATE

Discount rates play an important role in determining future marginal abatement costs as they determine how future cash flows are weighted with regard to present cash flows. The higher the discount rate, the more weight is put on costs and financial gains that occur early in the project phase, relative to those incurred later. For those technologies where a large proportion of investment costs occur at the start of a project, but the benefits accrue over time, they will be more economic the lower the discount rate.

In general, the research literature distinguishes between social and private discount rates. A social discount rate is used to determine whether an investment or policy is beneficial from society's perspective, i.e. whether it represents a good use of society's resources. All taxes, subsidies are excluded from this analysis as they are only transfers between groups in society. The discount rate is rather low around the 3.5% rate that the UK Government (HM Treasury, 2003) uses based on the assumption that governments can borrow at that rate if they want to incentivise capital-intensive abatement opportunities. This means that the financing burden is shifted from the private actor to the state. The SDR scenario assumes such a social discount rate, where also all technology-specific hurdle rates are removed.

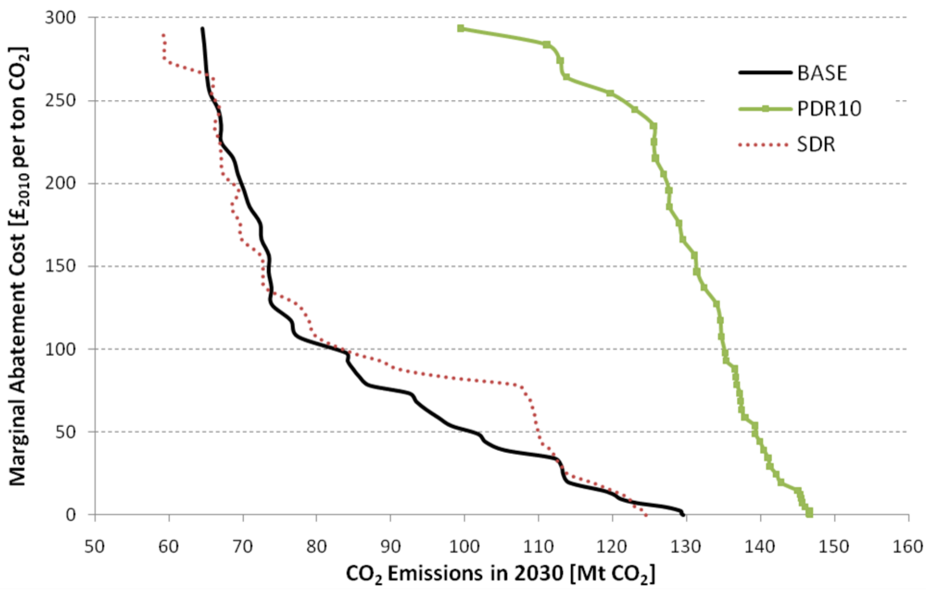
The application of a social discount rate can help to answer the question: "what should happen from a society's perspective on a least cost path?"; however, to understand what is likely to happen within the for-profit sector, a private cost-benefit analysis has to be applied.

Cost calculations from a private perspective differ from society's view, not only in the discount rate applied, which must reflect the private cost of capital, but also in that taxes and subsidies are included. Moreover, project risks are specific to the investor, and will, from the investor's perspective, not be averaged out across the economy. Consequently, the investor will require a higher rate of return, to justify proceeding, which is represented in the form of technology-specific hurdle rates in the UK MARKAL model. In general, individuals and companies additionally face several uncertainties. These uncertainties include project related risks, policy and regulatory risks and uncertainty about the future development of energy prices.

Observed discount rates can be relatively high (see e.g. Jaffe and Stavins 1994) and are, for example, assumed to be 7% for passenger cars in a MAC curve study for the Committee on Climate Change (AEA Energy & Environment et al. 2008, p. 18). The PRIMES energy system model, which is widely used by the EU, assumes discount rates as high as 17.5% for cars, 12% for aviation, inland navigation and HGVs, and 8% for buses and trains (Hendriks et al. 2001, p. A2). The PDR10 scenario represents the perspective of a private investor, where the discount rate and the technological hurdle rates were doubled with respect to the REF scenario, although both are separate and do not have to increase accordingly. The PDR10 scenario assumes a comparably high general discount rate of 10% and technology-specific hurdle rates of 20% for hydrogen vehicles and 15% for hybrid, plug-in and battery cars, which account for technology-specific uncertainties. This increased discount rate should not be seen as a change in pure time preference, but rather as measure of uncertainty involved when investing in low-carbon technologies.

Fig. 15 indicates that the emission curves are similar for the SDR and the REF scenario, while the emissions in the PDR10 scenario are, as expected, a lot higher. They are 17 Mt CO_2 higher without a CO_2 tax since no petrol hybrid cars and electric buses are introduced to the market. Emissions are only very slowly decreased with higher CO_2 taxes owing to the higher discount rate and hurdle rates that penalise low-carbon technologies. The SDR scenario shows slightly lower emissions in the case without a CO_2 tax because the market share of petrol hybrid cars is 30 percentage points higher. In other respects the emission curves of the REF scenario and the SDR scenario look relatively similar, though the SDR scenario shows more abatement potential at very high CO_2 taxes, where hydrogen vehicles become cost-efficient.

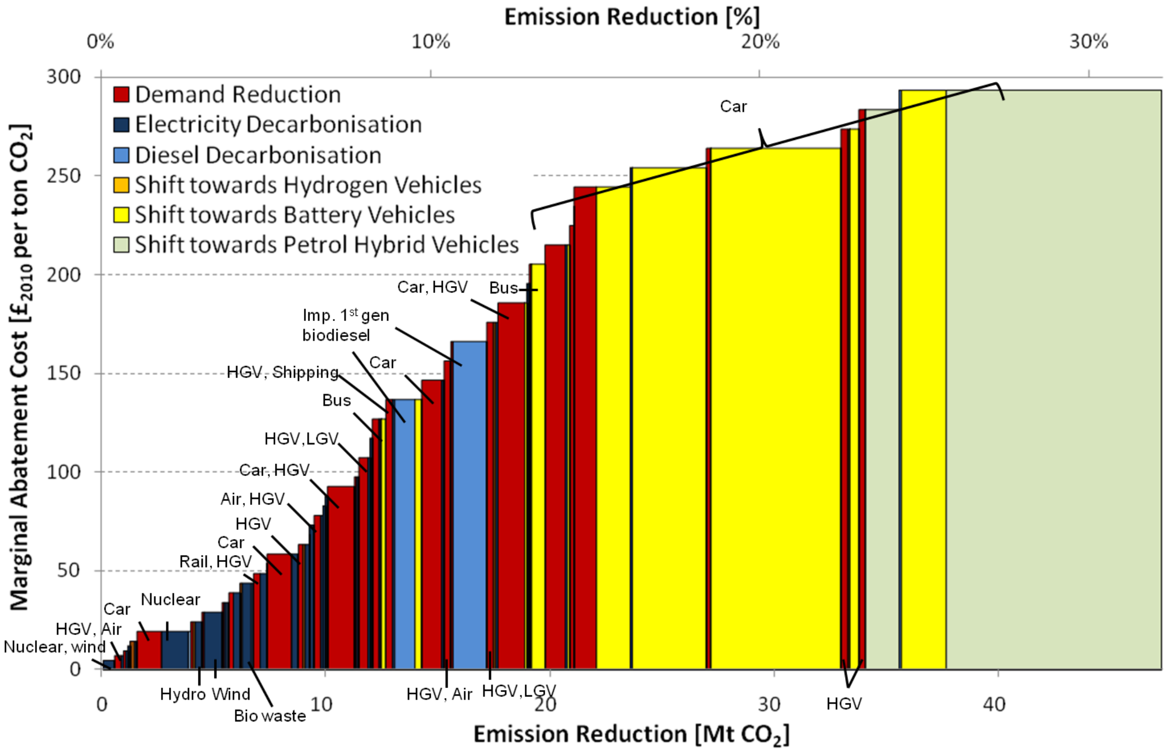
Fig. 15:: Emission curve along rising CO_2 abatement costs for different discount rate scenarios in 2030



The MAC curve for the PDR scenario (Fig. 16), where the discount rate and the hurdle rates were increased by 100%, shows that technological alternatives are very expensive. Hence, demand reduction plays an important role especially up to £250/t CO_2. Its contribution is with 13 Mt CO_2 about 90% higher compared with the REF scenario. The same holds true for the decarbonisation of diesel via the blending of biodiesel into diesel, though at a much smaller scale, where the contribution is 2 Mt CO_2 and 50% higher than in the REF scenario.

Taking a look at technological shifts reveals that increasing the hurdle rate for electric cars from 7.5% to 15% raises the marginal abatement cost of battery cars by £200/t CO_2. While petrol hybrid cars are cost-efficient at £0/t CO_2 in the REF scenario, they are only cost-efficient at a tax of £284/t CO_2, which highlights the sensitivity of hybrid vehicles not only to the underlying assumptions concerning the discount rate, but also the investment cost mark-up and efficiency gain.

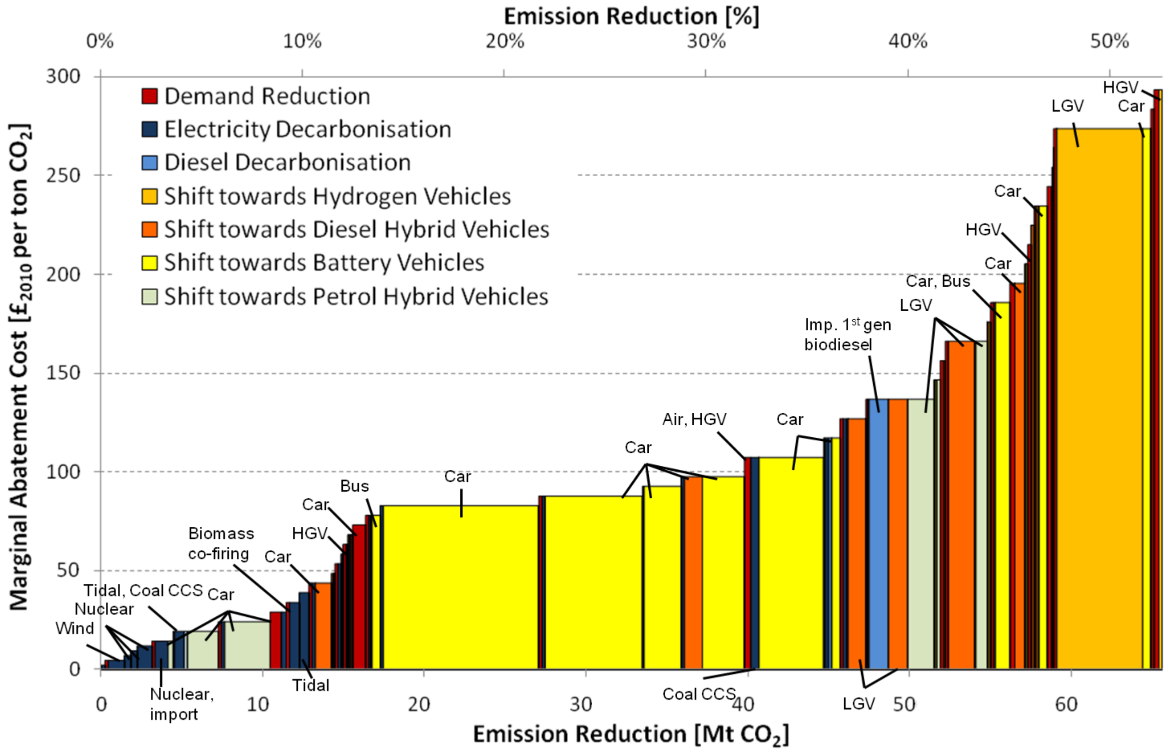
Fig. 16: MAC curve for the PDR10 scenario in 2030



The MAC curve for the scenario with a social discount rate looks very different from the previously discussed one (see Fig. 17). There are two effects that counteract each other: on the one hand low-carbon technologies save less fuel costs in the SDR scenario due to lower prices for petrol and diesel (taxes are removed). On the other hand, the investment cost premium for abatement technologies is less as there are no technological hurdle rates and the overall discount rate is lower with 3.5%. Differences in operating and maintenance costs, which include insurance, are comparably small and do not influence the overall result.

The SDR scenario shows a significantly higher proportion of petrol hybrid cars in the £0/t CO_2 run caused by a lower investment cost disadvantage compared with petrol ICE cars. This can be traced back to the discount factor, which is the same as the hurdle rates that were removed. The MAC curve for the SDR scenario (Fig. 17) shows a lower abatement cost level for diesel hybrid cars of around £70/t CO_2. There is no hurdle rate of 7.5% anymore on the hybrid technology so the investment cost disadvantage is roughly halved, while on the other hand the fuel cost advantage is reduced, but not to the same extent. Consequently, similarly to petrol hybrid cars, the reduction in the investment annuity outweighs the reduced fuel saving.

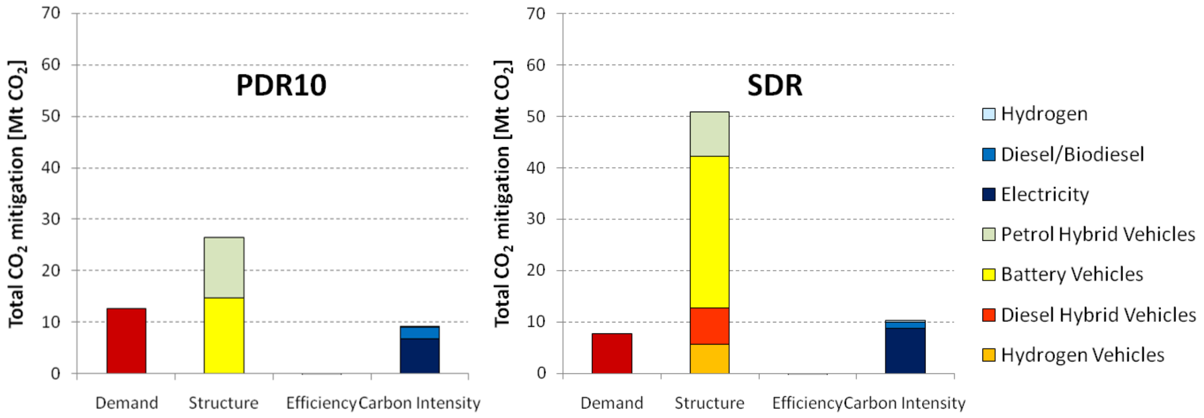
Fig. 17:: MAC curve for the SDR scenario in 2030



Furthermore, it is interesting to note that battery cars need a £44/t CO_2 higher tax in order to become cost-efficient, caused by the fact that the investment cost disadvantage is not reduced enough to offset the loss in fuel savings. A reason for this is that the reference technology for battery cars, namely petrol hybrid cars, has the same technological hurdle rate in the REF scenario. Lastly, hydrogen fuel cell vehicles show up on the MAC curve at a very high CO_2 tax of £274/t CO_2 because they do no longer have a technological hurdle rate of 10% and thus account for 6 Mt of CO_2 abatement (see Fig. 18).

Concerning the overall contribution to emission reduction (Fig. 18), demand reduction plays a much more important role in the PDR10 scenario with 27% compared to 12% in the SDR scenario due to a lack of low-priced technological alternatives. This is expressed in the overall contribution of structural shifts within the transport sector, which represents an emission reduction of 26 Mt CO_2 in the PDR10 scenario and about double that amount in the SDR scenario, which additionally includes diesel hybrid and hydrogen vehicles.

Fig. 18:: Total decomposition of transport MAC (PDR10 & SDR scenario) for the UK in 2030



The emission curves indicate a very different trajectory for a social discount rate scenario (SDR) and a private discount rate scenario (PDR10). This is reflected in the total cost needed to achieve an emission target of 100 Mt CO_2 in 2030, which is £0.76 billion in the REF scenario, £1.20 billion in the SDR scenario and £11.17 billion in the PDR10 scenario. In summary, from a risk-averse private investor's perspective with a general discount rate of 10% and hurdle rates up to 20%, the same target for transport-related emissions of 100 Mt CO_2 is 15 times more expensive to achieve compared with the discount and hurdle rates used in the REF scenario.

5 CONCLUSIONS

This paper studied the influence of path dependency and the choice of the discount rate on abatement potentials and costs for the UK transport sector. MAC curves were generated by combining an energy system model and decomposition analysis in order to avoid problematic inconsistencies of MAC curves based on the individual assessment of abatement options. The results showed that the electrification of the transport sector plays a key role in the process of decarbonisation. This is mainly realised via a shift towards electric cars and buses, but also plug-in LGVs. Furthermore, hybrid cars are a low-cost option to reduce emissions in the transport sector.

The path dependency sensitivity analysis revealed that the MAC curve in 2030 is not robust to different CO_2 tax pathways before and after 2030. The variation of the CO_2 tax path has a significant, but not substantial influence on the MAC curve. Nevertheless, for individual technologies the effect can be important. The marginal abatement cost for battery cars is, for example, £78/t CO_2 more in the ZERO-AFTER scenario and £30/t CO_2 less in the HIGH-BEFORE scenario compared with the REF scenario, resulting in a range of more than £100/t CO_2. This emphasises that earlier efforts and expectations about future carbon policies have a noticeable influence on abatement costs, requiring abatement cost studies to publish assumptions on carbon policies prior and past the considered year.

The variation of the discount rate level showed a bigger impact compared with the path dependency variation. This confirms studies dealing with the economics of climate change mitigation (Azar and Sterner 1996), but is in contrast to other studies analysing more specifically the influence of discount rates on MAC curves (Blok et al. 1993; Nauclér and Enkvist 2009). The results of this study indicate that a doubling of the discount rate led to a very substantial change in the emission profile. The same emission target of 100 Mt CO_2 in 2030 can only be achieved at costs that are 15 times higher. Unlike the only other existing MAC curve study for the UK transport sector (AEA Energy & Environment et al. 2008), the emission profile was found to be robust to a change from a private perspective to a societal perspective. The reason for this robustness is that a lower investment cost disadvantage is evened out by a lower fuel saving effect. The technological structure, though, is more affected by the lower discount rate and the substantial reduction in fuel prices due to the omission of fuel duty.

In order to assess the economics of climate change mitigation, most studies employ a social discount rate. The sensitivity analysis performed in this paper suggests that results from studies based on a societal perspective should be carefully interpreted as carbon abatement is significantly more expensive for private individuals. In summary, intertemporal aspects have a non-negligible influence on the shape and structure of a MAC curve. This should be taken into account when making decisions on the basis of such a curve.

References

AEA Energy & Environment, E4Tech, Metronomica, Ricardo, IEEP and CE Delft (2008). Building a UK Transport Supply-side Marginal Abatement Cost Curve. London, Committee of Climate Change.

Amir, R., M. Germain and V. Van Steenberghe (2008). "On the Impact of Innovation on the Marginal Abatement Cost Curve." Journal of Public Economic Theory **10**(6): 985-1010.

Anandarajah, G. and N. Strachan (2010). "Interactions and implications of renewable and climate change policy on UK energy scenarios." Energy Policy **38**(11): 6724-6735.

Ang, B. W. (2004). "Decomposition analysis for policymaking in energy: which is the preferred method?" Energy Policy **32**(9): 1131-1139.

Ang, B. W. and F. Q. Zhang (2000). "A survey of index decomposition analysis in energy and environmental studies." Energy **25**(12): 1149-1176.

Ang, B. W., F. Q. Zhang and K.-H. Choi (1998). "Factorizing changes in energy and environmental indicators through decomposition." Energy **23**(6): 489-495.

Azar, C. and T. Sterner (1996). "Discounting and distributional considerations in the context of global warming." Ecological Economics **19**(2): 169-184.

Baker, E. and E. Shittu (2007). Technical Change and the Marginal Cost of Abatement. Amherst, MA, University of Massachusetts.

Barker, T., M. S. Qureshi and J. Köhler (2006). The Costs of Greenhouse Gas Mitigation with Induced Technological Change: A Meta-Analysis of Estimates in the Literature. Tyndall Centre for Climate Change Research. Cambridge, Cambridge Centre for Climate Change Mitigation Research / Department of Land Economy / University of Cambridge. **89**.

Bauman, Y., M. Lee and K. Seeley (2008). "Does Technological Innovation Really Reduce Marginal Abatement Costs? Some Theory, Algebraic Evidence, and Policy Implications." Environmental and Resource Economics **40**(4): 507-527.

Blok, K., E. Worrell, R. Cuelenaere and W. Turkenburg (1993). "The cost effectiveness of CO_2 emission reduction achieved by energy conservation." Energy Policy **21**(6): 656-667.

Committee on Climate Change (2010). The Fourth Carbon Budget - Reducing emissions through the 2020s. London.

Criqui, P., S. Mima and L. Viguier (1999). "Marginal abatement costs of CO2 emission reductions, geographical flexibility and concrete ceilings: an assessment using the POLES model." Energy Policy **27**(10): 585-601.

Department of Energy and Climate Change (2010). Provisional 2009 results for UK greenhouse gas emissions and progress towards targets. London.

Ellerman, A. D. and A. Decaux (1998). Analysis of Post-Kyoto CO_2 Emissions Trading Using Marginal Abatement Curves. Cambridge, MA, Massachusetts Institute of Technology.

Fischer, C. and R. D. Morgenstern (2006). "Carbon Abatement Costs: Why the Wide Range of Estimates?" Energy Journal **27**(2): 73-86.

Fleiter, T., W. Eichhammer, M. Hagemann, M. Wietschel and S. Hirzel (2009). Costs and potentials of energy savings in European industry - a critical assessment of the concept of conservation supply curves. ECEEE 2009 Summer Study, La Colle sur Loup, France.

Hazeldine, T., M. Morris, S. Kollamthodi and L. Deller (2009). Review of cost assumptions and technology uptake scenarios in the CCC transport MACC model. Didcot, AEA Technology.

Hendriks, C., D. De Jager, K. Blok, J. de Beer, J. Harnisch, S. Joosen, D. Phylipsen, M. Kerssemeeckers, C. Byers, M. Patel, J. Bates, C. Brand, P. Davison, A. Haworth and N. Hill (2001). Economic Evaluation of Sectoral Emission Reduction Objectives for Climate Change - Bottom-up Analysis of emission Reduction Potentials and Costs for Greenhouse Gases in the

EU. Utrecht, The Netherlands, ECOFYS Energy and Environment, AEA Technology Environment.
HM Government (2009). Analytical Annex - The UK Low Carbon Transition Plan. London.
Jaffe, A. B. and R. N. Stavins (1994). "The energy paradox and the diffusion of conservation technology." Resource and Energy Economics **16**(2): 91-122.
Kannan, R., N. Strachan, N. Balta-Ozkan and S. Pye. (2007). "UK MARKAL model documentation." Retrieved November 18th 2010, from www.ukerc.ac.uk.
Kennedy, M. (2010). Ireland's Future: A Low Carbon Economy? The Impact of Green Stimulus Investment. IAEE European Conference. Vilnius, Lithuania.
Kesicki, F. (2010a). Marginal Abatement Cost Curves for Policy Making – Expert-Based vs. Model-Derived Curves. IAEE's 2010 International Conference. Rio de Janeiro.
Kesicki, F. (2010b). Marginal Abatement Cost Curves: Combining Energy System Modelling and Decomposition Analysis. International Energy Workshop 2010. Stockholm.
Klepper, G. and S. Peterson (2003). On the Robustness of Marginal Abatement Cost Curves: The Influence of World Energy Prices. Kiel Working Papers. Kiel, Kiel Institute for World Economics,. **1138**.
Kuik, O., L. Brander and R. S. J. Tol (2009). "Marginal abatement costs of greenhouse gas emissions: A meta-analysis." Energy Policy **37**(4): 1395-1403.
Loulou, R., G. Goldstein and K. Noble (2004). Documentation for the MARKAL Family of Models, Energy Technology Systems Analysis Programme.
Manne, A., R. Mendelsohn and R. Richels (1995). "MERGE : A model for evaluating regional and global effects of GHG reduction policies." Energy Policy **23**(1): 17-34.
McKitrick, R. (1999). "A Derivation of the Marginal Abatement Cost Curve." Journal of Environmental Economics and Management **37**(3): 306-314.
Morris, J., S. Paltsev and J. M. Reilly (2008). Marginal Abatement Costs and Marginal Welfare Costs for Greenhouse Gas Emissions Recutions: Results from the EPPA Model. Cambridge, MA, MIT Joint Program on the Science and Policy of Global Change.
Nauclér, T. and P. A. Enkvist (2009). Pathways to a Low-Carbon Economy - Version 2 of the Global Greenhouse Gas Abatement Cost Curve. McKinsey & Company.
Newell, R. G. and W. A. Pizer (2003). "Discounting the distant future: how much do uncertain rates increase valuations?" Journal of Environmental Economics and Management **46**(1): 52-71.
Nordhaus, W. D. (1999). Discounting and Public Policies that Affect the Distant Future. Discounting and intergenerational equity. P. R. Portney and J. P. Weyant. Washington, DC, Resources for the Future**:** ix, 186 p.
Stern, N. H. (2007). The economics of climate change : the Stern review. Cambridge, UK, Cambridge University Press.
Stoft, S. (1995). "The economics of conserved-energy `supply' curves." Energy Journal **16**(4): 109-140.
Strachan, N., R. Kannan and S. Pye (2008). Scenarios and Sensitivities on Long-term UK Carbon Reductions using the UK MARKAL and MARKAL-Macro Energy System Models. London, UKERC.
Strachan, N., S. Pye and R. Kannan (2009). "The iterative contribution and relevance of modelling to UK energy policy." Energy Policy **37**(3): 850-860.
Tol, R. S. J. and G. W. Yohe (2009). "The Stern Review: A deconstruction." Energy Policy **37**(3): 1032-1040.
van Vuuren, D. P., B. de Vries, B. Eickhout and T. Kram (2004). "Responses to technology and taxes in a simulated world." Energy Economics **26**(4): 579-601.
Webster, M. (2008). "Incorporating Path Dependency into Decision-Analytic Methods: An Application to Global Climate-Change Policy." Decision Analysis **5**(2): 60-75.