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Why are MAC curves robust to different fossil fuel prices? An application to the UK power sector*

Fabian Kesicki[a]

[a] Energy Institute

University College London

14 Upper Woburn Place

London WC1H 0NN, United Kingdom

E-mail: fabian.kesicki.09@ucl.ac.uk

Abstract

Marginal abatement cost (MAC) curves, which are used for the assessment of costs and potentials of CO_2 emissions reduction, have been criticised due to their sensitivity to a range of key assumptions notably in relation to fossil fuel prices. This paper addresses this question by generating several MAC curves under different fossil fuel prices for the United Kingdom with a focus on the electricity sector. A technology-rich, bottom-up energy system model, UK MARKAL, in combination with decomposition analysis is used to derive the MAC curves. The results of this study show that MAC curves are robust even for extreme fossil fuel price changes, particularly for the expected carbon tax levels in 2030. Reasons for this robustness are, amongst others, that the carbon tax level has a larger impact than a doubling of primary energy costs, and the two-way influence of higher fossil fuel prices, which reduce the abatement cost of renewables relative to the baseline development but increase the costs of coal CCS. The results help to reduce the apparent uncertainties concerning the costs associated with carbon emission reduction and should encourage the use of MAC curves as a reliable tool to analyse the economics of climate change mitigation.

Key words:

MAC curve, fossil fuel price, power sector, energy system modelling

JEL classification:

Q54, Q40, C61

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1 Introduction

Legal commitments in the form of the Kyoto Protocol, the European Union 20-20-20 goals or the UK Climate Change Act require policy makers in many countries around the world to reduce carbon emissions in a cost-efficient way. To assess the abatement possibilities and related costs, marginal abatement cost (MAC) curves have frequently been used by decision makers in the context of climate policy. A MAC curve is defined as a graph that indicates the marginal cost of emission abatement for varying amounts of emission reduction.

This paper focuses on economy-wide and sectoral MAC curves and does not consider theoretical MAC curves for a single firm (see e.g. McKitrick 1999; Bauman et al. 2008). Klepper and Peterson (2006) describe how an economy-wide MAC curve is linked to a curve for a single production plant. In recent years, MAC curves have been shifted into the focus of decision makers as an important decision-making aid through the work of McKinsey & Company (Confederation of British Industry 2007; Creyts et al. 2007; Nauclér and Enkvist 2009). Since then, MAC curves have been produced and used by decision makers in a range of countries (Chen et al. 2007; Morris et al. 2008; Sweeney et al. 2008; Kennedy 2010).

In the UK, MAC curves have recently played an important role in shaping the government's climate change policy. The UK government used abatement curves as a guide for the potential and future costs of technical measures for its UK Low Carbon Transition Plan (HM Government 2009).

Although MAC curves are one of the most frequently used tools to advise policy makers involved in climate policy, they are attacked on the grounds that they are not reliable since the curves are believed to be very sensitive to changes in fossil fuel prices. McKinsey (Creyts et al. 2007, p.25) state, for example, that oil and gas prices have a substantial impact on the abatement curve for the United States. Moreover, the latest assessment report of the International Panel on Climate Change (IPCC) explains that estimated ranges of mitigation costs and potential reflect key sensitivities to baseline fossil fuel prices (Barker et al. 2007, p. 621). Siddiqui (2010) also found a MAC curve for the Canadian economy to be sensitive to changes in the price for crude oil.

Klepper and Peterson (2003) studied the influence of energy prices on MAC curves with a computable general equilibrium (CGE) model. Their results indicate that energy prices play a decisive role and that marginal MAC curves depend, next to other factors, strongly on energy prices (Klepper and Peterson 2003, p.25). This statement was, however, qualified in a later paper, where the authors state that relative price effects do not affect MAC curves in a significant way (Klepper and Peterson 2006, p. 18).

This paper tests the hypothesis that MAC curves are significantly influenced by changing fossil fuel prices for the United Kingdom. The focus of this paper is on the year 2030 as an important medium-term target for emissions reduction. The robustness of a MAC curve is discussed with particular focus on a sectoral MAC curve for the UK power sector. This sector is a key element in an economy-wide decarbonisation due to the fact that electricity is used in all end-use sectors and low-carbon electricity has the potential to extend to electric vehicles in transport and electric heat in buildings. In addition, the power sector is currently a major source of emissions in the UK with 210 Mt CO_2 in 2008 or 32% of all energy-related CO_2 emissions. Major efforts will be necessary to bring down the average emissions from today's 540 g CO_2/kWh to almost zero in 2050. So far there has been one study that analyses the marginal abatement costs in the UK power sector for the year 2020 (Committee on Climate Change 2008). The authors found the marginal abatement costs in 2020 to be £30/t CO_2 for coal CCS (carbon capture and storage) plants, £55-133/t CO_2 for onshore wind, £85-152/t CO_2 for offshore wind, £39/t CO_2 for biomass co-firing into coal power plants and £193/t CO_2 for marine power.

A systems approach is used to generate MAC curves based on an energy system model (UK MARKAL) to capture interactions with demand sectors. Decomposition analysis is used to bring in more detail on the abatement cost and potential of individual abatement measures behind the MAC curve and show the consequences of varying fossil fuel prices on low-carbon technologies. Four scenarios with different assumptions on the development of the price for coal, oil and gas are presented within the scope of this study. The goal of this paper is to test the hypothesis that MAC curves are sensitive to fossil fuel price changes. Therefore, the paper quantifies the influence of changes to fossil fuel prices on MAC curves and presents the economics of decarbonising the UK power sector. Gracceva and Ciorba (2008) used a MARKAL model for Italy to establish a technologically detailed abatement cost curve. The resulting cost curves are, though, not marginal abatement cost curves, but rather specific policy scenario mean abatement cost curves as they only show the difference between predefined policy scenarios. The specific policy scenarios cannot guarantee that emission reduction is due to the specified changes, crucially because interactions are not accounted for, and the reduction potential varies with the logical order of the scenarios.

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 fossil fuel price scenarios that have been implemented and section 4 explains and discusses the results for the UK energy system and in particular for the power sector. Finally, section 5 presents conclusions and implications for policy use of MAC curves.

2 Methodology

The economics of decarbonising the UK power sector are illustrated with the help of MAC curves that are based on energy system modelling, decomposition and sensitivity analysis. For a detailed discussion of the approach, see Kesicki (2010).

2.1 Energy System Modelling

A bottom-up energy system model provides a solid theoretical basis for the calculation of MAC curves, 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:

$$Max \sum_{d}\sum_{t}(p_{d,t}^{0}(\frac{1}{q_{d,t}^{0}})^{\frac{1}{E_d}} * \frac{1}{\frac{1}{E_d}+1} * q_{d,t}{}^{*\frac{1}{E_d}+1}) - c * X \tag{1}$$

Summed over all demands *d* and over all time periods *t*, $p_{d,t}^{0}$ is the price, $q_{d,t}^{0}$ the demand in a given reference case, and $q_{d,t}^{*}$ the demand in the equilibrium. E_d is the own price elasticity of demand *d*, while the net present value of the total cost is abbreviated as $c*X$, where c represents specific costs and X is the vector of all decision variables.

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 the model documentation (Kannan et al. 2007) and the most recent policy report Usher and Strachan (2010). The UK MARKAL model, which is calibrated to the UK context concerning technologies, costs and constraints, has been used in many different research studies (e.g. Strachan et al. 2009; Anandarajah and Strachan 2010). In order not to distort the calculation of marginal abatement costs, all existing UK or EU climate policies were excluded from the UK MARKAL model from 2010 onwards. A 5% discount rate is applied in the model with technology-specific hurdle rates of up to 10% for low-carbon end-use technologies in the transport, service and residential sector.

The power sector in the UK MARKAL model encompasses all the relevant power plants and combined heat and power (CHP) plants, distinguished into centralised, distributed and micro generation. In total there are 17 different CHP plants and 108 different power plants. The supply of electricity matches the demand for electricity from the residential, service, agriculture, industrial, upstream and transport sector. A number of key data parameters that are required to characterise power technologies, such as technical efficiency, capital cost, fixed and variable operating costs, lifetime or annual availability, are defined in the model. Table 1 provides an overview of assumptions for the most important technologies in the power sector in 2030. The assumptions change over time as costs are assumed to come down and new technologies become available.

Table 1: Assumptions for key power technologies in UK MARKAL in 2030

2030	[£=1.4€=1.8$]	**Coal PF**	**Gas CCGT**	**Nuclear**	**Coal CCS**	**Gas CCS**	**Wind onshore**	**Wind offshore**	**Tidal (Severn barrage)**
Capital cost	[$£_{2010}$/kW]	1027	463	1363	1438	652	682	1224-1944	1947
Availability	[%]	83%	83%	83%	83%	83%	-	-	23%
Load factor	[%]	-	-	-	-	-	16-44%	36%	-
Efficiency	[%]	52%	57%	36%	45%	50%	-	-	-
Life time	[years]	50	35	50	50	35	25	25	120
Build rate limit	[GW/5 years]	10	12.5	7.5	2.5	2.5	10	10	-

2.2 Decomposition Analysis

Decomposition analysis (in this paper used as a synonym for index decomposition analysis) helps to bring technological detail into the representation of the MAC curve. In this study, the resulting CO_2 emission along increasing carbon tax levels in the transport sector are decomposed into four different effects: activity effect, structure effect, fuel intensity effect and carbon intensity effect:

$$CO_{2,Power} = activity \left(\sum_{j=technology} \frac{activity_j}{activity} * \frac{fuel_j}{activity_j} * \frac{CO_{2,Power,j}}{fuel_j} \right) \tag{2}$$

The activity is the demand for electricity in Petajoules, *activity*$_j$ is the electric output of one technology type j, *fuel*$_j$ describes the amount of fuel that is necessary to achieve this output with technology j. $CO_{2,Power,i,j}$ represent the amount of CO_2 released by the use of technology j. The first factor represents changes in the demand for electricity, while the first ratio in the brackets stands for changes in the electricity mix, for example a switch from coal to gas power plants. The second ratio permits insights into fuel efficiency gains of a particular power technology and finally the third ratio describes the CO_2 intensity of a fuel, which can be changed for example by co-firing biomass to a coal-fired power plant.

The emphasis is not on an absolute number but on what influences the change in CO_2 emissions in the power sector, so that Equation (2) can be expressed in the following way:

$$\begin{aligned} \Delta CO_{2,Power} = {} & \Delta activity\ effect + \Delta structure\ effect \\ & + \Delta fuel\ intensity\ effect + \Delta carbon\ intensity\ effect \\ & + residual \end{aligned} \tag{3}$$

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. 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 fossil fuel prices on the shape and structure of a system-wide MAC curve and a curve for the power sector. The consideration of uncertainty in the form of sensitivity analysis helps to draw conclusions about the robustness of a MAC curve. In total, four scenarios are considered: one reference scenario (REF) and three fossil fuel price scenarios (see Table 2).

In the GAS scenario the gas price is reduced by 50% to represent a scenario of continuously low gas prices, decoupled from oil prices, in anticipation of a significant amount of supply coming from shale gas. While the gas price is about 75% of the oil price on an energy-equivalent basis in the REF scenario, it is only 38% in the GAS scenario. The FF+

corresponds to a scenario, where all fossil fuel prices are increased by 100% due to supply shortages and increasing demand. In the last scenario, FF++, the fossil fuel prices are increased by 200% equivalent to supply shocks seen in the 1970s.

Table 2: Fossil fuel price assumptions in different scenarios

Scenario	Fuel	Unit	2010	2015	2020	2030	2040	2050
	Oil	**£$_{2010}$/GJ**	7.3	5.8	6.2	6.7	7.2	7.2
REF	Gas	**£$_{2010}$/GJ**	4.5	4.9	4.6	5.1	5.5	5.4
	Coal	**£$_{2010}$/GJ**	2.8	1.9	2.3	2.6	2.9	2.8
	Oil	**£$_{2010}$/GJ**	7.3	5.8	6.2	6.7	7.2	7.2
GAS	Gas	**£$_{2010}$/GJ**	4.5	2.5	2.3	2.6	2.7	2.7
	Coal	**£$_{2010}$/GJ**	2.8	1.9	2.3	2.6	2.9	2.8
	Oil	**£$_{2010}$/GJ**	7.3	11.6	12.3	13.4	14.4	14.4
FF+	Gas	**£$_{2010}$/GJ**	4.5	9.9	9.3	10.3	10.9	10.9
	Coal	**£$_{2010}$/GJ**	2.8	3.9	4.5	5.1	5.7	5.6
	Oil	**£$_{2010}$/GJ**	7.3	17.5	18.5	20.1	21.6	21.6
FF++	Gas	**£$_{2010}$/GJ**	4.5	14.8	13.9	15.4	16.4	16.3
	Coal	**£$_{2010}$/GJ**	2.8	5.8	6.8	7.7	8.6	8.4

In order to generate a MAC curve, one scenario consists of 46 model runs with different model-wide CO_2 tax levels, while fossil fuel prices changes apply to all 46 runs. The CO_2 tax increases in all scenarios over time from 2010 to 2050 with the model inherent discount rate of 5% p.a. Up to 2010, the EU ETS price and the UK renewables obligation is incorporated in the model. As an example, a CO_2 tax of £60/t CO_2 in 2020 corresponds to £98/t CO_2 in 2030, £160/t CO_2 in 2040, and £260/t CO_2 in 2050. In the model runs, the CO_2 tax is varied between £$_{2010}$ 0 per ton CO_2 to £$_{2010}$ 294 per ton CO_2 for the year 2030 (long-term exchange rate £=1.4€ and £=1.8$). Due to the release of CO_2 when burning fossil fuels, the price of coal, oil and gas increases with a rising CO_2 tax (Table 3). A CO_2 tax of £100/t CO_2 corresponds to an increase of about £47 for a barrel of crude oil.

Table 3: Increase in fossil fuel prices over price in 2010 for a given CO_2 tax

CO_2 tax [£/t CO_2]	**Hard Coal** [%]	**Crude Oil** [%]	**Natural Gas** [%]
£100	322%	105%	113%
£200	644%	210%	227%
£300	965%	315%	341%

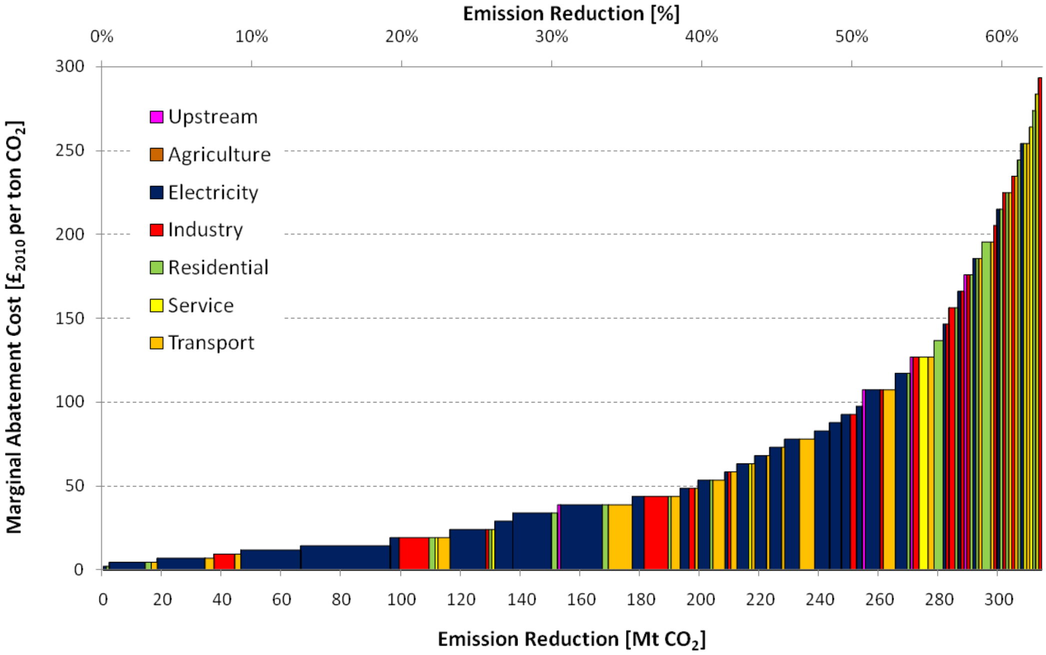
All the 46 model runs with different CO_2 taxes are calculated and consolidated into a single MAC curve for each scenario. The focus in this paper is on the year 2030 as an important medium-term emissions reduction target. All costs are given in $£_{2010.}$

4 Results and Discussion

4.1 System-wide MAC Curve

Before turning towards the results for the power sector, a MAC curve in the REF scenario for the whole energy sector in 2030 gives insights into the wider abatement structure (Fig. 1). The height of each bar represents the marginal abatement cost, while the width represents the emission abatement and the colour indicates the sector.

Fig. 1: Marginal Abatement Cost Curve for the UK Energy Sector in 2030 in the REF scenario



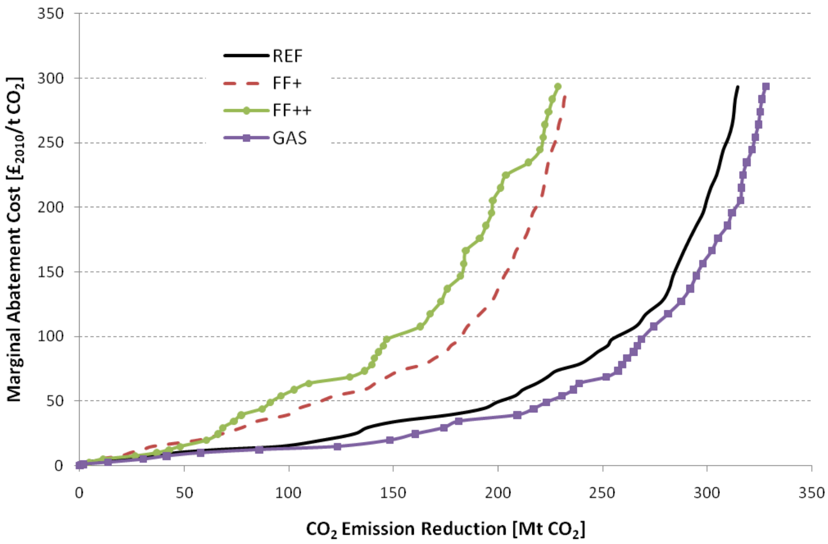
Model results indicate that total energy-related CO_2 emissions are 502 Mt CO_2 in 2030 without any CO_2 policy. In the model run with the highest implemented CO_2 tax of £294/t CO_2 315 Mt CO_2 are abated, reducing emissions to 187 Mt CO_2. This corresponds to an emission reduction of 63% compared to 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 in the baseline development. 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.

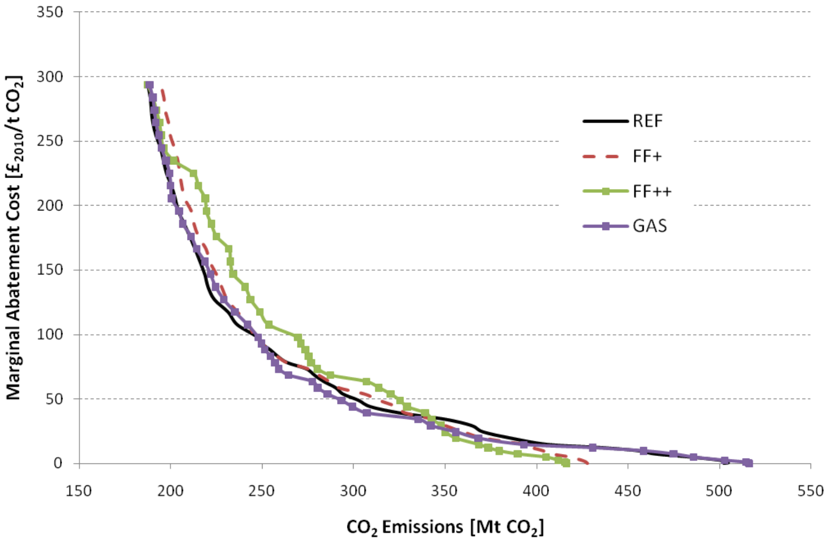
In order to achieve current legislation in the UK, CO_2 emissions in the energy system must be reduced from 579 Mt CO_2 in 1990 to 116 Mt CO_2 in 2050. This would require a substantial increase of the current implicit carbon tax rate, which was estimated to be $28 for the power sector by Vivid Economics (2010).

A look on the MAC curves for the four different scenarios (Fig. 2, top) gives the impression that the MAC curves in the FF+ and FF++ scenarios are very different from the REF and GAS scenario. The MAC curves could be interpreted in the way that emission reduction is far cheaper in the case where the fossil fuel prices are lower. This is misleading however. Baseline emissions without any carbon tax are very different. Compared with the REF scenario, emissions in 2030 are 14 Mt CO_2 higher in the GAS scenario, 74 Mt CO_2 lower in the FF+ scenario and 86 Mt CO_2 lower in the FF++ scenario.

An emission curve, which contrasts marginal abatement costs and total emissions (Fig. 2, bottom) and accounts for different baselines, shows clearly that overall emissions for a given CO_2 tax are very similar from £25/t CO_2 onwards. Reasons are related to the economics and availability of low-carbon technologies, which is discussed in more detail in the next subsections.

Fig. 2: Marginal abatement cost curves without baseline adjustment (top) and emission curve (bottom) for the UK Energy Sector in 2030 in all scenarios



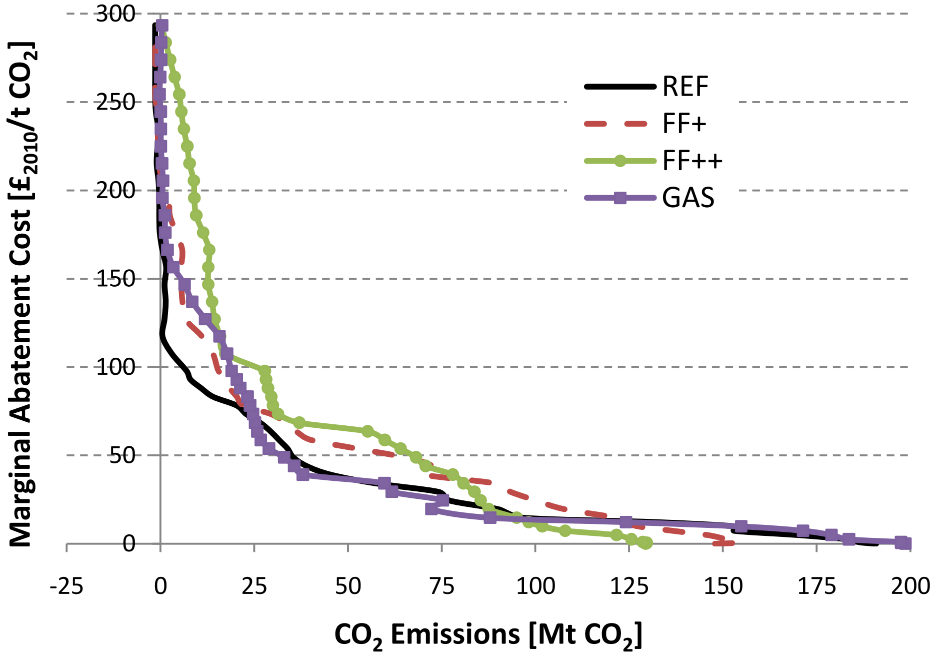


4.2 Electricity Sector: Reference Scenario

While Fig. 1 shows the contribution of each sector, the analysis in the next subsections focuses entirely on emissions from within the power sector. According to the model results, power sector emissions are 191 Mt CO_2 in 2030 in the REF scenario, which compares to 204 Mt CO_2 in 1990 and 174 Mt CO_2 in 2008. Thus, emissions are expected to increase by about 10% from current levels due to higher levels of coal in the electricity mix, but to be 6% lower compared with 1990 levels. Model results indicate that total electricity supply in the UK is roughly constant over the next 20 years with 356 TWh in 2030 compared with 367 TWh in 2008.

Fig. 3 shows emission curves for all four scenarios. This representation not only presents insights on the emission reduction from a baseline, but also puts the absolute emissions into perspective. The first aspect that is striking is that all four curves look similar, i.e. they confirm the robustness of MAC curves to fossil fuel prices in particular from around £25/t CO_2 upwards. At a tax rate of £70/t CO_2, the official UK central carbon price projection, the power sector would be decarbonised between 71% and 87% compared with the baseline in 2030.

Fig. 3: End-use emission curve for the electricity sector (REF scenario) in the United Kingdom in 2030



In general, one can observe that power sector emissions are quickly reduced up to £25/t CO_2, where emissions are reduced by 60% in the REF scenario. At a level of £176/t CO_2, all power sector emissions are abated, while emissions even turn negative at higher prices. This is possible when biomass is co-fired in coal power stations.

The emission curve in Fig. 3 only shows the overall emissions in the power sector, without giving any detail on the technologies and measures that are behind them. Before turning to a technologically detailed MAC curve it is important to know the electricity mix in the base case in order to judge the technological structure of the MAC curve. As can be seen in Fig. 4, the electricity system is dominated by coal as a fuel input without any CO_2 tax.

Fig. 4: Electricity generation mix for different marginal abatement costs in 2030 (REF scenario)

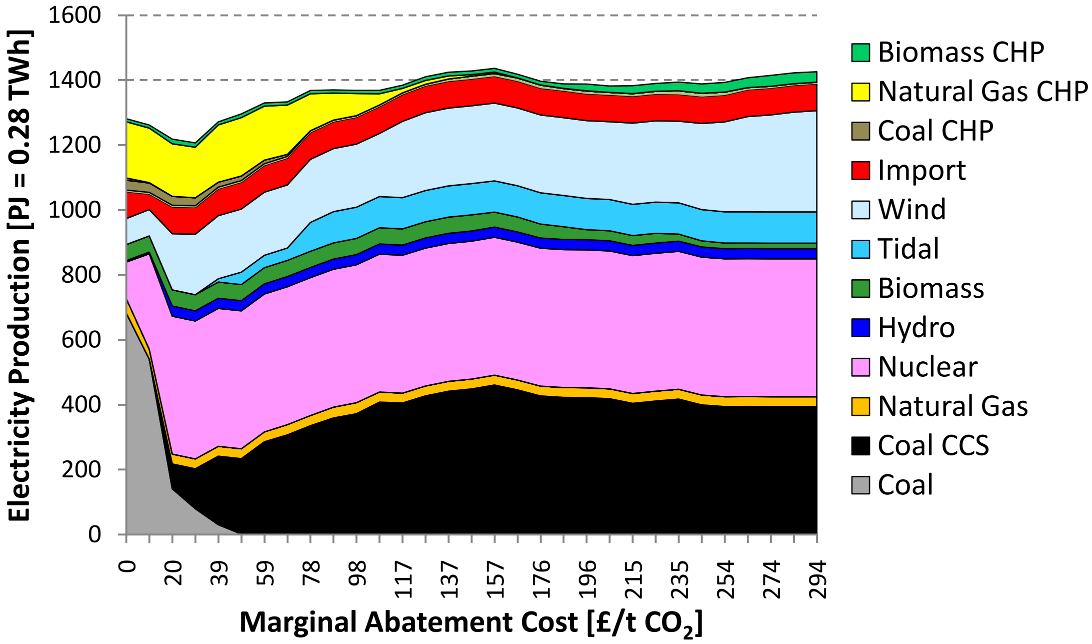
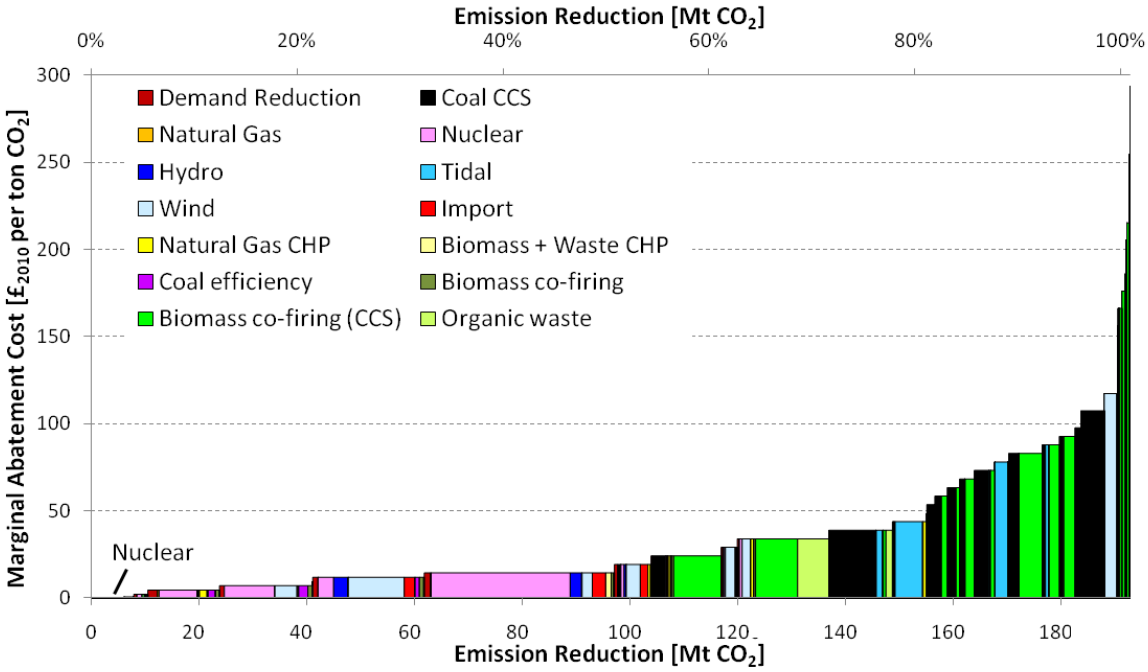


Fig. 5 shows that almost all abatement occurs at marginal abatement cost of below £100/t CO_2. Only 4.4 Mt CO_2 of emission reduction is realised at higher CO_2 tax levels. Moreover, one can see that the electricity sector is entirely decarbonised at a tax of £176/t CO_2 and becomes even an emission sink for 1.4 Mt CO_2 by capturing emissions from burning biomass. For the interpretation of the MAC curves it should be taken into account that each bar represents the marginal mitigation measure, i.e. the measure responsible for the emission reduction between two adjacent CO_2 tax runs. Because of the dynamic model character, the bars cannot be added together to form a total.

The technological detail reveals that nuclear power is the main technology to reduce carbon emissions cost-efficiently. Electricity generation is shifted away from coal-fired power plants to nuclear power plants from as low as £1/t CO_2 up to a tax level of £34/t CO_2, while the weighted average abatement cost for nuclear power is £12/t CO_2. Nuclear power does not have one single marginal abatement cost because a systems model with many input assumptions has been used to generate the MAC curve. Thus, the MAC of nuclear power is a range of costs because there is more than one type of nuclear power plant and because a supply cost curve for uranium is implemented in UK MARKAL. In addition, nuclear power, as with all other power technologies is subject to a build rate limit. In the case of nuclear, this starts at 2.5 GW and is gradually increased in the first half of the 21st century to 10 GW per five year period. This is one of the reasons for intertemporal interactions, i.e. that the conditions in one time period influence the result in a previous or later time period.

Furthermore, nuclear power competes with other low-carbon technologies that are also subject to changing economics, particularly coal CCS.

Fig. 5: MAC curve in the REF scenario in 2030



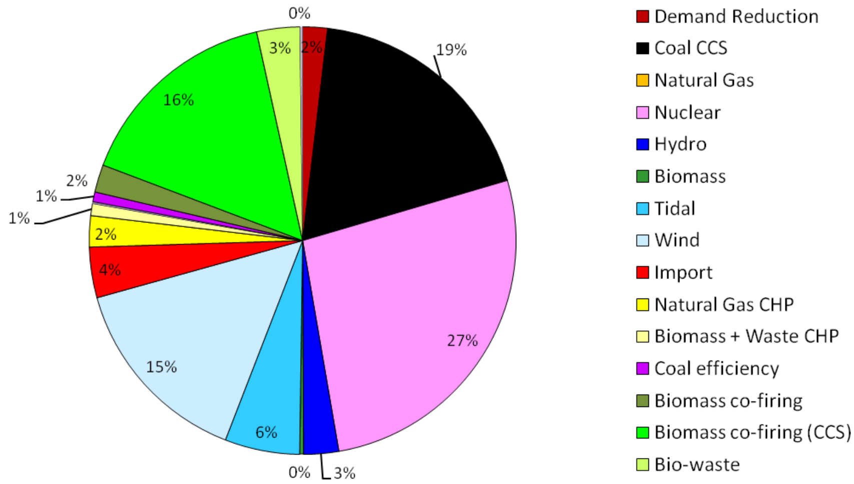
Coal CCS plays a significant role in the electricity mix from a higher tax level of £19/t CO_2, which is due to its slightly higher generation cost of 4.75 p/kWh (pence per kilowatt hour) in the base case compared to 3.74 p/kWh for nuclear power plants. The higher generation cost accounts for higher capital, operating and CO_2 capture and storage costs. The abatement cost range for coal CCS is significantly larger than for nuclear from £19/t CO_2 to £147/t CO_2 with a weighted average of £63/t CO_2. Reasons are that a variety of coal CCS alternatives, such as pre-combustion and post-combustion are implemented in the model, as well as conventional coal-fired power stations with retrofit. The possibility for co-firing brings in further interactions with a limited resource that has different qualities and costs and competes with other potential users, such as biofuels in transport or as a heating fuel in the building stock.

A further important mitigation option is biomass co-firing in CCS plants. On an energy-equivalent basis, particular types of coal CCS plants are assumed to be able to co-fire up to 20% of biomass. This can make co-firing coal CCS plants an emission sink, given the fact that they capture 85% of all emissions and biomass is almost carbon-free only accounting for emissions during cultivation, processing and transport.

Next to nuclear and coal CCS power plants, wind power represents another important abatement technology in the power sector. Marginal abatement costs for wind power range from £0/t CO_2, as it is already included in the baseline, up to £117/t CO_2, while the weighted average is £25/t CO_2. This range includes onshore as well as offshore wind power, while the potential electricity production from offshore is far higher than from onshore wind.

An idea of the overall contribution of different technologies and effects to emissions reduction up to the highest CO_2 tax of £294/t CO_2 in 2030, is given in Fig. 6. It can be seen that the reduction in the demand for electricity caused by higher prices, has a very minor (2%) contribution.

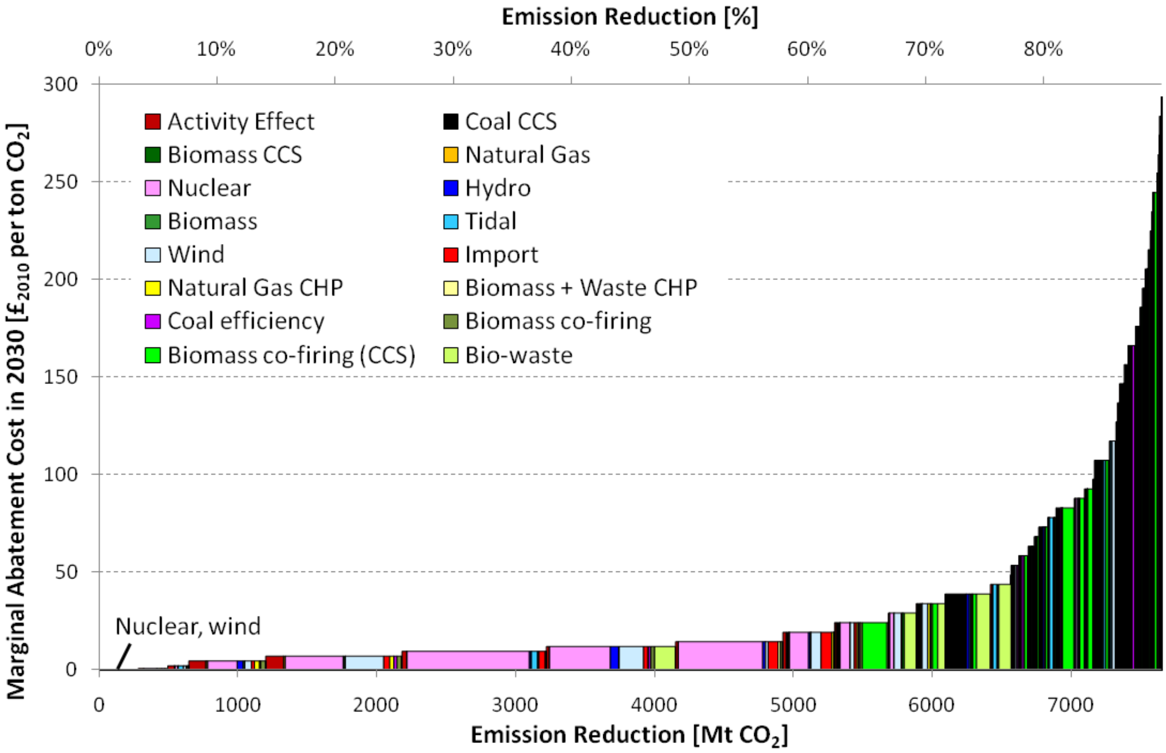
Fig. 6: Technology-specific contribution to overall emission reduction of 192 Mt CO_2 (REF scenario) in 2030



The most important effects are structural changes in the electricity mix. Nuclear power is the most important mitigation measure with a share of 27% in emission reduction followed by coal CCS with 19%. However, this share only includes the shift towards coal CCS power plants and not the additional emissions savings that are achieved by co-firing biomass, which accounts for an additional 16%. The other significant mitigation measure in the UK power sector is wind power with a contribution of 15%. Nuclear power, coal CCS (including biomass co-firing) and wind are responsible in total for 77% of all emission reduction.

The discussion so far has focused on emissions reduction in the year 2030. In order to address the static character of a usual MAC curve and take into account intertemporal interactions, Fig. 7 presents a cumulative power sector MAC curve for the period from 2010-2050. The y-axis represents the CO_2 tax level in 2030, which is however not constant but increases with the discount rate of 5% so that the tax level is lower prior to 2030 and higher thereafter.

Fig. 7: MAC curve in the REF scenario for the period 2010-2050



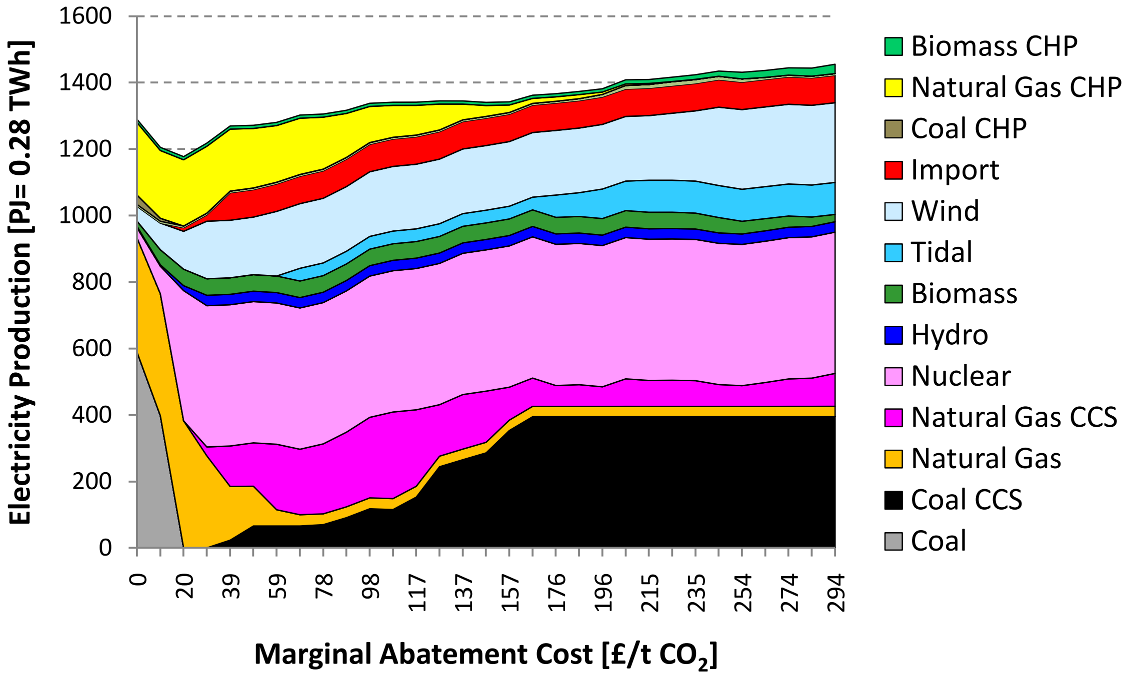
Within the 40 years, emissions are predicted to be 8.5 Gt CO_2, which corresponds to 216 Mt CO_2 per year for the UK power sector. The MAC curve indicates that emissions reduction is comparably inexpensive in the power sector, where half of all cumulative emissions can be abated with a CO_2 tax of £15/t CO_2 in 2030 (assuming a tax that increases with 5% per year). Similar to the MAC curve in 2030, nuclear power plays the most important role in decarbonising the power sector with a share of 39% in all emissions reduction. The share of nuclear is higher than in 2030 because nuclear can be deployed earlier than coal CCS power plants and nuclear power plants are less expensive. From 2040 on, the role of coal CCS power stations is diminished owing to the introduction of biomass CCS plants that can act as important carbon sinks by storing emission from biomass that have been taken out of the atmosphere during its lifetime. Accordingly the share of coal CCS power plants in overall emissions reduction is 16% (including biomass co-firing) and 2% for biomass CCS plants. Wind proves to be an equally important mitigation option with 11% of emissions reduction.

4.3 Low Gas Price Scenario

This scenario assumes a gas price that will drop from current levels of £4.5/GJ to £2.5/GJ in 2015 and then stay roughly constant. In comparison to the REF scenario the price for natural gas is reduced by 50%. This is a situation observed since 2009 for West Texas Intermediate (WTI) crude oil and Henry Hub natural gas in the United States. Such a low natural gas price can be explained with a significant increase of the supply of gas in the form of unconventional, in particular shale gas. With the potential for shale gas production in Europe, it is possible to see gas and oil prices decouple in the long-run.

Fig. 3 revealed that the emissions in the power sector are about 8 Mt CO_2 higher without any CO_2 tax in the GAS scenario compared with the REF scenario. This can be explained with a higher share of gas at the expense of wind power and electricity import. The emission curves look very similar over all tax levels except for the range between £75/t CO_2 and £150/t CO_2, where emissions in the GAS scenario are a maximum 15 Mt CO_2 higher for the same tax level. A reason is the higher share of natural gas in the power sector (see Fig. 8), while emissions are lower in return in the residential sector and industry. Overall, the MAC curves in both cases look very similar and are thus robust to lower gas prices.

Fig. 8: Electricity generation mix for different marginal abatement costs in 2030 (GAS scenario)



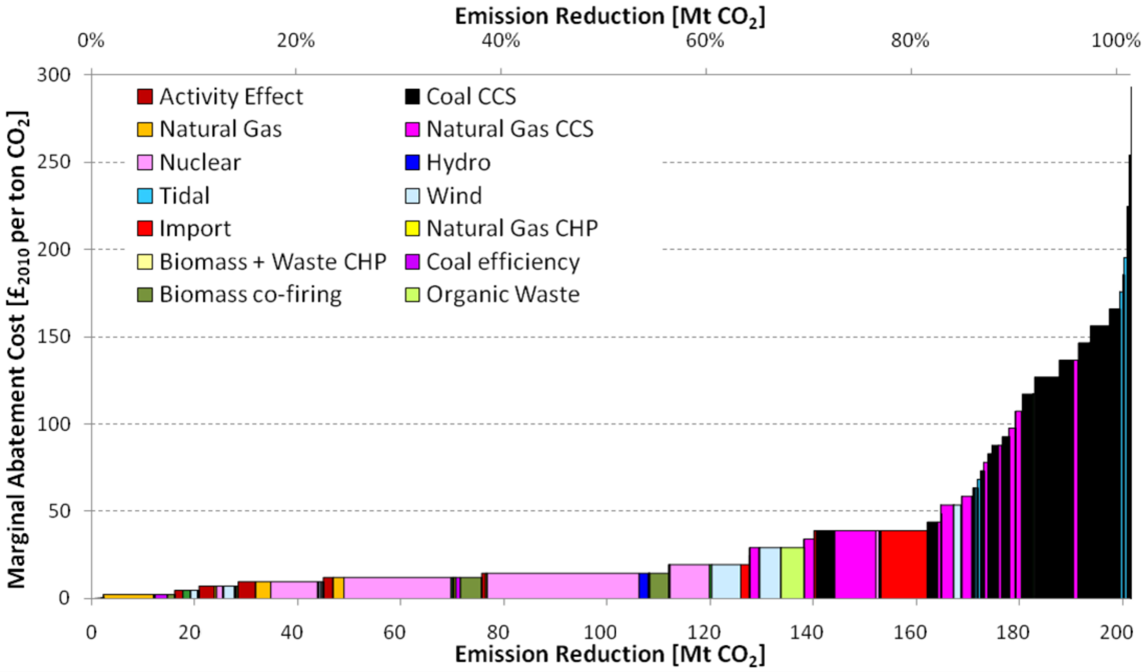
One can see that the baseline electricity mix is no longer as dominated by coal as in the REF scenario. The share of gas in electricity production increases from 17% to 25%. Combined-cycle gas turbines remain an important part of the electricity mix up to around £50/t CO_2 and natural gas CHP plants up to £150/t CO_2. Coal CCS plants only become cost-efficient from £39/t CO_2, i.e. £20/t CO_2 more than in the REF scenario.

Most interesting to see is that gas-fired power station with CCS enter the electricity mix at £29/t CO_2, while this plant type does not become cost-efficient in the REF scenario. Electricity production from gas CCS plants is highest at £107/t CO_2 at 261 PJ (72 TWh). This carbon tax is very close to the carbon tax of £98/t CO_2 calculated to be necessary in order to achieve an 80% emission cut in 2050. At higher tax levels, however, the share of gas CCS plants is significantly reduced as coal CCS power plants replace gas CCS plants. The reason is that coal CCS plants achieve negative emissions via biomass co-firing. Biogas is not co-fired to gas CCS plants due to the initial lack of infrastructure, limited resource potential and higher processing costs than for woody biomass.

Given lower gas prices, these results suggest that natural gas can play a significant role as a transition fuel in a decarbonisation strategy of the UK power sector in a specific tax and time window in the form of natural gas CHP plants and particularly natural gas CCS plants. Gas-fired power plants continue to play a role in electricity decarbonisation in 2030 up to a tax level of around £50/t CO_2. At a CO_2 tax of £108/t CO_2 a maximum of 18 GW of natural gas CCS power plants are built from 2023 to 2032, while the first CCS plants are retrofitted in 2020. After this period gas CCS plants are no longer competitive with coal CCS plants and nuclear power.

The MAC curve for the GAS scenario (Fig. 9) shows nuclear power as an important low-cost abatement option, similar to the REF scenario. Nuclear power is responsible for 34% of all emissions reduction in the power sector, while the average abatement costs are £14/t CO_2, thus £2/t CO_2 higher compared with the REF scenario. The contribution of coal CCS plants is significantly less as gas CCS plants become an important abatement measure and coal CCS power plants with biomass co-firing account at higher tax level only for the uncaptured emissions from gas CCS plants. In addition, the abatement costs for coal CCS plants increase to a range from £39/t CO_2 to 166/t CO_2 with a weighted average of £105/t CO_2 or £42/t CO_2 more than in the REF scenario. Natural gas CCS reduces CO_2 emissions by 24 Mt CO_2 or 12% at a cost range between £29/t CO_2 and £137/t CO_2 with a weighted average of £56/t CO_2. Furthermore, a switch from coal-based to gas-based electricity production proves to be one of the most cost-efficient mitigation options up to £20/t CO_2. A switch to natural gas saves in total 12 Mt CO_2 or 6%.

Fig. 9: MAC curve in the GAS scenario in 2030



In summary one can say that the MAC curve in the GAS scenario is robust to lower gas prices with small deviations around a tax level of £100/t CO_2 due to intersectoral interactions. Concerning the abatement structure, a lower gas price induces investments in natural gas CCS plants that make coal CCS plants more expensive.

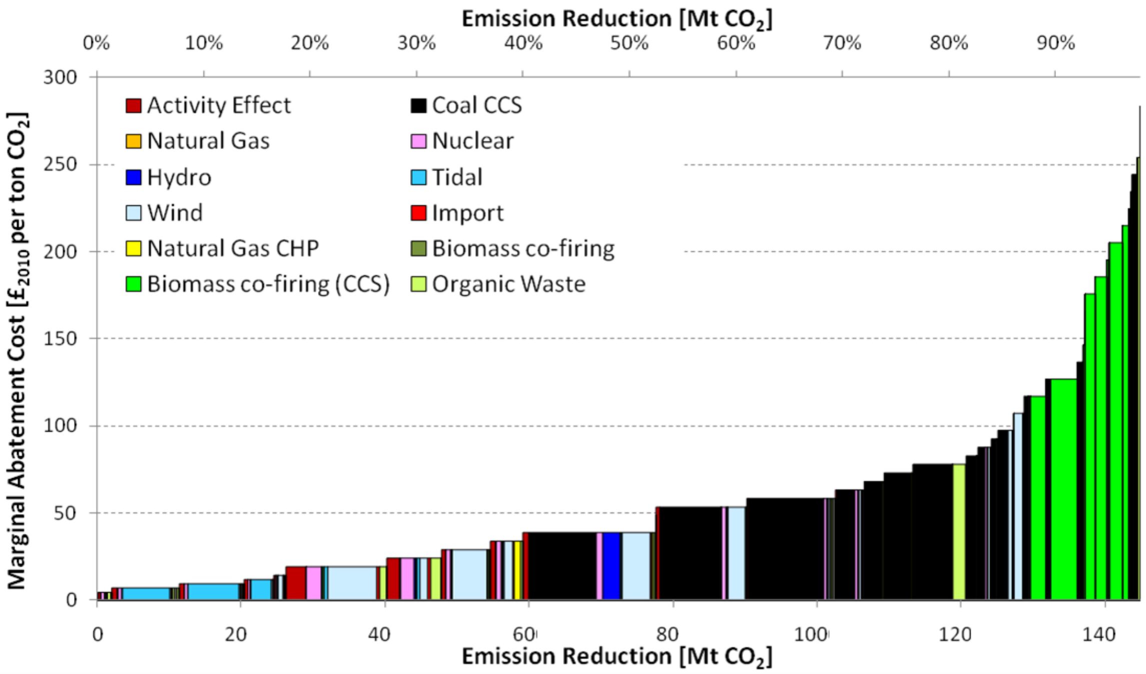
4.4 High Fossil Fuel Price Scenario (FF+)

The FF+ scenario differs from the REF scenario in the way that the price for hard coal, coking coal, natural gas, crude oil and refined products were increased by 100% from 2015 onwards. This corresponds to a scenario where global fossil fuel prices increase, for example, due to a significant demand increase from Asian countries or due to lacking investments that limit the supply of energy carriers.

Emissions without a carbon tax are 148 Mt CO_2 in the FF+ scenario, i.e. 43 Mt CO_2 less than in the REF scenario. This is caused by a lower share of coal in the electricity mix of 35% and natural gas CHP plants that are completely replaced by nuclear power plants (28% production share), wind power (13% production share), tidal power (3% production share) and hydro power (2% production share). As low-carbon alternatives have already been integrated in this scenario without a carbon tax, the electricity sector decarbonises slower with increasing tax levels compared with the REF scenario. Both curves intersect at £13/t CO_2 from where on emission abatement in the FF+ scenario is associated with a little higher costs. This is due to the fact that an important abatement option, coal CCS plants, becomes more expensive due to higher fuel costs. In addition, wind power, nuclear power and CCS plants are constrained by built rate limits. From a tax level of £50/t CO_2, which is at the lower end of what is needed to achieve the legally required emission cuts, the emission curve for the REF and FF+ scenario diverge by a maximum of 11 Mt CO_2.

Fig. 10 illustrates the MAC curve for the FF+ scenario. The curve looks very different from the REF scenario as it represents only 149 Mt CO_2 emissions reduction due to significant emissions savings already in the baseline development. Nuclear power does not play a significant role in the MAC curve with only 9% due to the fact that a significant share of electricity production comes from nuclear power plants in the base case. The relative contribution of coal CCS as a mitigation option is significantly higher with 33%, but also the absolute emission reduction is higher with 47 Mt CO_2. Due to the higher coal price the weighted average abatement cost of coal CCS plants increase to £71/t CO_2 (£8/t CO_2 higher than in the REF scenario) with a range from £39/t CO_2 to 245/t CO_2. Co-firing of biomass into coal CCS plants is substantially more expensive with a weighted average abatement cost of £160/t CO_2. This can be explained with the higher costs for coal CCS, but also with the same limited amount of biomass being used at lower tax rates in competing biomass power and CHP plants.

Fig. 10:: MAC curve in the FF+ scenario in 2030



Summing up, higher fossil fuel prices shift the start point of the MAC curve and lead to a slower decarbonisation of the electricity sector due to higher cost for electricity from coal CCS plants. Marginal abatement costs of renewable energy sources, such as wind and tidal power, are significantly lower due to higher fossil fuel prices. Overall, both MAC curves look very similar, which holds especially true for the range of likely carbon tax levels in 2030.

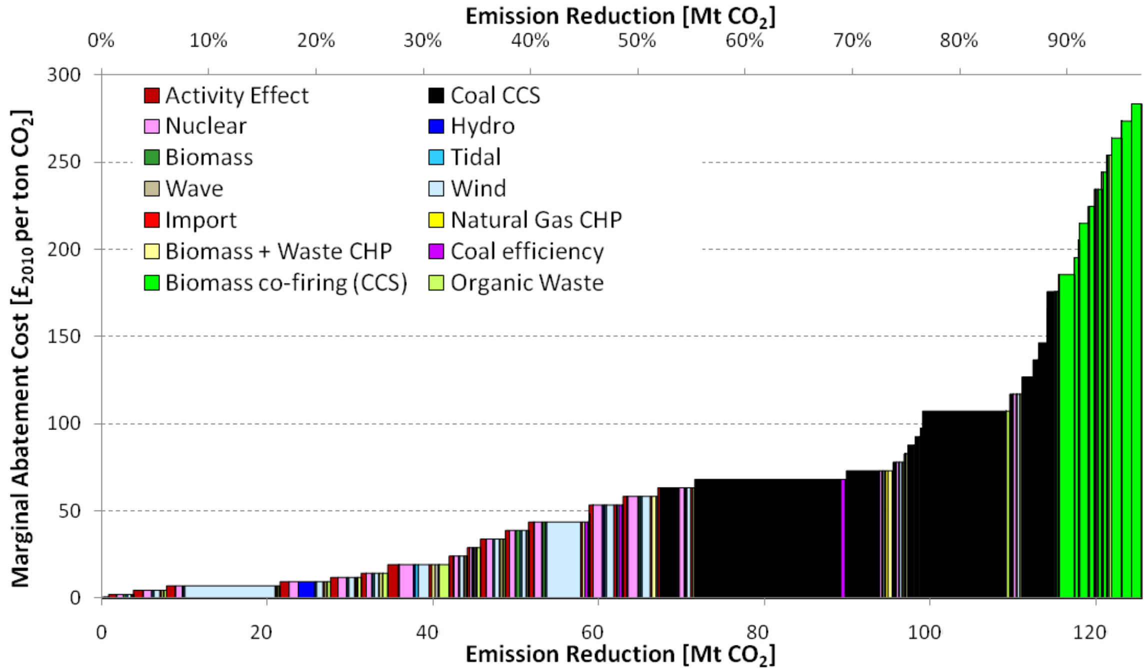
4.5 Very High Fossil Fuel Price Scenario (FF++)

In the FF++ scenario all fossil fuel prices are increased by 200% compared to the REF scenario, i.e. another 100% higher than in the FF+ scenario. Such a substantial price increase could be explained with supply shocks comparably to the 1970s. This scenario assumes extremely high fossil fuel prices with oil prices being above $\$_{2010}220$ per barrel for decades. Hence it is all the more interesting to see how robust the MAC curve reacts to such extreme assumptions.

Emissions without a carbon tax are 62 Mt CO_2 lower compared with the REF scenario and still 19 Mt CO_2 lower than in the FF+ scenario. This can be explained with an even lower share of coal in the electricity mix of only 20%. The reduced electricity production from coal is made up by biomass power and CHP plants, tidal power and wind power with a market share of 12%, 6%, and 17% respectively. Since many abatement options are already implemented without a carbon tax, further decarbonisation of the power sector requires, similar to the FF+ scenario, higher marginal abatement costs then the REF scenario. For a given carbon tax, carbon abatement remains less in the FF+ scenario compared with the REF scenario from £24/t CO_2 upwards with a maximal difference of 30 Mt CO_2 for the same carbon tax. This difference is reduced to 16 Mt CO_2 for a range of more likely carbon tax levels in 2030 of £50/t CO_2 to £150/t CO_2. Thus, even a substantial threefold increase in fossil fuel prices changes emission reduction for a given carbon tax by a maximum of 30 Mt CO_2, or, in relation to baseline emissions, by 16%.

As many low-carbon technologies are part of the baseline development, the MAC curve (see Fig. 11) covers only 129 Mt CO_2 of emissions reduction and its structure looks different. The abatement potential of nuclear power plants is more limited compared to the REF scenario. Nuclear power already makes up 29% of the electricity mix without a carbon tax and building a nuclear power plant requires long lead times. In addition, current plans in the UK intend to replace current nuclear power plants, but not to built additional capacity so that it is deemed unrealistic to see a faster build up of nuclear electric capacity. Caused by very high fuel prices, wind power is a substantial part of the baseline development, while the installation of further wind capacity contributes 20% or 26 Mt CO_2 to emissions abatement.

Fig. 11: MAC curve in the FF++ scenario in 2030



The most important abatement measure is coal CCS power plants with 31%. Owing to the significantly higher coal price, the abatement costs for coal CCS are in a range from £64/t CO_2 to £176/t CO_2 with a weighted average of £87/t CO_2. This is significantly higher than in the REF scenario with the lowest abatement cost being £45/t CO_2 higher and the average being £24/t CO_2 higher. Consequently, a 200% increase of the fossil fuel prices means that a threefold increase in the carbon tax would be necessary to make a first application of the coal CCS technology cost-efficient. The co-firing of biomass is equally more expensive with a weighted average abatement cost of £234/t CO_2, more than three times more than in the REF scenario. This can be explained with a significantly higher amount of biomass being used in biomass CHP plants and for heating purposes in the residential and service sector that have repercussions on the use of biomass as a co-firing fuel.

To conclude, the increase of fossil fuel prices has a significant effect on technology-specific MACs with wind power, tidal power and wind power having significantly lower marginal abatement costs. On the other hand, coal CCS with biomass co-firing becomes significantly more expensive as fuel prices triple. The shape of the MAC curve proves to be robust to an extreme increase in fuel prices, where the difference to the REF scenario in range of likely carbon taxes for the year 2030 of £35/t CO_2 to £105/t CO_2 is on average 21 Mt CO_2, thus only 11% with respect to baseline emissions in the REF scenario.

5 Conclusions

This paper presented the economics of carbon emission reduction in the UK power sector and the influence of varying fossil fuel prices on the shape and structure of an energy-system wide and power MAC curve. Concerning the economics of emission reduction in the UK power sector, nuclear power alongside coal CCS emerged as the main mitigation technologies, while the abatement costs for nuclear are significantly less than for coal CCS. A third significant mitigation option in all four presented scenarios is wind power with average abatement cost in 2030 of £25/t CO_2 and below. The use of solid biomass plays an important role, representing 21% of all emissions reduction in the power sector, in biomass CHP plants, pure biomass power plants, waste incineration, and foremost as a co-firing fuel in coal CCS plants.

The variation of fossil fuel prices has a noteworthy influence on the abatement structure. Halving the price for natural gas led to a situation where natural gas can play an important role as a transition fuel used with and without CCS. Increasing the price for coal, gas and oil meant on the one hand that the marginal abatement costs for renewable energy sources decreased, while on the other hand, electricity production from coal CCS plants increased. Increased cost for coal and an increased demand for biomass in the residential and service sector lead to coal CCS being introduced more gradually in the high fossil fuel price scenarios.

Once different baseline emission developments were accounted for the MAC curves look very similar across the scenarios and prove to be robust to changing fossil fuel prices. So the hypothesis that MAC curves are not robust to changing fossil fuel prices could not be proved. This not only holds true to uniform increases of all fossil fuel prices but also to lower natural gas prices. In the range of an expected carbon tax for the year 2030 of £35/t CO_2 to £105/t CO_2, the average deviation in abatement for a given tax level was 5% for the whole energy system and 11% for the power sector with respect to the baseline emission level in the REF scenario. The curves are even more similar at higher tax levels, while the range is wider for levels below £20/t CO_2 owing to the predominant influence of the baseline emission level. Nevertheless, drastic increases in the fossil fuel price have a very limited effect on the costs of decarbonising the energy system. Various reasons explain this:

- fuel costs for a coal-fired power station double at a CO_2 tax of £28/t CO_2, while this is the case at £100/t CO_2 for a gas-fired power plant. Consequently, with an increasing CO_2 tax the differences in fossil fuel production costs are dwarfed by the tax level, which is expected to be around £70/t CO_2 in 2030 if the UK is going to meet its legal obligations;

- the power sector is not reliant on one abatement option, but has several zero-carbon technologies with moderate abatement costs that can compensate for another abatement technology;
- on the one hand, higher fossil fuel prices induce investment into renewable energy sources at lower carbon tax levels as they become cheaper compared to fossil fuel based alternatives. On the other hand, higher prices increase the fuel cost of coal CCS power plants; and
- interactions between supply sectors and end-use sectors help to even out price differences.

When interpreting the results of this study it should be taken into account that the results are model-dependent and might change when using another energy model. The UK power sector has many influencing factors in common with numerous other countries, so that the results of this study should also apply to other countries.

The findings of this paper should make policy makers in the climate change mitigation field more confident in the use of MAC curves as a policy tool given the very limited influence of fossil fuel prices. Yet, MAC curve always need a nuanced treatment considering the underlying modelling work, the fact that they do not capture intertemporal aspects, and omit ancillary benefits of emissions reduction.

References

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

Barker, T., I. Bashmakov, A. Alharthi, M. Amann, L. Cifuentes, J. Drexhage, M. Duan, O. Edenhofer, B. Flannery, M. Grubb, M. Hoogwijk, F. I. Ibitoye, C. J. Jepma, W. A. Pizer and K. Yamaji (2007). Mitigation from a cross-sectoral perspective. Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. B. Metz, O. R. Davidson, P. R. Bosch, R. Dave and L. A. Meyer. Cambridge, United Kingdom and New York, NY, USA, Cambridge University Press.

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.

Chen, W., Z. Wu, J. He, P. Gao and S. Xu (2007). "Carbon emission control strategies for China: A comparative study with partial and general equilibrium versions of the China MARKAL model." Energy **32**(1): 59-72.

Committee on Climate Change (2008). The Costs of Decarbonising Electricity Generation - Technical Appendix to Chapter 5. London.

Confederation of British Industry (2007). Climate change: Everyone's business. London.

Creyts, J., A. Derkach, S. Nyquist, K. Ostrowski and J. Stephenson (2007). Reducing U.S. Greenhouse Gas Emissions: How Much at What Cost?, McKinsey & Company.

Gracceva, F. and U. Ciorba (2008). Abatement Cost Curves by (Group of) Technologies for Italy. ETSAP Semi-annual Workshop. IEA. Paris.

HM Government (2009). Analytical Annex - The UK Low Carbon Transition Plan. London.

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. (2010). 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**.

Klepper, G. and S. Peterson (2006). "Marginal abatement cost curves in general equilibrium: The influence of world energy prices." Resource and Energy Economics **28**(1): 1-23.

Loulou, R., G. Goldstein and K. Noble (2004). Documentation for the MARKAL Family of Models, Energy Technology Systems Analysis Programme.

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.

Siddiqui, M. S. (2010). Impacts of External Change on a Regional Marginal Abatement Cost Curve: A Canadian Perspective. Fourth World Congress of Environmental and Resource Economists. Montreal, Canada.

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.

Sweeney, J., J. Weyant, T. T. Chan, R. Chowdhary, K. Gillingham, A. Guy, S. Houde, A. Lambie, R. P. Naga, R. Raybin, A. Sathe, A. Sudarshan, J. Westersund and A. Y. Zheng (2008). Analysis of Measures to Meet the Requirements of California's Assembly Bill 32. Stanford, Precourt Institute for Energy Efficiency, Standford University.

Usher, W. and N. Strachan (2010). UK MARKAL Modelling - Examining Decarbonisation Pathways in the 2020s on the Way to Meeting the 2050 Target. London, University College London, Energy Institute.

Vivid Economics (2010). The implicit price of carbon in the electricity sector of six major economies, report prepared for the Climate Institute.