



Marginal abatement cost curves for policy making – expert-based vs. model-derived curves*

Fabian Kesicki^a

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

Abstract

Legal commitments to reduce CO₂ emissions require policy makers to find cost-efficient means to meet the obligations. Marginal abatement cost (MAC) curves have frequently been used in this context to illustrate the economics associated with climate change mitigation. A variety of approaches are used to generate MAC curves with different strengths and weaknesses, which complicates the interpretation. This paper points out the usefulness and limits of the concept of MAC curves and presents a review of the weaknesses and strengths inherent to different methods to derive MAC curves. In the next step, the use of the different types of MAC curves for the assessment of policy instruments is discussed. It concludes that expert-based curves can serve as guides for non-incentive-based instruments, while model-derived curves are suitable to assess incentive-based instruments. Finally, policy makers have to be aware of the general and type-specific shortcomings of abatement cost curves in order to arrive at a balanced decision.

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1 Introduction

Policy makers in many countries around the world have agreed to substantially reduce carbon emissions over the coming years. The first concerted, multilateral effort to tackle rising greenhouse gas emissions was undertaken at the third Conference of the Parties of the United Nations Framework Convention on Climate Change (UNFCCC) with the Kyoto protocol (United Nations 1998). Additionally, within the European Union, member states agreed to reduce greenhouse gas emission by at least 20% by 2020 compared to 1990 (Commission of the European Communities 2008). On a national level, the United Kingdom (UK) has adopted a law with the goal to ensure that carbon emissions in 2050 are 80% below the level in 1990 (The Parliament of the United Kingdom of Great Britain and Northern Ireland 2008).

Confronted with a situation of legally binding commitments, the question arises of how to reduce carbon emissions in a cost-efficient way. For this purpose, marginal abatement cost (MAC) curves, which contrast marginal abatement cost and total emission abatement, have been frequently used in the past to illustrate the economics of climate change mitigation and have contributed to decision making in the context of climate policy. The concept of carbon abatement curves has been applied since the early 1990s to illustrate the cost associated with carbon abatement (see e.g. Jackson 1991).

MAC curves are not only restricted to the analysis of CO₂ reduction – the earliest cost curves developed after the two oil price shocks in the 1970s were aimed at reducing crude oil consumption [\$/bbl] and later for the saving of electricity consumption [\$/kWh] (Meier 1982). At the time, the curves were not called MAC curves, but rather saving curves or conservation supply curves. Furthermore, those curves were widely used for the assessment of abatement potential and costs of air pollutants [\$/kt] (see e.g. Silverman 1985; Rentz et al. 1994), waste reduction [\$/kg] (Beaumont and Tinch 2004) and lately for additional water availability [\$/m³] (Addams et al. 2009).

In recent years, the concept has become very popular with policy makers and is used in many countries. Policy makers now find themselves confronted with MAC curves that are derived in different ways. Zhang et al. (1998) studied more generally the strengths and weaknesses of modelling approaches used to estimate costs related to carbon emission reduction. However, there exists a lack of understanding as to the extent curves can help in informing climate policy. This is because carbon curves possess strengths and weaknesses inherent to the underlying approach, which means that one approach can be well suited for the analysis of a certain category of policy instruments and unsuitable for another.

The goal of the paper is to confront this lack of knowledge by presenting a review of the concept of MAC curves, the existing approaches to generate those curves and to compare their respective strengths and weaknesses. The usefulness of the different approaches for the assessment of various climate policy instruments is also discussed and a perspective of how to improve current MAC curve generation is given.

The next section will explain and compare in detail the existing approaches to the generation of MAC curves, namely expert-based and model-derived cost curves. Section 3 then turns towards climate policy instruments and demonstrates the degree to which MAC curves can provide valuable insights for policy makers. Section 4 looks more closely at the use of MAC curves in the United Kingdom, while section 5 concludes the paper by giving an outline of future work.

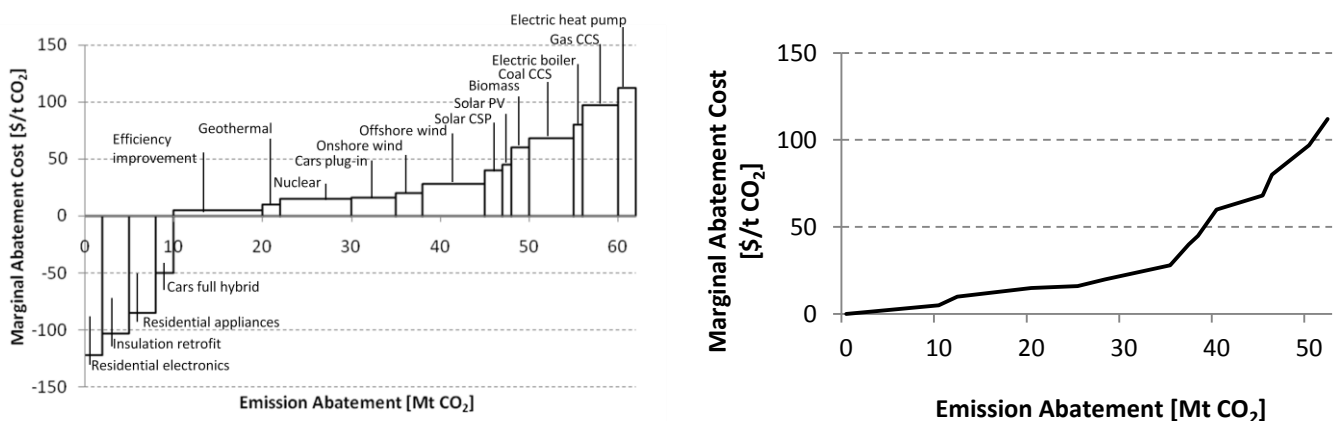
2 The concept of marginal abatement cost curves

2.1 General aspects

Marginal abatement cost curves come in a wide variety of shapes. They differ in regard to the regional scope, time horizon, sectors included and approach used for the generation. This section describes the concept of MAC curves and discusses the distinction between expert-based and model-derived curves.

A marginal abatement cost curve is defined as a graph that indicates the cost, associated with the last unit (the marginal cost) of emission abatement for varying amounts of emission reduction (in general in million/billion tons of CO₂). Therefore, a baseline with no CO₂ constraint has to be defined in order to assess the marginal abatement cost against this baseline development. A MAC curve allows one to analyse the cost of the last abated unit of CO₂ for a defined abatement level while obtaining insights into the total abatement costs through the integral of the abatement cost curve. The average abatement costs can be calculated by dividing the total abatement cost by the amount of abated emissions. According to the underlying methodology, MAC curves can be divided into expert-based and model-derived curves. Typical graphical presentations of both types are given in Figure 1.

Figure 1: Stylised examples for an expert-based (left) and model-derived MAC curve (right)



Expert-based MAC curves (see section 2.2), assess the cost and reduction potential of each single abatement measure based on educated opinions, while model-derived curves (see section 2.3) are based on the calculation of energy models.

On the one hand, MAC curves in general have been very popular with policy makers because of their very simple presentations of the economics related with climate change mitigation. Policy makers can easily see the marginal abatement cost associated with any given total reduction amount and can also see the mitigation measures responsible for the reduction of CO₂ emissions in the case of expert-based curves.

On the other hand, the concept of MAC curves contains several shortcomings. One weakness concerns the transparency of assumptions. Firstly, the assumptions concerning the baseline development and assumptions on the costs of abatement technologies are often not stated. In order to increase the confidence of decision makers using this research tool and to increase the accuracy of the decisions made, publishing key assumptions together with the MAC curves can be helpful. Secondly, MAC curves represent the abatement cost for a single point in time. Due to this representation, they cannot capture differences in the emission pathway

and are subject to intertemporal dynamics. This means that the marginal abatement costs depend on abatement actions realised in earlier time periods and expectations about later time periods.

Furthermore, in the case when MAC curves contain technological detail (see Figure 1, left), they suggest that one can add any abatement measure when one wishes to increase the abatement amount. Thus, this form of illustration does not permit the representation of path dependency of the technological structure. For example, in such a curve it is not possible to integrate a low-carbon technology (e.g. coal carbon capture and storage) that is responsible for emission abatement at low cost levels but is replaced at higher cost by a zero-carbon technology.

In addition, these curves usually concentrate only on carbon emission abatement and thus attribute all of the costs associated with the abatement to carbon emission reduction. In most cases, however, the reduction of CO₂ emissions generates a range of ancillary benefits. These co-benefits include, amongst others, improved energy security and the reduction of other greenhouse gases, such as CH₄ and N₂O, as well as air pollutants (Fisher et al. 2007, p. 213f).

Ancillary benefits, e.g. energy security or health improvements, where estimates show a wide range (given the lack of standard metrics), are usually not included in MAC curves because they are difficult to quantify as these involve different spatial and temporal scales and because there is little overlap in research institutions between research on air pollutants and greenhouse gas reduction. An exception is the GAINS (GHG-Air pollution Interaction and Synergies) model (Klaassen et al. 2005), which minimises the total control cost for pollutants as well as greenhouse gases. Nevertheless, the frequent disregard of ancillary benefits can lead to a substantial overestimation of the actual MACs.

A final shortcoming relates to the representation of uncertainty. Marginal abatement cost estimates are subject to assumptions that become more uncertain the further the estimation is in the future, e.g. 2050 vs. 2020. This sets out the need for a better representation of uncertainties, i.e. not only presenting one MAC curve, but different MAC curves with varying assumptions for key drivers. Table 1 summarises the strengths and weakness of MAC curves.

Table 1: Advantages and disadvantages of MAC curve concept

ADVANTAGES	DISADVANTAGES
<ul style="list-style-type: none"> ▪ Present the marginal abatement cost for any given total reduction amount ▪ Give the total cost necessary to abate a defined amount of carbon emissions ▪ Allow the calculation of average abatement costs 	<ul style="list-style-type: none"> ▪ Limited to one point in time ▪ No representation of path dependency ▪ Limited representation of uncertainty ▪ Lacking transparency of assumptions ▪ No consideration of ancillary benefits

2.2 Expert-based MAC curves

Expert-based approaches, sometimes also called technology cost curves, are built upon assumptions developed by experts for the baseline development of CO₂ emissions, the emission reduction potential and the corresponding cost of single measures (including new technologies, fuel switches and efficiency improvements). Subsequently, the measures are explicitly ranked from cheapest to most expensive to represent the costs of achieving incremental levels of emissions reduction (see Figure 1, left).

This concept was first applied to the reduction of crude oil and electricity consumption in the 1970s; the earliest examples of carbon-focused curves date back to the early 1990s (Jackson

1991). Expert-based curves received much attention in recent years due to a number of detailed country studies from McKinsey & Company (2010). While McKinsey & Company started with abatement cost curves on a country level, they published one of the few expert-based global marginal abatement cost curves.

Depending on the discount rate used and the consideration of subsidies and taxes, one can differentiate expert-based curves into abatement curves from a private and societal perspective. Abatement curves based on a societal perspective use a discount rate of e.g. 3.5% (HM Treasury 2003) to reflect society's preference over time, while curves from a private perspective integrate subsidies, taxes and higher interest rates up to 10% and higher to measure the costs faced by private individuals when making investment decisions. Integrating higher technology specific discount rates can, for example, represent financial constraints for households and uncertainty associated with investment decisions (see e.g. Pye et al. 2008).

The principal advantage of expert-based abatement cost curve is that they are easy to understand. Marginal costs and the abatement potential can be unambiguously assigned to one mitigation option. If a particular abatement level is targeted, one knows what measures need to be implemented in order to achieve the goal. Furthermore, the technological detail can be extensive, depending on the refinement of the study.

Expert-based MAC curves typically show the technological potential of abatement measures. As abatement curves that are based on expert judgement consider each technology individually they can, to a limited extent, integrate technology specific existing tax and subsidy distortion in their assessment. Nevertheless, they present a maximum abatement potential since they do not consider behavioural aspects, nor institutional or implementation barriers. Behavioural aspects, i.e. demand adjustments to changing prices for energy service demands and rebound effects leading to an increased energy service demand in the case of efficiency improvements, are sometimes accounted for by exogenously adjusting the reference demand. The disregard of market imperfections is a reason for the representation of negative abatement costs, i.e. abatement measures that can simultaneously save money. However, these savings can only be realised once market distortions are overcome. These distortions can take the form of split incentives, a lack of information and significant upfront payments associated with a long payback period.

Disadvantages of expert-based curve include that certain curves achieve some of the aforementioned aspects by simplifying reality. Although it is implausible to assign only one cost level to a technology, this is a simplification that is often made with many curves. For many renewable energy sources, like photovoltaic or wind, different cost steps exist depending on the siting of power generation capacities and environmental conditions. Furthermore, expert-based studies consider only a selection of mostly existing technologies, e.g. according to the probability of realisation, which can exclude promising future technologies. For sectoral studies, e.g. the transport sector, a problem can arise when mitigation costs are implemented from the perspectives of different decision makers, which would mean that an accumulation of abatement costs across sectors is not possible.

Another disadvantage of expert based cost curves can be possible inconsistencies in their baseline assumptions. This concerns, for example, assumptions in the reference case. The calculation for the abatement potential and marginal cost is undertaken by comparison to a reference development. In this context, it is important to adapt the reference scenario to the extent that cheaper abatement options have already been implemented in order to avoid double counting.

Most important is the non-consideration of different types of interactions. One type is intertemporal interactions of emission abatement. The form of the emission pathway, i.e. the abated amount and the emission reduction path prior to and after the considered point in time has a significant impact on the abatement curve. This is caused by possible cost reduction caused by technological learning and by varying expectations about future conditions. Moreover, expert-based MAC curves are not able to adequately capture interactions between abatement measures, economy-wide dependencies and behavioural interdependencies. Consequences of a higher use of electricity in the transport sector for power generation can hardly be integrated into an assessment that is based on the assessment of single measures.

A last weakness is the representation of uncertainty considering influencing factors, like technology costs, energy prices, discounting or demand development. Curves that summarise abatement costs and potentials for dates far in the future are subject to major uncertainties concerning financial and technological parameters. Table 2 summarises the strengths and weaknesses of expert-based curves.

Table 2: Strengths and weaknesses of MAC curves based on expert judgement

STRENGTHS	WEAKNESSES
<ul style="list-style-type: none"> ▪ Extensive technological detail ▪ Possibility of taking into account technology specific market distortions ▪ Easy understanding of technology-specific abatement curves 	<ul style="list-style-type: none"> ▪ No integration of behavioural factors ▪ No integration of interactions and dependencies between mitigation measures ▪ Possibility of inconsistent baseline emissions ▪ No representation of intertemporal interactions ▪ Limited representation of uncertainty ▪ In some cases, limited to one economic sector without the possibility to accumulate abatement curves across sectors ▪ No representation of macroeconomic feedbacks ▪ Simplified technological cost structure

2.3 Model-derived MAC curves

Another widespread approach to MAC curves is to derive the cost and potential for emission mitigation from energy models. A number of models have been used in this way using a range of techniques. The most common way is to distinguish models into economy-orientated top-down models and engineering-orientated bottom-up models. In both cases, abatement curves are generated by summarising the CO₂ price resulting from runs with different strict emission limits or by summarising the emissions level resulting from different CO₂ prices. The focus on absolute emissions means that the graphical presentation of a model-derived MAC curve does generally not contain any technological detail.

Bottom-up energy models are partial equilibrium models representing only the energy sector in contrast to top-down models, which cover endogenous economic responses in the whole economy. Bottom-up models are either simulation models or optimisation models that calculate a partial equilibrium either through the minimisation of the system costs or by

maximising consumer and producer surplus. Compared to top-down models, bottom-up models contain more detail of energy technologies along the transition from primary to useful energy. Top-down models rely on substitution elasticities, predominantly estimated on the basis of historic rates and assumed to be valid in the future. Hourcade et al. (2006) and Böhringer et al. (2008) provide further detail on this subject.

The Emission Prediction and Policy Analysis (EPPA) model was the first top-down model to be used to derive a MAC curve (Ellerman and Decaux 1998). The EPPA model belongs to the class of Computable General Equilibrium (CGE) models that map the flows of products, services and money in the whole economy. In CGE models, which are the most common type of top-down models, a general equilibrium structure is combined with economic data to numerically calculate demand, supply and the resulting price.

In comparison to top-down models, bottom-up models are not as frequently used for the calculation of MAC curves. An example of a bottom-up model, used to derive MAC curves, is the Targets IMage Energy Regional (TIMER) model (van Vuuren et al. 2004). It is an energy system model that focuses on several dynamic relationships within the energy system, such as inertia, endogenous ‘learning-by-doing’, fossil fuel depletion and trade among the different regions.

In the past, top-down models were usually accused of overestimating marginal abatement costs. This is explained with the fact that top-down models rely on substitution elasticities between input factors, which are estimated on historic data and therefore project a limited transformation potential of the economy into the future. Conversely, bottom-up models were accused of underestimating marginal abatement costs owing to the failure to include micro- and macroeconomic feedback effects (Hourcade et al. 2006). Comparison studies (Fischer and Morgenstern 2006; Kuik et al. 2009) could not, however, verify these general differences in reference to abatement cost between bottom-up and top-down models. Assumptions on other key input drivers, such as baseline emission levels, are usually more important than the model structure.

The generation of MAC curves with both model types has certain advantages. The most important advantage of top-down models is that they are able to explicitly take into account macroeconomic feedbacks and the effect of climate change mitigation policies on income and trade. Thus, the system boundaries are extended beyond the energy sector, as the calculation of technology-rich bottom-up models is usually constrained to the energy system and can therefore not consider macro-economic feedbacks.

Both top-down and bottom-up models consistently, possibly not always accurately, take into account interactions between mitigation measures. Models are not susceptible to the same inconsistencies as expert-based approaches since they follow a systems approach. Intertemporal interactions and consistent baseline emission pathways can be represented within the scope of a model. In general, models are far more capable of representing uncertainty. This has been demonstrated in comparison studies via structured sensitivity analyses, where the focus has been mainly on inter-model comparison (Edenhofer et al. 2006; Weyant et al. 2006). This can be extended by using probabilistic or stochastic techniques. There is also no difficulty in accumulating sectoral abatement curves, in contrast to some expert-based approaches. This is due to the fact that the models maximise welfare from a societal perspective. Thus, model-derived curves address many of the shortcomings of the expert-based approach.

A major disadvantage of a MAC curve based on top-down models is the lack of technological detail. Most model-derived MAC curves do not permit insights into which technologies or

measures are responsible for emission abatement. Top-down models cannot explicitly illustrate the technologies used for emission reduction due to their aggregated character. Although there have been some improvements, top-down models generally do not possess sufficient technological detail. Top-down models also do not reflect the different substitution possibilities in the energy system, their different costs, and technical characteristics in the same way as bottom-up models.

As bottom-up models do not rely on substitution elasticity in contrast to most top-down models, a bottom-up model user has to limit the phenomenon of ‘penny-switching’, where small changes in costs can lead to large shifts in the energy system. Nevertheless, bottom-up models have the significant advantage of technological detail. In theory, this detail permits the tracking of emission reductions to the technologies or even technology chains that are responsible for this change, e.g. efficiency gains or technology switches. Few attempts have been made in the past to break down the curve into different measures, since it requires further complex analysis. Behavioural aspects are included in the bottom-up approach to the extent that technology-specific risks and a price elastic demand function can be integrated. In the same way, uncertainty concerning technology costs, availability, efficiency or start date and the influence on cost curves can be illustrated with bottom-up models.

A last point concerns the insufficient representation of cost-independent market distortions in energy models. Since both energy model types assume rational agents with cost-effective behaviour, such distortions cannot be represented in optimisation models. The result is that these models do not show negative abatement costs. Nevertheless, in bottom-up models there are opportunities to incorporate higher hurdle rates and upper limits for the use of mitigation technologies to represent problems connected to high upfront investment costs and other distortions with regard to no-regret measures. Furthermore, once the energy model is developed and calibrated, MAC curves can be derived very quickly in comparison to expert-based curves. Table 3 summarises the advantages and disadvantages of model-derived cost curves.

Table 3: Strengths and weaknesses of model-derived MAC curves

STRENGTHS	WEAKNESSES
<p>Bottom-up</p> <ul style="list-style-type: none"> ▪ Model explicitly maps energy technologies in detail 	<p>Bottom-up</p> <ul style="list-style-type: none"> ▪ No macroeconomic feedbacks ▪ Direct cost in the energy sector ▪ Risk of penny-switching ▪ No reflection of indirect rebound effect
<p>Top-down</p> <ul style="list-style-type: none"> ▪ Macroeconomic feedbacks and costs considered 	<p>Top-down</p> <ul style="list-style-type: none"> ▪ Model lacks technological detail ▪ Possible unrealistic physical implications
<p>Both</p> <ul style="list-style-type: none"> ▪ Interactions between measures included ▪ Consistent baseline emission pathway ▪ Intertemporal interactions incorporated ▪ Possibility to represent uncertainty ▪ Incorporation of behavioural factors ▪ Comparably quick generation 	<p>Both</p> <ul style="list-style-type: none"> ▪ No technological detail in representation of MAC curve ▪ Assumption of a rational agent, disregarding most market distortions

3 Climate policy assessment via MAC curves

Having examined the different existing approaches towards the generation of MAC curves, this section discusses their usefulness regarding the assessment of various climate policies. For this purpose policy instruments are divided into incentive-based and non-incentive-based instruments in this section, while this is only one possibility to categorise climate policy instruments.

3.1 Incentive-based instruments

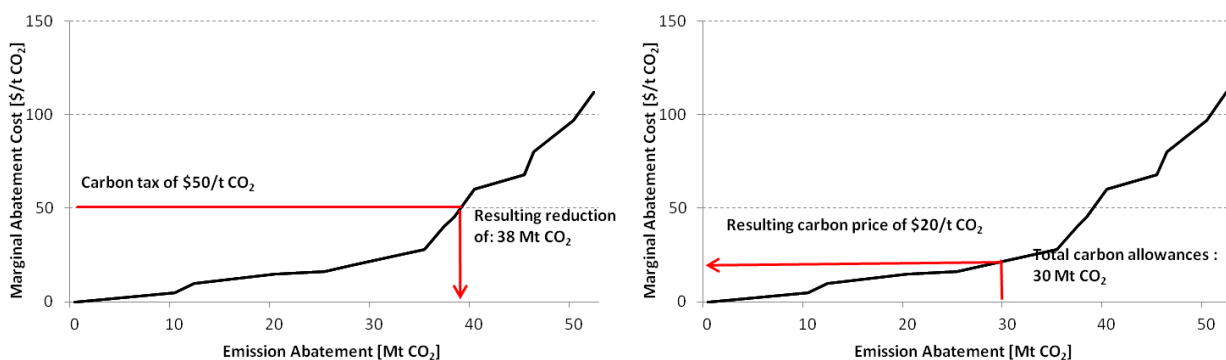
These instruments are called incentive-based because they create a price for the emission of CO₂ and thereby incentivise emitters to reduce their environmental impact. Incentive-based instruments can again be subdivided into price-based and quantity-based instruments. In this context, MAC curves can give valuable insights to policy makers concerning both the introduction of a CO₂ tax (price-based) and the introduction of a CO₂ permit system (quantity-based).

For this assessment, it is important to consider market distortions in the form of existing subsidies and taxes. This includes subsidies for fossil fuels and for low-carbon fuels or technologies, but also existing taxes, e.g. on transport fuels.

For the assessment of incentive-based instruments, which in general covers more than one sector, model-derived cost curves should be preferred over expert-based since they are able to consistently consider system-wide interactions and behavioural aspects. Since the expert-based approach individually evaluates each option, it is not well suited to assess the most cost-efficient mix of abatement measures. Top-down models have the comparative advantage over bottom-up models to consider the whole economy and thus being able to assess the impact of policies on employment, competitiveness and economic structure.

A MAC curve shows in a simple manner the reduction amount that can be expected with the introduction of a CO₂ tax at different levels. This is based on the logic that all abatement measures with costs up to the CO₂ tax will be realised. Conversely, it shows the resulting CO₂ permit price associated with the introduction of a cap-and-trade system, where total emissions are limited (see Figure 2). CO₂ taxes were introduced in the 1990s in the Scandinavian countries, while the EU's Emission Trading Scheme is a typical example for CO₂ permits.

Figure 2: Illustration of a carbon tax (left) and a permit allowance (right)



Both instruments are, in general, preferred over non-incentive-based instruments since they let the market decide how to reduce CO₂ emissions and do not specify a solution.

Additionally, in most cases they imply a lower overall cost to achieve the same reduction target when compared to regulatory instruments. In a case without any uncertainty, quantity-based and price-based instruments will be equally efficient, however, neither marginal abatement costs nor the benefits of carbon abatement are precisely known for the coming years. In this regard, MAC curves can help by quantifying the uncertainties linked to marginal abatement costs via sensitivity analysis and thus present a range of possible outcomes. This allows conclusions to be drawn on the possible efficiency of policy instruments.

3.2 Non-incentive-based instruments

Next to the category of incentive-based instruments there exists a range of instruments that are non-incentive-based. Researchers generally judge them to be less cost-efficient and flexible than market-based instruments, i.e. they do not let the market find the ‘best way’ (Hahn and Stavins 1992; Stern 2007, p. 381). Nevertheless, they can be necessary in areas where market-based instruments are ineffective in the presence of failures and barriers in many relevant markets. An advantage of non-incentive based instruments is that they provide more stability and remove uncertainty implied in cap-and-trade systems. Furthermore, regulations offer the possibility to differentiate between technologies and sectors, even though this can lead to distortive advantages for certain industries.

3.2.1 Research, development and deployment policies

Research, development and deployment policies are primarily aimed to foster innovation and bring down the costs of technologies with currently high marginal abatement costs. On the one hand, research policies focus on funding university research and the development of new technologies. Furthermore, funding of demonstration projects, e.g. for carbon capture and storage plants, falls also in this category of policy instruments. On the other hand, deployment policies target existing market technologies in order to facilitate market entry. Deployment policies can be equally divided into price-based and quantity-based incentives. Price-based incentives take the form of fiscal incentives, e.g. reduced taxes on biofuels or feed-in tariffs, which represent a fixed price support. Tenders for electricity (e.g. in France) from renewables or a Renewable Portfolio Standard (RPS) for renewable electricity (e.g. in the UK) are representatives of quantity-based schemes.

Technologically detailed expert-based MAC curves can help in this context by providing insights into the marginal abatement cost of technologies and give an indication about the necessary level of fiscal incentives or feed-in tariffs in order to allow a large-scale deployment. A MAC curve can set out minimum level tax rebates or feed-in tariffs for low-carbon technologies. At the same time, expert-based curves can generate insights into the abatement potential of technologies and relative cost-efficiency of several abatement measures. Nevertheless, this information comes at the expense of not taking into account barriers within the system that can limit policy adoption.

3.2.2 Command-and-control policies

The last category of instruments to reduce CO₂ emissions are command-and-control policies. These instruments do not give the market a choice, but impose regulation on specific technologies or sectors. In theory, they are less efficient than market mechanisms but can be necessary where irremovable or unavoidable market imperfections exist. Market imperfections in the context of CO₂ emission reduction can be, amongst other things, a lack of information, split incentives or hidden costs.

To confront these problems, regulations can restrict or ban the use of inefficient technologies. Standards enforce the uptake and availability of better performing alternatives or remove existing ones. They play a significant role in the building sector because of existing market distortions, such as split incentives between the occupier and the tenant of a building. Building codes therefore accelerate the uptake of energy efficiency measures in the residential and commercial sector. Standards are not only applied in buildings but also play an important role for appliances and particularly in the transport sector in the form of fuel standards. Another type of command-and-control instrument are voluntary industry agreements, e.g. information campaigns, and mandatory labelling (e.g. for refrigerator), certification or metering. An example of such voluntary industry action is the European voluntary colour-coded car CO₂ labelling (SMMT 2009). Finally, technology specific loans, subsidies and tax rebates e.g. for the implementation of insulation in buildings are an alternative command-and-control instrument.

Command-and-control instruments play an important role concerning the reduction of CO₂ emission where market-based instruments fail. Well-known examples include no-regret measures in the residential sector. Those measures could be profitable and simultaneously reduce carbon emissions. However, they are not taken up because of existing market distortions. Expert-based MAC curves give policy makers guidance on the maximum abatement potential and financial benefits of no-regret measures once market distortions have been overcome, e.g. in the context of standards for residential appliances or building codes. The same is true for vehicle efficiency standards and standards for residential electronics and appliances. MAC curves can also facilitate the setting of necessary subsidy levels, e.g. for biofuels.

3.3 Summary

The previous paragraphs have described which policy instrument is most suited to which type of MAC curve. Typical examples for policy instruments where MAC curves can provide insights are:

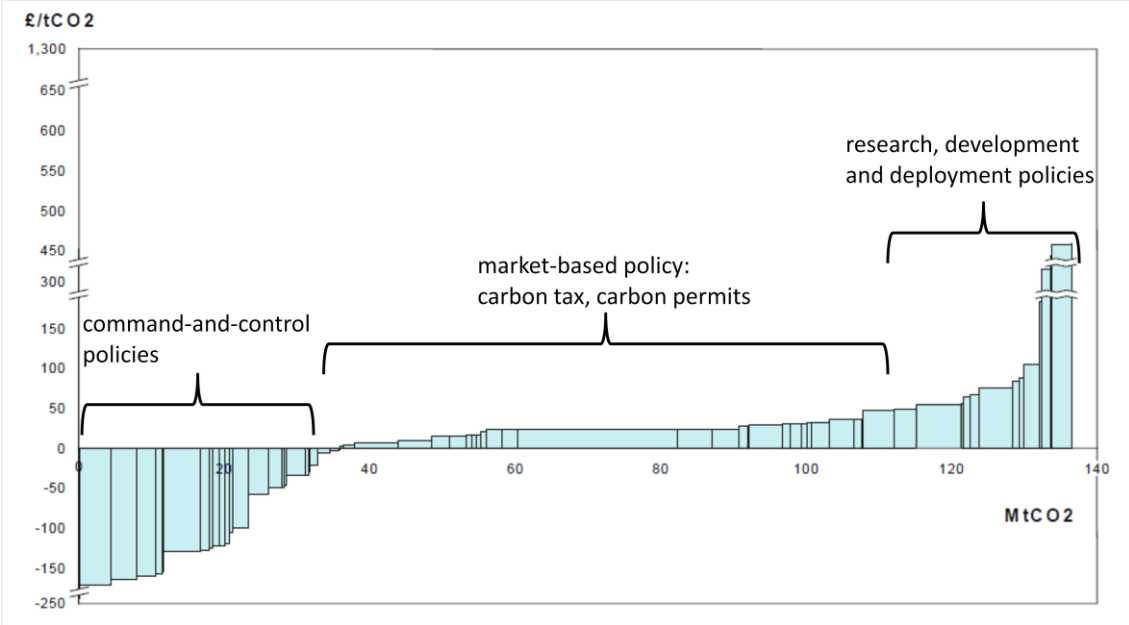
- Expert-based MAC curves:
 - Assessment of a subsidy level for biofuels
 - Emission reduction potential of building codes
 - Level and scope of feed-in tariffs
- Model-derived MAC curves:
 - Implementation of a CO₂ tax
 - Implementation of a cap-and-trade system

Figure 3 demonstrates the usefulness of MAC curves for the formation of climate policies. The left part of the graph generates important insights into possible abatement potentials once market barriers are overcome, in particular in the end-use sectors, such as industry, buildings and transport. The right part indicates necessary information for the installation of deployment policies and research policies with the goal to foster innovation. The middle part of the abatement cost curve is most interesting for the implementation of market-based policies and the resulting level of abatement or carbon price.

The three categories of policy instruments are not necessarily restricted to their section of the graph but can overlap and indeed this graph is not designed to imply that command-and-control instruments are always more cost-efficient than market-based policies. In theory, regulation can be cost-inefficient and therefore be shifted towards the right part of the graph.

In this regard sectoral abatement cost curves can generate more specific insights if policies are restricted to certain sectors of the economy.

Figure 3: MAC curves and climate policy instruments



Finally, there exist factors that limit the use of MAC curves as decision making aids. While MAC curves can integrate existing taxes and subsidies to a limited extent (e.g. expert-based curves from a private perspective), most of the present work on climate policy instruments does not take into account existing taxes or subsidies. Therefore, the efficiency advantage of market-based policies over command-and-control policies can be eliminated by pre-existing taxes or subsidies (Goulder et al. 1999). German subsidies for domestic coal production, for example, amounted to almost €2.5 (\$3.4) billion in 2008, corresponding to a CO₂ subsidy of €47 (\$64) per ton CO₂.

In addition, it is difficult to transform insights from MAC curves straight into policy making. This is due to overlapping climate policies, implementation costs linked to the introduction of policy instruments and some policies being restricted to specific economic sectors. The success of policy implementation is dependent on cost uncertainty in the relevant technologies resulting in different required payback periods and discount rates.

4 MAC curve use in the United Kingdom

In 2005, a report for the UK Department for the Environment, Food and Rural Affairs (Watkiss et al. 2005, p.10) did not find any other government, apart from the Netherlands, using MAC curves for policy and decision making. However, since then many countries have begun to assess their climate policies via MAC curves. The European Union (EU) has relied on MAC curve studies for the cost assessment of emissions reductions concerning different sectors and gases (see e.g. Blok et al. 2001). Similarly, the US EPA (2006) and the US Climate Change Science Program (Clarke et al. 2007) have commissioned reports using MAC curves as an illustrative tool. Moreover, MAC curves have influenced actions of supra-national bodies, such as the World Bank and the International Maritime Organisation (Buhaug et al. 2009), as well as governments in many countries around the world including, Ireland (Kennedy 2010), Mexico (Johnson et al. 2009) and Poland (Poswiata and Bogdan 2009).

UK governments have used MAC curves to evaluate climate policy (HM Government 2009). Therefore, this section sheds light on existing climate policy instruments in the UK and what type of abatement curves have contributed to decision making. The implicit carbon price of existing climate policies is also presented in order to demonstrate how much marginal abatement costs vary for different policy instruments. In previous years, UK governments have introduced various climate related policies; five instruments are summarised in Table 4 (for the calculation see Appendix).

Table 4: Policy Instruments and their corresponding CO₂ price in 2010

Policy Instrument	Energy Source	Implicit price in \$/t CO₂*
EU ETS	-	21
Climate Change Levy	Electricity	13
	Natural Gas	14
	LPG	6
	Coal	8
Feed-in Tariff	Biomass	148 - 220
	Hydro	20 - 461
	PV	730 – 1073
	Wind	20 - 878
Renewables Obligation	-	106
Hydrocarbon Oil Duty	Petrol	381
	Diesel	333
	Heavy Oil	277

*Prices apply to different sectors. Exchange rate of \$=£0.64

Since 2005, the UK has participated in an EU-wide CO₂ permit trading scheme, the EU-ETS, which covers the electricity sector and industry. In 2001 the UK introduced sector-specific carbon tax with the Climate Change Levy, which covers the use of fossil fuels in industry, commerce and agriculture. A similar tax, initially not targeted at CO₂ reduction, is the Hydrocarbon Oil Duty, which taxes the use of refined oil products. Deployment policies have been implemented for electricity generating technologies, including a renewable quota system, the Renewables Obligation, in 2002 and a feed-in tariff in 2010.

Comparing the CO₂ prices, which are implied in different government policies, reveals that the implicit CO₂ price for deployment policies is relatively high since they have the goal to drive down the cost of renewable energy sources. The feed-in tariff is highest for photovoltaic with up to \$1073, which is 10 times higher than the CO₂ price of the Renewables Obligation and 51 times as much as the EU ETS certificate price. The implicit price of the Renewables Obligation is however not directly comparable to the feed-in tariff as the obligation covers in general larger installations of UK electricity supply in 2010.

A comparison of the Hydrocarbon Oil Duty and the Climate Change Levy, reveals that the tax on hydrocarbons, primarily used in the transport sector, is almost two orders of magnitude higher than the tax of the Climate Change Levy, which confirms that this carbon tax only presents a small incentive for energy consumers to reduce fossil fuel based energy consumption in comparison to other already existing taxes. In addition, it can also reflect different levels of abatement costs in different energy sectors.

In the UK, MAC curves have recently played an important role in shaping the Government's domestic as well as international general climate change policy. On a domestic level, the Committee on Climate Change (CCC), an independent body set up to advise the UK Government on reducing greenhouse gas emissions, established expert-based MAC curves for several sectors (Hogg et al. 2008; Weiner 2009). These MAC curves are mostly based on expert information, while some aggregate the information in sectoral models for the calculation of an abatement curve. This reliance on sectoral expert-based MAC curves is critical since these present the technical abatement potential without taking into account behavioural aspects and market distortions or considering intersectoral interactions. Consequently, the abatement potential will be somewhat lower in reality. It is therefore questionable whether expert-based MAC curves, which cannot take into account intertemporal aspects, should be used for long-term policy assessment.

The UK Government itself used abatement curves as a guide to the potential and future costs of technical measures for the Energy White Paper (HM Government. Department of Trade and Industry 2007, p. 286) and the UK Low Carbon Transition Plan (HM Government 2009, p. 40ff). DECC (2009a) used a global expert-based MAC curve to compare projections of global carbon prices and, in addition, different expert-based MAC curves were used in order to assess the CO₂ price in the 'non-traded' sectors for a reduction target. This was performed despite the fact that expert-based curves cannot adequately capture system-wide interdependencies and interactions.

For carbon reduction in an international context, the results of the Global Carbon Finance model (GLOCAF) (Carmel 2008; Gallo et al. 2009) inform the decisions of the Department of Energy and Climate Change in international negotiations for a post-Kyoto protocol. This model uses a business-as-usual emission scenario as well as MAC curves for different regions and sectors as inputs. With these assumptions, the model can be used to estimate costs and international financial flows that arise from international emission reduction commitments. Limits of this model include, however, the use of regional, static MAC curves from other models as an input, which assumes that MAC curves are not influenced by regionally different abatement actions.

5 Conclusion and further research

MAC curves are widely used as a decision-making aid in climate policy. The paper characterised the strengths and weaknesses of different MAC curve methods and showed that different types of MAC curves can be helpful for the implementation of new policies or the evaluation of existing ones, such as technology subsidies, technical standards, carbon taxation or emissions trading systems. On the one hand, expert-based curves are suitable for the assessment of non-incentive based policy instruments because of their technology-specific representation. Nevertheless, those curves are unsuitable for the assessment of market-based policies as they show the maximum abatement potential. Thus, they are not able to capture the full amount of market distortions and several types of interactions that limit the CO₂ abatement potential. On the other hand, the system approach of model-derived curves provides useful insights for the implementation of a CO₂ tax or an emissions trading system. The lack of technological detail, however, limits the use of model-based MAC curves for policy makers to incentive-based instruments, so that they are unsuitable for technology-specific policies such as subsidies or minimum standards.

Yet, both expert-based and model-derived MAC curves possess important disadvantages that limit their usefulness to policy makers. No MAC curve is at present capable of combining a technologically detailed representation based on consistent assumptions with a system-wide approach in order to include intertemporal, technological, economic and behavioural interactions and present an accurate framework for the incorporation of uncertainty. This opens up an avenue for further research.

In order to combine the strengths of both approaches, a viable alternative can be to use a bottom-up model, which has the necessary technological detail, to generate a consistent MAC curve. Index decomposition analysis can be used to analyse the results of the energy system model and to attribute emission reduction amounts to changes in the energy system. In this way, it is possible to illustrate what measures are responsible for the emission reduction, while maintaining a consistent framework, which is able to consider system-wide interactions. This can again significantly enhance the usefulness of MAC curves for policymakers as it overcomes several of the shortcomings in existing approaches and is still easy to understand. While methodology-specific weaknesses can be overcome, MAC curves do not consider ancillary benefits and remain a static concept that does not illustrate dynamic aspects.

Appendix

This appendix explains the calculations underlying the data presented in Table 1.

Information on the level of the feed-in tariff according to the different technologies is taken from DECC (2010) and on the buy-out price under the Renewables Obligation from OFGEM (2010). Current rates for the Climate Change Levy and the Hydrocarbon Oil Duty are taken from HM Revenue & Customs (2009b; 2009a).

The calculation of the CO₂ price for carbon-free technologies in regard to the Feed-in tariff and the Renewables Obligation are based on an average wholesale electricity price of £38 per MWh (RWE AG 2009, p. 9) and an electricity emission factor of 0.546 kg CO₂/kWh (DEFRA 2009). The conversion factors used for the CO₂ price calculations can be found in Table 5.

Table 5: Conversion factors (DECC 2009b)

Emission Intensity	kg CO ₂ /l	kg CO ₂ /t	kg CO ₂ /kWh
Petrol	2.3		
Diesel	2.6		
Heavy oil	3.2		
Natural Gas			0.184
LPG		2534	
Coal		2506	

References

- Addams, L., G. Boccaletti, M. Kerlin and M. Stuchtey (2009). Charting Our Water Future - Economic frameworks to inform decision-making. New York, McKinsey & Company.
- Beaumont, N. J. and R. Tinch (2004). "Abatement cost curves: a viable management tool for enabling the achievement of win-win waste reduction strategies?" Journal of Environmental Management **71**(3): 207-215.
- Blok, K., D. de Jager, C. Hendriks, N. Kouvaritakis and L. Mantzos (2001). Economic Evaluation of Sectoral Emission Reduction Objectives for Climate Change - Comparison of 'Top-down' and 'Bottom-up' Analysis of Emission Reduction Opportunities for CO₂ in European Union. Brussels, Ecofys Energy and Environment, National Technical University of Athens.
- Böhringer, C. and T. F. Rutherford (2008). "Combining bottom-up and top-down." Energy Economics **30**(2): 574-596.
- Buhaug, O., J. J. Corbett, V. Eyring, O. Endrese, J. Faber, S. Hanayama, D. Lee, D. Lee, H. Lindstad, A. Markowska, A. Mjelde, D. Nelissen, J. Nilsen, C. Palsson, W. Wanquing, J. J. Winebrake and K. Yoshida (2009). Second IMO GHG study 2009. London, International Maritime Organisation.
- Carmel, A. (2008). Paying for mitigation - The GLOCAF model. United Nations Framework Convention on Climate Change COP 13. Bali, Indonesia.
- Clarke, L., J. Edmonds, H. D. Jacoby, H. Pitcher, J. M. Reilly and R. Richels (2007). Scenarios of Greenhouse Gas Emissions and Atmospheric Concentrations. Sub-report 2.1A of Synthesis and Assessment Product 2.1 by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research. Washington, DC., Department of Energy / Office of Biological & Environmental Research.
- Commission of the European Communities (2008). 20 20 by 2020 - Europe's climate change opportunity. Brussels.
- DECC (2009a). Carbon Valuation in UK Policy Appraisal: A Revised Approach. London, Department of Energy and Climate Change.
- DECC (2009b). Digest of United Kingdom Energy Statistics 2009. London, Department of Energy and Climate Change.
- DECC (2010). Feed-in Tariffs - Government's Response to the Summer 2009 Consultation. London, Department of Energy and Climate Change.
- DEFRA (2009). BNXS01: Carbon Dioxide Emission Factors for UK Energy Use. London, Department for the Environment Food and Rural Affairs.
- Edenhofer, O., K. Lessmann, C. Kemfert, M. Grubb and J. Köhler (2006). "Induced Technological Change: Exploring its Implications for the Economics of Atmospheric Stabilization: Synthesis Report from the Innovation Modeling Comparison Project." Energy Journal **27**(Special Issue: Endogenous Technological Change and the Economics of Atmospheric Stabilization): 57-107.
- Ellerman, A. D. and A. Decaux (1998). Analysis of Post-Kyoto CO₂ 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.
- Fisher, B., N. Nakicenovic, K. Alfsen, J. C. Morlot, F. d. I. Chesnaye, J.-C. Hourcade, K. Jiang, M. Kainuma, E. L. Rovere, A. Matysek, A. Rana, K. Riahi, R. Richels, S. Rose,

- D. V. Vuuren and R. Warren (2007). Issues related to mitigation in the long-term context. Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Inter-governmental Panel on Climate Change. B. Metz, O. R. Davidson, P. R. Bosch, R. Dave and L. A. Meyer. Cambridge, Cambridge University Press: 169-250.
- Gallo, F., A. Carmel, S. Prichard, J. Rayson, N. Martin, R. Dixon and A. MacDowall (2009). Global Carbon Finance - A quantitative modelling framework to explore scenarios of the Global Deal on Climate Change. London, Office of Climate Change.
- Goulder, L. H., I. W. H. Parry, R. C. Williams and D. Burtraw (1999). "The cost-effectiveness of alternative instruments for environmental protection in a second-best setting." Journal of Public Economics **72**(3): 329-360.
- Hahn, R. W. and R. N. Stavins (1992). "Economic Incentives for Environmental Protection: Integrating Theory and Practice." The American Economic Review **82**(2): 464-468.
- HM Government (2009). Analytical Annex - The UK Low Carbon Transition Plan. London.
- HM Government. Department of Trade and Industry (2007). Meeting the energy challenge : a white paper on energy. London, Stationery Office.
- HM Revenue & Customs (2009a). Climate Change Levy (CCL) - rates to rise at 1 April 2009. London.
- HM Revenue & Customs (2009b). Hydrocarbon Oils: Duty Rates. London.
- HM Treasury (2003). The Green Book - Appraisal and Evaluation in Central Government. London.
- Hogg, D., A. Baddeley, A. Ballinger and T. Elliot (2008). Development of Marginal Abatement Cost Curves for the Waste Sector. Committee on Climate Change. Bristol, eunomia research & consulting.
- Hourcade, J.-C., M. Jaccard, C. Bataille and F. Gherzi (2006). "Hybrid Modeling: New Answers to Old Challenges - Introduction to the Special Issue of The Energy Journal." Energy Journal **27**: 1-11.
- Jackson, T. (1991). "Least-cost greenhouse planning supply curves for global warming abatement." Energy Policy **19**(1): 35-46.
- Johnson, T. M., C. Alatorre, Z. Romo and F. Liu (2009). Low-Carbon Development for Mexico. Washington D.C., World Bank.
- Kennedy, M. (2010). Ireland's Future: A Low Carbon Economy? The Impact of Green Stimulus Investment. IAEE European Conference. Vilnius, Lithuania.
- Klaassen, G., C. Berglund and F. Wagner (2005). The GAINS Model for Greenhouse Gases - Version 1.0: Carbon Dioxide (CO₂). IIASA Interim Report. Laxenburg, International Institute for Applied Systems Analysis.
- 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.
- McKinsey & Company. (2010). "Climate Change Special Initiative - Greenhouse gas abatement cost curves." Retrieved August 19th 2010, from <http://209.172.180.101/client-service/ccsi/costcurves.asp>.
- Meier, A. K. (1982). Supply Curves of Conserved Energy. Lawrence Berkeley Laboratory. Berkeley, University of California. **PhD**: 110.
- OFGEM (2010). The Renewables Obligation Buy-out Price and Mutualisation Ceiling 2010-11. London, Office of Gas and Electricity Markets.
- Poswiata, J. and W. Bogdan (2009). Assessment of Greenhouse Gas Emissions Abatement Potential in Poland by 2030. Warsaw, McKinsey & Company.
- Pye, S., K. Fletcher, A. Gardiner, T. Angelini, J. Greenleaf, T. Wiley and H. Haydock (2008). Review and update of UK abatement costs curves for the industrial, domestic and non-domestic sectors. Didcot, AEA Energy & Environment.

- Rentz, O., H. D. Haasis, A. Jattke, P. Ru, M. Wietschel and M. Amann (1994). "Influence of energy-supply structure on emission-reduction costs." Energy **19**(6): 641-651.
- RWE AG (2009). Report on the First Three Quarters of 2009. Essen.
- Silverman, B. G. (1985). "Heuristics in an Air Pollution Control Cost Model: The "Aircost" Model of the Electric Utility Industry." Management Science **31**(8): 1030-1052.
- SMMT (2009). The Society of Motor Manufacturers and Traders New car CO₂ report 2009. London.
- Stern, N. H. (2007). The economics of climate change : the Stern review. Cambridge, UK, Cambridge University Press.
- The Parliament of the United Kingdom of Great Britain and Northern Ireland (2008). Climate Change Act 2008. London.
- United Nations (1998). Kyoto Protocol to the United Nations Framework Convention on Climate Change. United Nations. New York.
- US EPA (2006). Global Mitigation of Non-CO₂ Greenhouse Gases. Washington, DC, United States Environmental Protection Agency.
- 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.
- Watkiss, P., D. Anthoff, T. E. Downing, C. Hepburn, C. Hope, A. Hunt and R. S. J. Tol (2005). The Social Costs of Carbon (SCC) Review - Methodological Approaches for Using SCC Estimates in Policy Assessment. London, AEA Technology Environment.
- Weiner, M. (2009). Energy Use in Buildings and Industry: Technical Appendix. London, Committee on Climate Change.
- Weyant, J. P., F. C. de la Chesnaye and G. J. Blanford (2006). "Overview of EMF-21: Multigas Mitigation and Climate Policy." Energy Journal **27**(Multi-Greenhouse Gas Mitigation): 1-32.
- Zhang, Z. and H. Folmer (1998). "Economic modelling approaches to cost estimates for the control of carbon dioxide emissions." Energy Economics **20**(1): 101-120.