UCL ENERGY INSTITUTE

Marginal Abatement Cost Curves:

A call for caution

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This report reflects the authors' research, opinions and conclusions, and not those of the UCL Energy Institute, which does not take positions on detailed issues such as those discussed here.

Executive Summary

This report critically reviews various issues relating to the construction and interpretation of marginal abatement cost curves (MACC, or MAC curves) for reducing emissions of greenhouse gases, the most well-known and widely used of which have been compiled by McKinsey and Company. It also reveals various weaknesses related to the cost curves and points out their limited usefulness. The creators of the McKinsey MAC curves have been careful to include some suitable caveats with the presentation of their results. However, the apparent simplicity and straightforwardness of the graphic MAC curve, with its summary and presentation of a great deal of complex numeric data in an easily-digestible form, often lead to these caveats being over-looked, so that excessive confidence is placed in the curves and the ranking of carbon abatement measures that they suggest.

There are many methodological problems at the heart of the MAC curve, many of which are acknowledged by the authors from McKinsey's. These problems can be divided into those that are general shortcomings of MAC curves and those that are specific to McKinsey's approach.

The general shortcomings include the focus on greenhouse gas abatement without considering ancillary benefits, such as the health improvements that result from reducing air pollution, and the static representation of costs for a single year, which fails to consider path dependency. In general, the MAC curve is unable to capture wider social implications related to climate change mitigation.

On the other hand, McKinsey-specific weaknesses include the lack of full disclosure of the set of assumptions behind the calculations, and the non-consideration of various types of interdependencies and intersectoral, intertemporal, behavioural, macroeconomic, and international interactions, which can also lead to problems defining an emissions baseline: though the curve itself cannot display those interactions, it is a methodological choice as to whether or not those interactions are included when calculating the costs and abatement potentials displayed in the curve. Abatement measures interact, creating synergies and conflicts that mean that the cumulative outcome of two measures may be more than the sum of its parts, or less. Technology cost, the direct average financial cost of implementing a technology, as used by McKinsey in its cost curve study, is one important element of total cost, but does not capture implementation barriers and wider cost definitions that can be considered when using a systems approach. Further inadequacies concern the limited representation of uncertainty and a simplified technological structure.

Measures to reduce greenhouse gas emissions from deforestation and forest degradation (REDD) exhibit many of the above-mentioned problems, but have problems of their own that are very different to those of the energy sector. There are hidden costs, for example in building institutional capacity to prevent deforestation, transaction costs and monitoring costs. Land ownership is not always clearly defined in the tropical forests, and leakage is a very serious problem connected to reducing deforestation. A MAC curve does not capture a range of benefits to indigenous communities and to biodiversity that go far beyond carbon abatement. Finally, there are interactions with the wood market and with other abatement measures, including potential conflicts with bio-energy.

Caveats on the use of MAC curves

The following recommendations on the use of MAC curves by policy makers and others are intended to enable them to realise their potential in decision support:

Embrace complexity: there are complex political and economic decisions to be made. The usefulness of simple summary presentations of complex issues is limited. Hard decisions about complex systems require a more sophisticated, whole-system analysis and approach; there are complex trade-offs that cannot be summarised into a simple list of monetised values.

Pay attention to the assumptions behind a MAC curve, alongside the MAC curve: keeping the assumptions and the MAC curve together can help ensure transparency, comprehensibility and accountability.

Always look beyond estimated technology cost: not all cost elements can be monetised; decisions about which abatement measures are prioritised must look beyond the costs presented in any MAC curve, to consider costs that may have escaped monetisation and wider issues. Basing decisions on estimated technology costs alone may not only fail to produce the promised carbon savings but also result in unintended or perverse consequences.

Accept uncertainty: answers presented as a single set of numbers are appealingly simple, but can conceal more than they reveal. Forecasts of future costs and technical potential are better presented as ranges, not point values. The cost differentials between several of the competing alternatives are less than the cost uncertainties within each alternative.

Understand path dependencies: Abatement costs depend on actions pre-dating the year of the MAC curve; abatement strategies are better presented and considered as scenarios or trajectories, in which decisions in one period influence the trajectory thereafter. Cumulative emissions are a more scientifically robust indicator of global warming commitment than abatement potentials in one or two horizon years.

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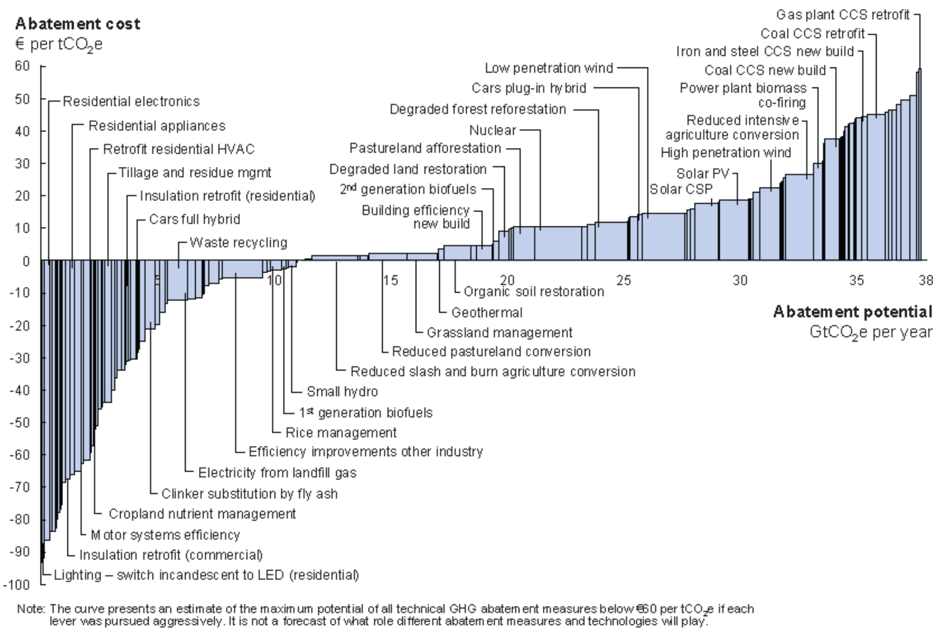
1 INTRODUCTION

Within the context of targets for reducing emissions of greenhouse gases, policy makers in many countries around the world are confronted with the challenge of finding affordable means of reducing carbon emissions. For this purpose, marginal abatement cost (MAC) curves have frequently been used to illustrate the economic and technological feasibility of climate change mitigation. A MAC curve is defined as a graph that indicates the marginal cost (the cost of the last unit) of emission abatement for varying amounts of emission reduction.

Recently, MAC curves have come increasingly into the focus of researchers and policy makers involved in climate change mitigation largely as a result of the work of McKinsey & Company. McKinsey published 14 cost curves for different countries and a global cost curve (see Fig. 1 between 2007 and 2009. McKinsey updated its global MAC curve in Enkvist et al. (2010) to reflect the current reduction in emissions due in part to the global financial crisis and to reflect expectations of higher fossil fuel prices. Recently, McKinsey created a Climate Desk, which makes the data, though not the assumptions, behind its reports available to academic research and corporate users.

FIG. 1: MCKINSEY'S GLOBAL COST CURVE FOR THE YEAR 2030



SOURCE: NAUCLÉR AND ENKVIST (2009)

The curves are directed at stakeholders that do normally not engage in the discussion about the technological and economic difficulties associated with climate change mitigation. According to the authors of the study, the curve should serve as *"a starting point for global discussion about how to* *reduce GHG emissions, showing the relative importance of different sectors, regions, and abatement measures, and providing a factual basis on the costs of reducing emissions"* (Nauclér and Enkvist 2009, p. 20).

The McKinsey MAC curves are based on the individual assessment of abatement measures, such that the cost and emission reduction potential of each measure are assessed in isolation, and subsequently the measures are ranked according to their cost from cheapest to most expensive. It is implied in this kind of representation that the imposition of a carbon tax will lead to all measures with cost below the carbon tax being realised.

Cost curves for the reduction of energy consumption or emissions pre-date McKinsey's MAC curves. The research concept of the MAC curve has been applied since the early 1980s. After the oil price crises of the 1970s, Meier (1982) developed the first cost curves for the reduction of electricity consumption [$/kWh]. These saving curves, also called conservation supply curves, became widely-used analytical tools for the assessment of energy-efficiency improvements in transport, industry and buildings (Difiglio and Duleep 1990; Rosenfeld et al. 1993; Blumstein and Stoft 1995). Furthermore, those curves were widely used for the assessment of abatement potential and costs of air pollutants such as SO_2 [$/kt] (Rentz et al. 1994). The earliest examples of carbon-focused curves, which used similar methods to the ones used by earlier cost curves for energy savings, date back to the early 1990s (Jackson 1991; Mills et al. 1991; Sitnicki et al. 1991).

In the UK, MAC curves have recently played an important role in shaping the government's climate change policy. This is emphasised by Government reports that use MAC curves, such as the UK Low Carbon Transition Plan (HM Government 2009), and a number of cost curve studies commissioned by the Committee on Climate Change (CCC), an independent body set up to advise the UK government on reducing greenhouse gas emissions. The UK Department for Energy and Climate Change (DECC) uses the Global Carbon Finance (GLOCAF) Model (Carmel 2008) to forecast financial flows based on MAC curves between various world regions (Committee on Climate Change 2008, Chapter 4). MAC curves have also been used in many other countries and regions, including Ireland (Kennedy 2010), Mexico (Johnson et al. 2009), Poland (Poswiata and Bogdan 2009), Nicaragua (Casillas and Kammen 2010) and California (Sweeney et al. 2008).

McKinsey's MAC curves are an easy to understand tool, intended to convey the cost and abatement potential associated with numerous GHG mitigation measures. Because MAC curves underpin much of the analysis of the costs and potentials related to climate change mitigation carried out by and for policy makers, it is important to ensure that the numbers on which they are based are robust. Whether this is so depends on two factors: the quality of the assumptions and the method employed to generate the cost curve.

This report reviews the assumptions and methodology of the study "Pathways to a Low-Carbon Economy" written by Tomas Nauclér and Per-Anders Enkvist at McKinsey & Company. The next section focuses on the assumptions used in this cost curve study, while section 3 discusses concerns surrounding negative abatement costs. Section 4 reflects upon time-related issues and section 5 highlights the static character of a cost curve and consequences resulting from this. Further methodological issues in relation to the cost curve are discussed in section 6; wider social implications are highlighted in section 7, while aspects surrounding reduced deforestation are addressed in section 8. Concluding remarks are given in section 9.

2 ASSUMPTIONS

Any analysis that seeks to compare the cost of reducing energy-related, industry-related and land use-related emissions, such as that carried out by McKinsey, necessarily relies on numerous input assumptions. As its MAC curves are formulated for the year 2030, i.e. 20 years into the future, and cover many technologies, some of which are still in development and all of which are subject to change, the assumptions are inevitably highly uncertain. Such assumptions typically embody a particular world view, and so although the MAC methodology itself is objective, it is based on a subset of assumptions drawn from a larger set of possible assumptions. Nauclér and Enkvist (2009, p.3) state in their preface that the purpose of their report is *"to provide an objective and uniform set of data"*. The extent to which these assumptions represent some form of objective truth is, in the absence of full disclosure of those assumptions, hard to ascertain.

To enable the curves to be understood and used with confidence, it is important that the assumptions underlying them are published, together with analysis showing the sensitivity of the results to changes in the input assumptions.

In the research community, complex but well-documented energy models and integrated assessment models have been combined to derive abatement cost curves. Examples for these models, which come with good documentation of the model structure and the underlying assumptions, are the EPPA model (Paltsev et al. 2005) used at MIT in the United States and the IMAGE model (van Vuuren et al. 2006) used at PBL in the Netherlands.

Nauclér and Enkvist (2009) do publish their assumptions on population growth, economic growth, discount rate and oil price. For most technologies, investment cost ranges are given for the year 2005, and sometimes but not always the technology-specific learning rate. Since it is not clear where technologies are on the learning curve, and as the investment cost is only given for the year 2005, no information about the technology cost in 2030 can be derived.

For some, but not for all technologies, operating costs are given, together with capacity factors for power technologies. No information is disclosed on efficiency levels, life time, nor cost steps for the same technology. For the transport sector, initial costs and expected cost reductions are given, but important information on the efficiency, life time and operating costs are not given. Only a few of these assumptions have a reference, while in most cases the source remains unclear.

In conclusion, the published assumptions are at best incomplete, while in general little information is available concerning the source of the assumptions. The scientific discussions as to the clear and present dangers of anthropogenic climate change have greatly benefited from being held openly with the peer-reviewed press, with assumptions and methodology presented to be reviewed. In the interest of an open and effective decarbonisation of the economy, the economic discussions should take place within a similar atmosphere of openness and transparency.

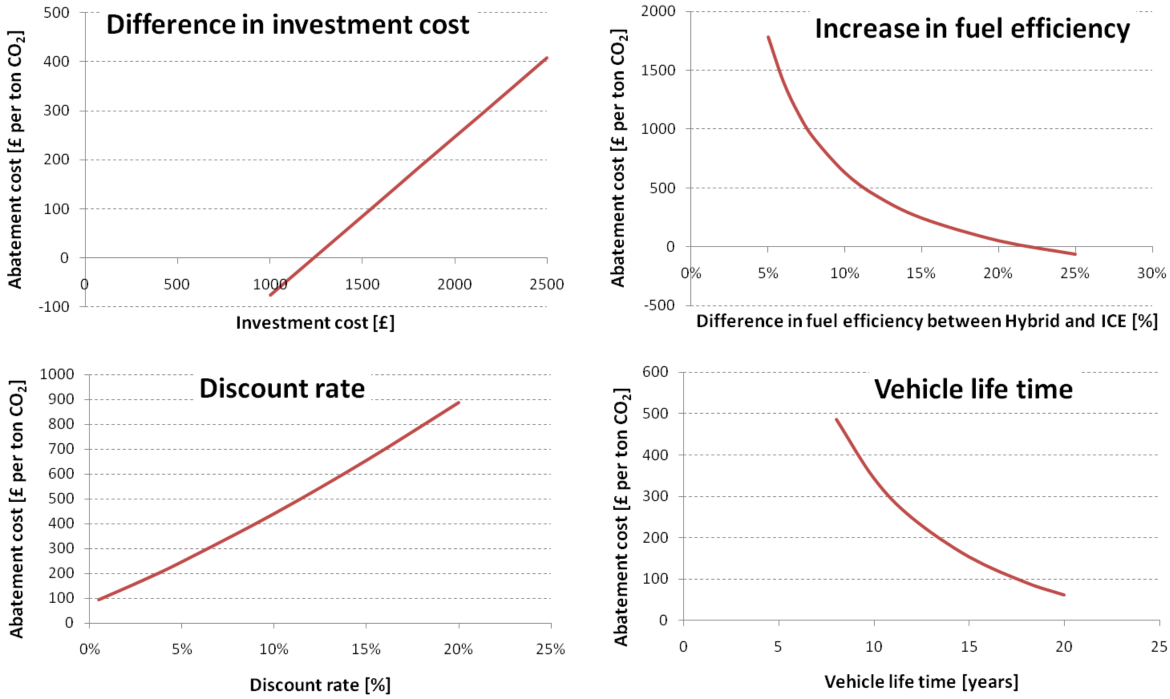
To illustrate the sensitivity of abatement cost to assumptions, we offer an example here of petrol hybrid cars, with internal combustion engine (ICE) cars as the reference technology. The cost consists of three components: initial investment cost, annual operating cost and fuel cost. Operating costs include maintenance, insurance and tax. The assumptions are presented in Table 1. The emission factor is based on data from DEFRA and DECC (2009).

TABLE 1: ASSUMPTIONS FOR HYBRID CAR EXAMPLE

Parameter	Unit	Petrol ICE	Petrol Hybrid
Discount rate	%	5	5
Lifetime	years	12	12
Investment cost	£	14000	16000
Operating cost	£/a	1193	1237
Annual kilometrage	km/a	14481	14481
Fuel consumption	l/100 km	7	5.95
Petrol price	£/l	1.2	1.2
Emission factor	kg CO_2/l	2.3	2.3

The price of a petrol hybrid car is more expensive than a petrol ICE car and the hybrid car has slightly higher operating cost, but is assumed to be 15% more fuel efficient than the ICE car. The higher the carbon price, the higher the fuel price and the more the consumer will benefit from the fuel-efficient hybrid engine. Based on the assumptions given in Table 1, a carbon price of £247/ t CO_2 is required to prefer a hybrid car over an ICE car. However, this result is very dependent on the assumptions. In order to illustrate the sensitivity to assumptions, the investment cost for the petrol hybrid car, the difference in fuel efficiency, the discount rate and the vehicle life time have each been varied (see Fig. 2), one parameter at a time, holding the others constant.

FIG. 2: SENSITIVITY OF ABATEMENT COST TO HYBRID CAR INVESTMENT COST, FUEL EFFICIENCY, DISCOUNT RATE AND LIFETIME



SOURCE: OWN CALCULATIONS

As Fig. 2 shows, the abatement cost is very sensitive to the assumptions, rising with the discount rate and difference in investment costs, and falling as the fuel efficiency and vehicle lifetime is increased. For example, for the specified investment cost range for the hybrid vehicle of £15,000 - £16,500 (a cost difference of £1,000 - £2,500), the abatement cost varies between £-75/t CO_2 and £408/t CO_2. Even bigger ranges for the abatement cost can be observed for changes in fuel efficiency and the discount rate. This small example emphasises the need for a transparent disclosure of assumptions.

3 NEGATIVE ABATEMENT COST

The McKinsey cost curve shows a significant amount of negative-cost abatement potential; that is to say, it has a negative carbon price: these measures already pay for themselves, even in the absence of any carbon price. 11 Gt CO_2e or 30% of the whole abatement potential below €60/t CO_2e could be abated where discounted savings exceed the project cost. An interpretation is that these measures have a net benefit when implemented without any CO_2 price. This phenomenon of negative abatement costs is not compatible with an efficient market, as is, for example, assumed in general equilibrium models (see Ackermann and Bueno 2011)How can negative costs be explained? Assuming the project costs are correctly estimated, the explanation may be one of insufficiently extensive cost definition, non-financial barriers to implementation, or inconsistent discount rates.

3.1 COST DEFINITION

Costs play a pivotal role in MAC curves. Cost definitions can vary widely and can be broadly distinguished into several different levels, from the narrowest to the widest, they are: project cost, technology cost, sector cost, and macroeconomic cost.

The narrowest abatement cost definition, project cost, describes the cost of an individual abatement option which is assumed to have no significant indirect economic impacts on markets and prices (Halsnæs et al. 2007, p.135). It considers for example technical change in production plants, efficiency improvements, fuel switches or the implementation of infrastructure. Cost measurement includes investment cost, operation and maintenance cost and fuel cost (Risø National Laboratory 1994, p. 11ff). Technology cost considers a specific technology with many applications in different projects and takes evidence on learning curves into account.

This rather narrow cost definition is the one used by McKinsey in its cost curve study. Nauclér and Enkvist write on page 147 that *"the abatement cost represents the pure 'project cost' to install and operate the low-emission technology."*, yet technology cost is more adequate since the average of many projects is represented and learning rates are considered. Indirect cost, such as the cost of foregone demand from consumers, economy-wide costs, costs for welfare implications and non-financial costs are excluded. Non-financial costs include the cost of clearing out a loft in order to be able to lag it; waiting in at home for workers to come round to work on the property; or the cost of searching for information. These additional costs are discussed in more detail in the next subsection. The other cost concepts include some of those costs. Sector cost includes all impacts of policies for the whole sector, and macroeconomic cost includes the impact across all sector and markets (Halsnæs et al. 2007, p.135).

Furthermore, no transaction and policy implementation costs are considered in the project cost used. In the literature, their burden is estimated to be inversely correlated with the size of the project: that is to say, transaction costs make up a higher proportion of total costs for smaller projects than for larger projects; and they vary significantly from project to project: see, for example, Mundaca and Neij (2006), who found that transaction costs may make up between 9% and 40% of total investment costs. In this context, the baseline technology against which the cost is compared is another important factor, which is discussed in section 5. In summary, it is important to note that the abatement cost definition in the McKinsey cost curve lacks important cost components and in many cases does not represent the actual real-world costs of implementation. Including such additional costs could easily alter significantly not only the cost level but also the cost order of the abatement measures.

3.2 IMPLEMENTATION BARRIERS

In the first section of the report, the authors of the study make it clear that they *"apply a strictly economic lens to the issue of emission reductions"* (Nauclér and Enkvist 2009, p. 38). Nevertheless, it is acknowledged that the implementation of emission reduction measures involves many other considerations such as agency issues and imperfect information. On the other hand, the cost curve assumes rational agents, perfect information and no transaction costs. In reality markets are not perfect but suffer from various imperfections.

Agency issues, or split incentives, describe the problem that the investor in energy saving measures is in many cases not the person who benefits from lower energy expenses. An often cited example is the insulation of rented property, where although the property owner would pay for house insulation, it would be the tenant who would benefit from lower energy bills. Thus, the tenant would have an incentive to invest in house insulation, but without any expectation or security of long-term tenure, the incentive is insufficient; conversely, the property owner has no direct incentive, as the benefits accrue to the tenant, and there is no guarantee that the benefit of lower heating bills could be captured as higher rent, nor that the efficiency measures would increase the sale price of the house sufficiently.

Information failures result in the making of sub-optimal decisions. These failures accrue especially in the residential sector due to uncertainty about future energy prices, or due to the search cost relating to energy efficiency measures. Costs arise due to time spent on research for information on the implementation of energy efficiency options. Furthermore, there is a lack of awareness about potential savings opportunities.

Financing hurdles and other barriers to capital markets can prevent both individuals and businesses from implementing energy efficiency measures that require high upfront payments. Solid-wall insulation, for example, requires an investment of several thousand pounds, which will only be paid back via reduced energy bills over several years. Not all property owners will be able to access the upfront capital to implement this, even when the measures have a positive net present value.

Inertia and satisficing behaviour means that both individuals and companies act habitually and according to existing norms, rather than maximising the utility at every single potential decision point: the frictional costs of finding an optimum are perceived as being greater than the gains of moving from a near-optimal position to the optimum. In particular, in less energy-intensive businesses, companies will not take advantage of cost-effective energy efficiency measures, due to internal structures, cultures, and strategies.

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Lastly, **path dependency** or existing network externalities and inertia of long-lived capital can result in a situation where businesses get locked-in to carbon-intensive technologies, although it might be beneficial to shift to low-carbon technologies. Sunk costs, an established network of technologies, and lobbying to prevent assets becoming stranded can all enforce a lock-in to high carbon technologies. This issue will be discussed in more detail in section 4.

For policy makers it is important to consider what imperfections can be overcome in order to exploit the abatement potential. While this is possible in the case of information failures, agency issues, financing hurdles and inertia, it is not the case for transaction or adoption costs. The acquisition of an energy-saving technology involves different costs, which are very hard to lower by policy makers. For a further discussion on what barriers can be overcome and the distinction between market failures and non-market failures see Jaffe and Stavins (1994) and Sutherland (1991). Due to the neglect of several cost aspects and hard to overcome barriers, the negative abatement potential is possibly substantially overstated.

3.3 DISCOUNTING

A last factor that can explain negative abatement costs is the choice of the discount rate. Discount rates are used in order to compare costs and benefits that occur in different time periods. The higher the discount rate, the more weight is put on costs and financial gains that occur early in the project phase, relative to those incurred later. For those technologies where a large proportion of investment costs occur at the start of a project, but the benefits then accrue over time, they will be more economic the lower the discount rate; a market participant with a higher individual discount rate will require a higher carbon price to justify investment, than one with a lower discount rate.

In general, the research literature distinguishes between social and private discount rates. A social discount rate is used to determine whether an investment or policy is beneficial from society's perspective, i.e. whether it represents a good use of society's resources. The McKinsey cost curve uses a discount rate of 4% and excludes taxes and subsidies. The discount rate of 4% is claimed to be in line with long-term government bonds and it is chosen because governments can borrow at that rate if they want to incentivise capital-intensive abatement opportunities (Nauclér and Enkvist 2009, p. 40). All taxes and subsidies are excluded from this analysis as they are only transfers between groups in society. The discount rate of 4% is close to the 3.5% rate the UK Government (HM Treasury 2003) uses based on a per capita growth of 2% per annum. This rate might be appropriate for industrialised countries, as their borrowing costs are in that range and per capita economic growth is relatively low. These conditions do not hold for developing countries, where borrowing costs are significantly higher and per capita growth rates vary more and can be a lot higher; for example in China the annual per-capita growth rate was an average 10% over the last ten years.

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

Cost calculations from a private perspective differ from society's view, not only in the discount rate applied, which must reflect the private cost of capital, but also in that taxes and subsidies are included. Moreover, project risks are specific to the investor, and will, from the investor's perspective, not be averaged out across the economy. Consequently, the investor will require a higher rate of return, to justify proceeding. In general, individuals and companies do not have the opportunity to borrow at a rate as low as the government's can, and additionally they face several uncertainties. These uncertainties include project related risks, policy and regulatory risks and uncertainty about the future development of energy prices. Observed discount rates in the industrial, commercial and residential sectors can be relatively high if one accounts for barriers and uncertainties involved (see e.g. DeCanio 1993).

The Committee on Climate Change (2008, Technical Appendix to Chapter 5, p. 10) used for its MAC curve a flat real rate of 10% across the power sector. In the transport sector, a private discount rate of 7.05% was applied for passenger cars; whereas for HGVs, the rate was 5.4%, to reflect businesses' access to lower financing costs (AEA Energy & Environment et al. 2008, p. 18). In buildings and industry, the CCC used a rate of 10% to reflect incentives as perceived by the private sector (Weiner 2009, p. 20).

By taking a social discount rate of 3.5%, a MAC curve for the transport sector was generated from a social instead of a private perspective (AEA Energy & Environment et al. 2008, p20) within which the cost-order of interventions was largely preserved, but (with the exception of biofuels) all measures showed negative marginal abatement costs. From a private perspective, less than 4 Mt CO_2 of abatement was available at a zero carbon price, with 15 Mt CO_2 abatement requiring a positive carbon price; whereas from the perspective of society as a whole, almost 14 Mt CO_2 abatement is available at a zero carbon price, and only 5 Mt CO_2 would require a positive carbon price.

McKinsey (Nauclér and Enkvist 2009, p. 55) performs several sensitivity analyses, one on discount rates. It is striking that the ordering of the curve is stable as the discount rate is raised to 10% and the average abatement cost increases from €4 to €14 per t CO_2e. This curve-wide cost might be relatively low due to measures with relatively low capital intensity, such as preventing deforestation, and it does not say anything about the marginal cost of specific technologies.

In conclusion, with the current discount methodology the cost numbers tell policy makers what might be preferential from a least-cost point of view of society as a whole. However, not all decarbonisation investment decisions are made from that perspective: the private sector will make decisions within the context of its own MAC curve, one based on a different discount rate, and one that consequently is, in places, very different to the social MAC curve. Hence, the social MAC curve may give some guidance to the reader as to what may be desirable from the perspective of maximising social welfare, but will not tell the reader what the market will do.

4 INTERTEMPORAL ISSUES

Marginal abatement cost curves are a static snapshot of one period of time, usually one year. This means that abatement costs are associated with abatement potentials for one year without presenting any information on what happened before that year and what is assumed to happen afterwards. The abatement curve does not permit any insights into the timing and rate of investments in each specific technology. Historic investments in low-carbon technologies and existing policies influence the abatement costs and potentials as well as the expectation about future climate policies. For a given year and CO_2 price level, the overall abatement level and the technology-specific abatement level can vary significantly depending on earlier investment, which can drive down technology costs. Furthermore, the expectation of an increasing CO_2 tax in the future can remove uncertainty and induce investors to invest in abatement measures. Thus, the form of the emission pathway or carbon price trajectory before and after the considered point in time have a significant impact on the abatement curve.

It is crucial to present the best information taking into account intertemporal uncertainties, as they are the basis for long-lasting decisions in the context of climate policy. Time considerations are especially important in the context of the energy system, because power plants, refineries and infrastructure have a long life time of up to 60 years. If the decision is made to build a new power plant in 2010, it will still be affecting abatement opportunities in 2050. According to Weyant (1993) the transition period to a low-carbon world is likely to take 40 to 60 years, due to the long life of much energy sector infrastructure, and the time needed to phase in new technologies.

The authors of the McKinsey study on the global cost curve have dedicated three pages to the importance of time in their report and emphasise the urgency to act early in order to avoid a lock-in into a high-carbon economy. It is stated that if abatement action is delayed by one year 1.8 Gt CO_2e of abatement potential is foregone in 2030 and cumulative emissions would rise by 25 Gt CO_2e. Nothing is said in the report on the influence of this delay on costs. In this context, Edenhofer et al. (2006, p. 98) stated that findings from the Innovation Modeling Comparison Project indicate that climate policy induces additional technological change, which can result in a significant reduction of abatement costs. Policy incentives can also bring a technology further down the learning curve and subsequently create a lock-in effect, where the technology becomes cheaper than other low carbon technologies.

Commitments towards emission reductions go as far as 2050, e.g. in the United Kingdom or recently in Germany, and therefore have to be taken into consideration when interpreting McKinsey's cost curve for the year 2030. Investment decisions that are appropriate for the year 2030 might no longer be so in the face of an 80% emission reduction in 2050 compared with 1990. For example, if, in order to deliver 80% reductions in overall emissions by 2050, the electricity generation sector must reduce its emissions by 95% to compensate for the relatively high costs associated with emission abatement in other sectors, then a fossil-fuel power plant with carbon capture and storage (CCS) that removed up to 90% of CO_2 from the flue gases might appear to be an appropriate investment for 2030, but could become a stranded asset by 2050. Even with only 10% of its original emissions, it would still be too carbon-intensive for the overall 2050 emission limit to be met.

Concluding, the cost curve depicts only one year, while it relies on unclear assumptions about investments and technological developments made in earlier years. But cost and abatement potentials depend crucially on previous efforts. The costs of decarbonisation over time are much more usefully considered in terms of scenarios or trajectories of emissions, in which measures (and their associated costs) implemented in one period, affect the available measures and costs in subsequent periods. Such trajectories have the further advantage that they reveal accumulated emissions over a period, and it is this figure that most closely reflects the scale of the climate's warming response (Allen et al 2009).

Thus the MAC curve, in disclosing information only about a single year's emissions, gives a very incomplete picture of matters that decision makers need to know when considering decarbonisation strategies and measures. Such intertemporal issues are a big problem for all MAC curves, not just those of McKinsey's. This can be mitigated by presenting a MAC curve that shows the abatement of total accumulated emissions within a specific period instead of a single year, or by presenting full emission scenarios or trajectories with their associated costs.

5 INTERACTIONS

McKinsey & Company assessed each abatement measure, such as cavity wall insulation, nuclear power plants and heat pumps, independently to arrive at specific cost and abatement estimations (Nauclér and Enkvist 2009, p. 145). However, changes in the energy system and emission mitigation are dynamic processes with interactions that go unconsidered when single measures are assessed separately.

If one abatement measure is implemented then the baseline for the remaining mitigation measures changes: the decarbonisation of electricity would drastically reduce the abatement potential of insulating electrically-heated homes. The emissions that have been abated once, cannot be abated a second time. Failing to recognise such interactions means that the abatement potential can be double-counted and thus overestimated. An approach that is based on the individual abatement of technologies is prone to such baseline inconsistencies. There exist systems approaches which deal with these and other interactions.

Though Nauclér and Enkvist (2009, p. 24) state that baseline assumptions are taken from the World Energy Outlook 2007 of the International Energy Agency (2007), little is said about the specific reference technologies that each different abatement measure displaces, in order to derive the abatement cost. The reference technology is, however, a decisive variable to assess the abatement cost and potential. The size and cost-effectiveness of abatement delivered by a wind turbine is relative to the type of generator it displaces: in general, abatement will be higher, and more cost-effective, if a wind turbine displaces coal, than if it displaces natural gas.

Besides baseline issues, mitigation measures interact in other ways. One example is that a poorly-insulated solid-wall property heated by fossil fuels will have high emissions: these can be abated in part by dry-lining the walls: however, in doing so, the cost-effectiveness and total abatement potential, of subsequently switching the heating to a wood pellet boiler, both lessen. Conversely, if the biomass boiler is introduced as the first measure, the abatement potential of building insulation would be very low, as the heating fuel could now have a very low CO_2 intensity.

Interactions can exist not only within a sector, but also across sectors. The demand for electrical heat pumps or electric vehicles will depend on the availability and price of electricity. Conversely, the price of electricity depends on the demand level and daily/seasonal patterns from end-use sectors. Biomass can be used as a heating fuel in buildings, as a transport fuel in the form of biofuels in the transport sector or can be used as an input fuel for power production, but the overall availability of biomass is limited. If, for example, it is widely used to heat buildings, less will be available for biofuels or power generation. Consequently, the implementation of one measure in the building sector can have significant repercussions on the abatement costs and potentials in the power and transport sectors.

McKinsey's representation of the cost curve evokes the impression that abatement technologies will be added together with increasing carbon prices without a change in the previous composition of technologies. However, in reality, this will not happen. While it can be beneficial in terms of emissions to introduce hybrid cars at low carbon prices, they can be replaced by plug-in hybrid vehicles or battery vehicles at higher CO_2 prices, once the carbon intensity of electricity is sufficiently low. In the power sector coal-fired power plants may be replaced with gas-fired power plants at a low carbon price to save a limited amount of emissions, but it will be economic to replace all fossil-fuel based power plants by low-carbon technologies if the carbon price, or, equivalently, required emission reductions, are sufficiently high.

In addition to these intrasectoral and intersectoral interactions, there are also international interactions that arise from ongoing emissions abatement. If one region aggressively invests in one abatement technology, this may decrease the cost of that technology; via technology transfer, this can reduce abatement costs for the rest of the world. Alternatively, if one region's pursuit of a technology constricts the global supply chain for that technology, it may increase the price of it elsewhere in the world; if the rest of the world has fewer and more expensive alternative options to that technology than the region in question does, this will increase the global cumulative cost of abatement.

Furthermore, as energy prices affect individual abatement costs in different ways, the decarbonisation pathway itself will change the shape of future MAC curves: while the energy system decarbonises, the demand for oil, gas and coal will reduce, lowering their price relative to business-as-usual; this will make further emission abatement less economically competitive (see Klepper and Peterson 2003).

Beyond the energy system, greenhouse gas emission abatement has further consequences. A massive demand for capital-intensive abatement technologies can influence the price of capital. Emission reduction can influence the wider economy, such as household consumption; the labour market; the demand for metals and other resources; and the income structure of governments. The social implications of climate change mitigation are further discussed in section 7.

The problems arising from the way in which some treatments of abatement, such as the MAC curve, exclude consideration of several types of interactions, have been discussed in the research literature going back some time: Stoft (1995) discussed interactions between abatement measures and the difficulty of a consistent baseline. A comprehensive discussion of the failure to take into account interactions and other shortcoming can be found in Fleiter et al. (2009).

Summarising, the MAC curve, as presented in McKinsey's study, is not able to capture intersectoral, international and economy-wide interactions appropriately, while it is not clear to what extent interactions between abatement measures are captured. These interactions can only be adequately considered through the use of a systems approach, such as is employed with an energy systems model. The inability to consider interactions, inherent to MAC curves, significantly limits the value of the information the curves can convey, because abatement potentials can be overestimated and abatement costs can be overly optimistic.

6 OTHER METHODOLOGICAL SHORTCOMINGS

6.1 BEHAVIOURAL ASPECTS

The McKinsey cost curve includes only technical abatement and excludes all measures that have *"a material effect on the lifestyle of consumers"* (Nauclér and Enkvist 2009, p. 9). Examples for behavioural change and the corresponding abatement potential are given for business and private travel, shifting road transport to rail, accepting higher domestic temperature variations and reducing meat consumption, but no cost estimates are given. While it is acknowledged that it is very difficult to quantify the costs and emission savings related to lifestyle changes, there are two relatively well-understood behavioural responses: price-induced energy service demand changes and the rebound effect.

The first response, price-induced changes to the demand for energy services, comes about because demand shows some price elasticity: car drivers will reduce the distance they drive, when petrol and diesel prices go up; space heating will decrease if natural gas prices go up; and electric appliances will be used less if the electricity price rises. Thus, rising prices for energy services can bring about demand reduction, which then plays a role in reducing greenhouse gas emissions. Vaillancourt et al. (2008) found that in a climate stabilisation scenario, global aviation demand-reduction may be as high as 23% by 2100.

The second response is the rebound effect, whereby improvements in energy efficiency can encourage greater use of energy services such as heating or transport. Thus, many energy efficiency improvements do not decrease energy consumption to the extent predicted. This arises because energy efficiency measures can make the energy service cheaper, so that consumers may choose to make more use of this energy service and thereby offset part of the reduction in energy consumption. Even if the consumption of energy services remains unchanged, indirect effects can increase the demand for other energy services. The consumer can save money with an efficient car and decide not to drive more but to spend the saved money on a flight. The existence of the rebound effect and its implication that consequently savings curves overestimate the energy savings was documented almost thirty years ago, by Meier (1982). For an overview on the rebound effect see Sorrell (2007).

Since the rebound effect is not considered by Nauclér and Enkvist (2009, p. 27), the curve possibly overestimates the abatement potential of mitigation measures. On the other hand, the curve does not take into account demand responses to changing prices, which can lead to interactions in other sectors.

6.2 TECHNOLOGICAL ISSUES

As with the cost definition, the extent of the potential for abatement for each technology in the McKinsey cost curve is disputable. Although the authors (Nauclér and Enkvist 2009, p. 146) state that the abatement potential is the economic potential, it is not possible to dissect the curve to understand how the limits on the extent of deployment have been considered. There are three possible sets of constraints: on rate of deployment, on technical potential, and on the economic potential. The technical potential can change over time, as technology changes: for example, recent developments in deep-water offshore wind open up large new areas of technical potential for that measure. Conversely, hidden costs and market barriers can restrict the genuine potential to a figure smaller than the theoretical economic potential.

Another point concerns the aggregated character of individual abatement measures. All technologies are represented at a single average cost level, though inevitably costs will vary by installation; for example, the capacity factors of most renewable technologies is highly location-sensitive, and so the technologies have different cost levels depending on the site. Nauclér and Enkvist (2009, p. 9) note that cost is a weighted average across sub-opportunities, regions, and years: accuracy and meaning are sacrificed to produce a clearer, simpler MAC curve. It does make the MAC curve easily comprehensible, but , to provide a clearer guide to policy-making, the detail of the range of technology costs should be given somewhere else.

There are also reasons for caution about the scenario against which abatement is measured: the business-as-usual scenario that is used as a baseline within the McKinsey MAC curve exclude the development of coal-to-liquids and gas-to-liquids, because currently: *"their greenhouse gas emissions are too small to be material"* (Nauclér and Enkvist 2009, p. 67). However, the World Energy Outlook 2007 (International Energy Agency 2007, p.125), which Nauclér and Enkvist cite as a basis for their work, predicts that output from coal-to-liquids plants will increase to 0.75 mb/d in 2030 in China alone; in that case, the global greenhouse gas emissions by 2030 would, in the absence of abatement, be material.

6.3 ANCILLARY BENEFITS AND COSTS

The focus of the cost curve is exclusively on greenhouse gas emissions, while the reduction of greenhouse gas emissions has many effects beyond the level of greenhouse gas emissions. For example, if cars switch from diesel and petrol to electricity, then not only will greenhouse gas emissions reduce, but so will local air pollution. The reduction of air pollution and the subsequent positive health effects are benefits of reducing greenhouse gas emissions, which decrease the net cost of the reduction (Woodcock et al 2009). The improvement to health conditions is not the only ancillary benefit or co-benefit. Reducing the consumption of fossil fuels and thereby the reliance on imports of crude oil, natural gas or coal can significantly improve energy security, when substituted by local energy forms such as wind or tidal energy are used.

Improving insulation or installing double-glazed windows can help to reduce fuel poverty, as well as enabling greater energy efficiency. This can be a very effective way to reduce excess winter deaths, which have been estimated at 25,000-45,000 per year in England and Wales (DEFRA 2004). Energy efficiency measures in residential buildings can increase indoor air quality and drastically reduce external noise. Noise related co-benefits can be substantial as was shown by Jakob (2006) for the case of Switzerland. A last co-benefit of introducing carbon taxation can be the so-called double-dividend, whereby a welfare gain can be created by lowering other, distortionary taxes.

On the other side, there exist also examples where abatement technologies come with ancillary costs. This can include energy-efficient light bulbs that require new fittings, or energy-efficient washing machines that have lower limits on their maximum loads.

Thus it should be kept in mind that the reduction of greenhouse gases can have wider benefits. If ancillary benefits are accounted for, they reduce the abatement cost attributed to greenhouse gas emission reduction.

6.4 TREATMENT OF UNCERTAINTY

A last methodological issue is the representation of uncertainty considering various factors, such as technology learning, energy prices, discounting or demand development. The authors note that many figures contain a considerable uncertainty (Nauclér and Enkvist 2009, p. 21) and that the abatement data should be interpreted as directional estimates rather than exact quantifications due to the significant uncertainties (Nauclér and Enkvist 2009, p. 53). The significance of this statement is easily lost, though it carries the largest caveat on the use of the MAC curve as a reference point in policy-making. In particular, for those curves set far in the future, such as 2030, there exist major uncertainties concerning many factors that influence the abatement cost curve. This extends to interdependencies and interactions between the uncertainties.

The study presents four sensitivity cases, including energy prices, technological learning and discount rates, although only the cost curve with higher energy prices is represented. It is noteworthy that the baseline is kept constant in all sensitivity cases despite the fact that fundamental assumptions change. It is, for example, implausible that baseline emissions will stay the same if the oil price is doubled. It is more likely to lead to fewer emissions in the case without any carbon price and accordingly reduce the abatement potential. McKinsey produced version 2.1 of its MAC curve in 2010 as a response, in part, to changes in expectations of future oil prices (Enkvist et al. 2010).

Concluding, it is important to place greater emphasis on the uncertainty related to cost and abatement potential estimates, so that decision makers are more fully aware of them and can factor the uncertainty into their decisions. The result of this should be the development of policy instruments that can cope with uncertainty; including research into, and stimulation of, those measures lying further up the MAC curve, to allow for the possibility that those measures become economically viable faster than expected. This will reduce reliance on a small number of technologies that may achieve neither the low costs nor the technical potential forecast of them.

7 WIDER SOCIAL IMPLICATIONS OF CLIMATE CHANGE MITIGATION

McKinsey's cost curve has a clear economic focus based on a least-cost approach. Policy makers dealing with the reduction of greenhouse gas emissions, however, must not only consider the cost efficiency of policy tools, but also the wider effects of climate change mitigation on society. This includes co-benefits, discussed in section 6.3; but there are other wider effects: on distributional equity, energy security of supply, competitiveness, the labour market and capital markets.

Distributional equity includes all questions raised concerning possible different impacts of climate policies on agents, sectors or income groups. Climate change policies may negatively affect or favour particular income groups. For example, subsidies for electric vehicles may benefit particular income groups over others. However, distributional effects are routinely omitted from MAC curves, even if they have been estimated.

Energy security is a strategic issue that is distinct from carbon abatement, but is nevertheless entangled with it: when implementing climate change policies, policy makers try to maximise synergies with energy security policy such that emissions reductions are made in a way that helps to secure diverse and sustainable supplies of energy at competitive prices. Reducing dependence on imported fossil fuels by substituting renewables can at the same time strengthen energy security through reduced exposure to import risk and abate carbon emissions. However, the impact of different kinds of intermittency onto the grid introduces new security issues that must be explicitly managed and compensated for: affordable technical solutions already exist, but existence isn't sufficient, they must also be implemented (Gross et al 2006).

The implementation of a local carbon tax or other sub-global climate change policies can open up the potential for carbon leakage in internationally competitive sectors, i.e. that carbon-intensive production will be relocated abroad.

There are other system-wide effects: the creation of jobs in low-carbon industries will be partially offset by jobs that are lost from high-carbon industries. Similarly, in capital markets, when capital is redirected to decarbonisation from other sectors, there will be consequences of reduced capital spending in those other sectors.

In summary, by boiling down the complex decision framework related to climate change mitigation into financial terms, it can create the impression that greenhouse gas emission reduction is simply about cost minimisation. This could lead decision makers to believe that it is enough to set a carbon price at the required level and that all the abatement potential that becomes viable at the price will be realised, with all consequential effects already priced in. The lesson to be drawn from the MAC curve is actually different. A carbon price is only the beginning of mitigation, and the complex web of interactions and hidden costs means that ongoing intervention beyond simple carbon pricing or carbon trading is required. The very presence of technologies that have a negative abatement cost makes the point that merely ensuring that measures are economically justified will not ensure that they get implemented. In fact the MAC curve just gives an uncertain indication of the relationship between carbon abatement and the carbon price that might bring it about. Actually realising the abatement may require the carbon price to be supplemented or supported by a range of other policies.

8 THE MAC CURVE AND REDD

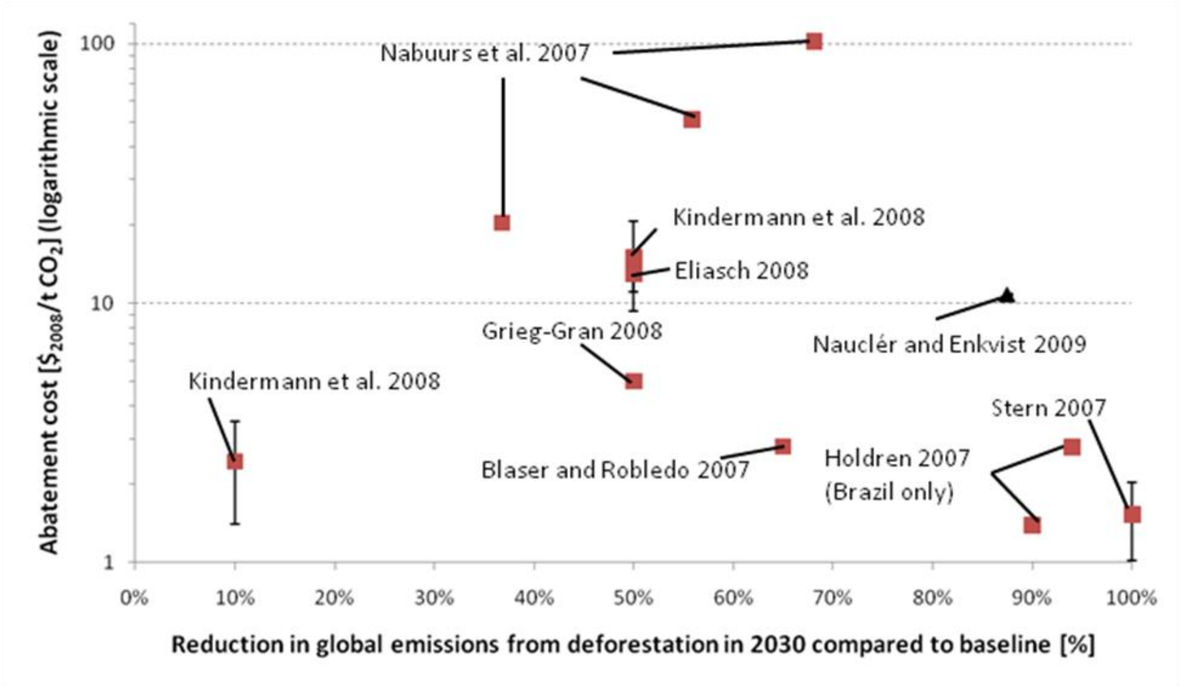
Reducing Emissions from Deforestation and Forest Degradation (REDD) is identified as a major abatement opportunity by McKinsey (Nauclér and Enkvist 2009, p.117). REDD+ extends REDD to include forest conservation, sustainable management of forests and enhancement of forest carbon stocks. In this section we will mainly focus on REDD. The IPCC (Nabuurs et al. 2007, p. 543) estimates annual emissions from deforestation to be in the order of 5.8 Gt CO_2 per year, approximately the same amount as all CO_2 emissions in the USA, while baseline emissions for 2030 are expected to be the same or slightly lower (Nabuurs et al. 2007, p. 547). It is important to note that emissions from forests are hard to measure because young forests take up CO_2 emissions, while mature, older forests will stabilise their carbon content, and if not properly managed will release emissions again.

Mitigation options in the forest sector are not directly comparable to the energy sector. Whereas the logic behind a MAC curve for the energy sector is that a carbon tax at a certain level could mobilise abatement measures with a marginal abatement cost below that level and achieve the indicated level of cumulative abatement, this is not applicable to the forest sector. The idea behind REDD is rather to offer financial incentives to stakeholders in order to reduce deforestation mainly in Latin America and developing countries in Asia and Africa. Using a MAC curve to assess the potential and costs of this approach leads to extra difficulties in addition to many of the issues we have discussed above.

Focussing on the cost issue first, there have been many studies that estimate the amount of money necessary, so-called opportunity cost, in order to compensate people for the benefit that is lost as they have to pursue an alternative action. McKinsey (Nauclér and Enkvist 2009, p. 186) cite a study (Holdren, 2007) for the cost calculation of avoided deforestation from slash and burn agriculture, but do not give information on further assumptions. Nauclér and Enkvist (2009, p. 118) assume optimistically that 100% of emissions from deforestation can be stopped in Latin America and Asia and 70% in Africa, which yields a global reduction of almost 90%. In order to make McKinsey's cost estimates comparable to other global studies, the weighted average abatement cost for REDD can be calculated to be around €7.4 per t CO_2, which is $10.8 per t CO_2 given the exchange rate in 2008 of 1.47$=1€.

In order to put this cost estimate into a broader context, Fig. 3 gives an overview of other cost assumptions for REDD in 2030 from different studies. It becomes apparent that there is no trend in the cost estimates, but that they differ significantly. Global forest sector models used in the Fourth Assessment Report of the IPCC (Nabuurs et al. 2007, p.559) indicate costs of up to \$100/t CO_2 for a 70% reduction of emissions from deforestation, while the Stern report (Stern, 2007, p. 217) forecasts costs to be in a range of \$1-2/t CO_2 to stop all emissions from deforestation.

FIG. 3: OVERVIEW OF ABATEMENT COST ESTIMATES FOR GLOBAL REDD IN 2030



SOURCE: HOLDREN (2007), NABUURS ET AL. (2007), STERN (2007), ELIASCH (2008), GRIEG-GRAN (2008), KINDERMANN ET AL. (2008), NAUCLER AND ENKVIST (2009)

The wide range of estimates of the costs of carbon abatement of REDD is due to estimates that are based on different types and models and that differ concerning the extent to which they consider particular local conditions. Some studies give cost estimates for the case where authorities can target landowners individually and pay different rates according to individual opportunity cost. In practice that would mean paying less to a landowner in the tropical forest for halting deforestation, than to neighbours who grow more valuable crops or the same crops more efficiently. Such price discrimination is considered to be difficult to implement (see e.g. Eliasch 2008, p. 74). Summarising, the focus on a single number for any particular measure is not very helpful, as the number is very uncertain and dependent on very many difficult assumptions, which are what largely determine its position, or ranking, on the cost curve.

But opportunity costs are not the only costs involved with REDD. There are also transaction, administration, implementation, and monitoring costs. None of these cost elements are included in the cost curve (Nauclér and Enkvist 2009, p. 121), despite the fact that costs to build institutional capacities, as well as costs to set up monitoring and management frameworks can be substantial (see e.g. Eliasch 2008, p. 70). Legal issues, in the form of vaguely defined statutory rights in tropical forests, are an important barrier to any implementation of payments for the reduction of deforestation.

Monitoring is of particular importance in the context of REDD as deforestation projects are notoriously difficult to make effective and are subject to potential leakage. Leakage describes the phenomenon where deforestation is stopped in one location and consequently taken up in another one. It can happen that landowners neighbouring a REDD area start to deforest in order to be included into such a scheme to profit from compensation payments. According to Kindermann et al. (2008, p. 10306) current estimates of leakage in forestry projects range from 10% to more than 90%.

As in the energy sector, costs in the forest sector are not static. They are subject to interactions with supply and demand on the wood market. A surge in the demand for bioenergy can affect the rate of deforestation. Opportunity costs are not static: they change with market forces and technological changes (Gregersen et al. 2010). Furthermore, ancillary benefits exist as well in the forest sector. Reducing deforestation can protect biodiversity; furthermore, it can have positive consequences on rainfall, reducing drought-driven energy shortages and ultimately reducing fire-related costs.

A last issue concerns the wide-ranging implications any global scheme for the reduction of forest-related emissions will have. As noted by Nauclér and Enkvist (2009, p. 28), "*...they [abatement opportunities] are tightly linked to the overall social and economic situation in the concerned regions, and addressing the opportunities at this scale has not before been attempted*." REDD can cause taxes from logging and exports to drop, and can reduce employment in the forestry sector, which can create a shortfall of income that overshadows the received payments. For people depending on forest-related income, it is not simply enough to provide them with compensation payments, but social and economic alternatives have to be offered.

In summary, REDD highlights many of the problems and risks associated with basing policy on a MAC curve analysis. In the case of REDD, the MAC curve is barely a beginning, and because of the issues of hidden costs, non-abatement benefits, wider implications and uncertainty, a market approach to carbon abatement based on opportunity costs not only will not yield the envisaged abatement on its own but may have perverse and unintended effects that make deforestation worse. If deforestation and forest degradation are to be reduced, measures of far greater sophistication than can be derived from MAC curves will have to be employed.

9 CONCLUSIONS

McKinsey developed its global cost curve to provide a quantitative indication of the technical and economic feasibility of emission reduction. However, this report has identified several significant flaws with this analytical tool, some of them inherent to the construction of the curve. For example, it does not take into account interactions and the dynamic character of decarbonising the economy; it summaries average costs across a technology, though we know the variation in project costs within a technology can be much greater than variations between the average costs of competing technologies; it presents information about a single year's emissions, though they depend crucially on earlier abatement actions.

Other problems relate to the way that the MAC curve is presented. Within the Executive Summary of McKinsey's reports on v2.0 and v2.1 of its curve, no mention is made of the caveats that the rest of the report is rightly leavened with, and further problems come from the way that the curve has been propagated, without caveats or documented assumptions, that encourages far more weight to be attached to the cost figures, and the ranking of measures, than is justifiable.

What does this mean for policymakers? Firstly, that the MAC curve is not, and should not be used as, a one-stop shop for ranking abatement policies. A MAC curve is a simple and useful illustration tool to engage various stakeholders in the debate about climate change mitigation. Provided it is constructed in a sound way and the drawbacks are set out, it can be a first, rough guide to abatement costs and potentials in a specific point in time. Therefore, the MAC curve of McKinsey and Company, or anyone else, can only be one component of the decision-making aids on which policy is based.

In addition, MAC curves themselves should have their assumptions transparently laid out. Those assumptions, together with the caveats on the data that we have identified in this report, should accompany the MAC curves: to present the curves without the assumptions behind them, and without the caveats, is to risk policy-makers being mislead into the pursuit of an unworkable or unaffordable portfolio of policies.

More broadly, a system-wide approach is needed and should be employed to understand the consequences of implementing several different abatement measures together. This will ensure that path dependencies, important behavioural interactions and the interactions between measures, are identified and are taken into consideration within the policy-making process.

On page 20 of the report on version 2.0 of the McKinsey MAC curve, the authors state that *"we might characterise the first version of the global cost curve as a 16th century map of the world of the economics of global climate change mitigation. Version 2 has perhaps brought us into the 18th century"*. If McKinsey & Company are willing to take up some of our suggestions, and share all of the assumptions behind their MAC curves with carbon economists and policy makers in an open peer review, the MAC curve can be brought into the modern world.

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