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Marginal Abatement Cost Curves

Mitigation Decision Tools

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Marginal Abatement Cost Curves

Mitigation Database Support Tools

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This Technical Guide draws decision makers' attention to important considerations when using MAC curves. It demonstrates the difference between expert-based and model-based MAC curves, and explains the usefulness and weaknesses of MAC curves. It also demonstrates how MAC curves results are sensitive to certain details of implementation that are not necessarily obvious and rarely documented.

INTRODUCTION

The rapidly increasing greenhouse gas emissions (GHG) in the world have been proven to contribute to climate change, with dramatic harmful consequences to human communities and many non-human animal and plant species. This has led policy makers in many countries to attempt curbing national emissions. The fact that developed and developing countries have differing resources, capability and responsibilities (through either burden sharing or effort sharing), and yet are required to cooperate closely if they want to avoid the harmful consequences of climate change, complicates mitigation efforts. Despite this complexity, decisions need to be made and tools developed to aid decision-makers. Various information-processing tools (such as multi-criteria analysis) are used to aid decision-making, the most widely used being marginal abatement cost (MAC) curves.

MAC curves analyse the mitigation options available to a region or country, the emission reduction potential that would result, and the marginal abatement costs associated with their implementation. The marginal abatement cost is the cost of eliminating an additional unit of emissions (Morris, Paltsev and Reilly, 2008). MAC curves are used to compare the cost-effectiveness of different mitigation options. These curves show the set of mitigation options available to an economy to achieve increased levels of emissions reduction (Bloomberg, 2010). According to Morris, Paltsev & Reilly (2008), a MAC curve represents a relationship between abated emissions and the price of CO2. McKinsey describes a MAC curve as a curve that presents how much emissions can be abated per specific mitigation option and the associated amount of money it will cost or save you per tCO2e (Kesicki 2013; Ekins, Kesicki and Smith, 2011). McKinsey estimates cost and potential CO2 savings of the abatement option. The cost is calculated as the annual additional operating costs less the potential cost savings divided by the amount of emissions avoided. The potential of abatement to reduce CO2 is a technical potential. For example, in power supply, the potential of a technology involves the capacity and efficiency of the technology and its operation or availability. McKinsey cost curves are constructed using a mixture of bottom-up and top-down approaches. For example, in building the UK cost curve, all mitigation actions of particular relevance to the UK were subject to detailed bottom-up analysis, whereas abatements that were thought to be similar to OECD countries were estimated using top-down approaches (CBI, 2007).

The transactional and opportunity cost associated with alternative investments are not included. MAC curves have been developed for countries such as Mexico, Poland, the United Kingdom, Ireland and Nicaraqua (Casillas and Kammen, 2012; Kennedy, 2010), and organisations such as the Food and Agricultural Organisation of the United Nations and the World Bank (Bockel et al., 2012). In each country for which the curves were developed, they were used to inform climate change policies, such as the UK's Low Carbon Transition Plan (HM Governemnt, 2009). Besides being used to inform climate change policy, Ellerman and Decaux (1998) and Spalding-Fecher et al. (2012) developed MAC curves to analyse the benefits of the Kyoto Protocol emissions trading scheme and the clean development mechanism (CDM). Although MAC curves are currently being used extensively for mitigation actions, the MAC curve research concept was first developed in the 1980's after the two oil price shocks with the aim of reducing oil and electricity consumption (Bockel et al., 2012).

According to Kesicki (2013), there are two types of MAC curves, expert-based and model-based. Expert-based MAC curves represent technological costs and do not rely on any model. They are built upon assumptions for the emission reduction potential and the corresponding cost of single abatement measures (for a single or group of technologies). The model-based MAC curves derive the cost and potential emission reduction from energy or economic models (Kesicki, 2013). The following section gives a detailed account of how the curves are classified based on the methodology used to construct them.

METHODOLOGY FOR CALCULATING MARGINAL ABATEMENT COSTS

There are several different approaches to constructing MAC curves, depending on whether the aim is to construct an expert-based or model-based curve (Figure 1). Irrespective of the methodology followed, the starting point when constructing a MAC curve is to estimate the baseline. The baseline usually projects how emissions might evolve if no additional initiative is taken. Whatever mitigation action is taken, the result of such mitigation will be assessed against the baseline.

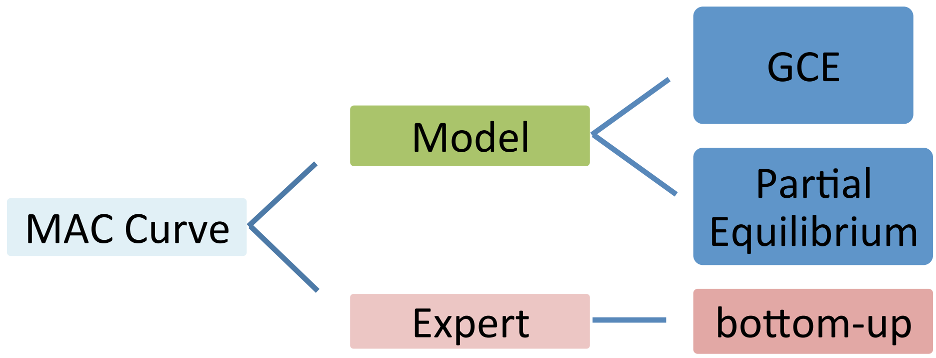

Figure 1: Types of MAC curves and approaches used to construct

When constructing an expert-based model, the analyst considers technological costs and possible emissions reductions per mitigation action or per technology. Examples of expert-based curves are those constructed by McKinsey (Naucler and Enkvist, 2009), those used by Charlie Heaps in his LEAP mitigation exercise (Stockholm Environment Institute, 2012) and by the World Bank's Energy Sector Management Assistance Program (ESMAP, 2010). Expert-based MAC curves are based on a simplified methodology of calculating marginal abatement costs. For each mitigation action under consideration, Equation [1] is used.

$$C_t = \frac{C_{mi} - C_{bi}}{CO_{2ebi} - CO_{2emi}} \quad [1]$$

Where C_t stands for the abatement costs in R/T CO_2e, C_{mi} is the cost incurred by the implementing agent when intervention/mitigation (i) is implemented, C_{bi} is the cost incurred by the implementing agent in the baseline, assuming that mitigation action (i) was not implemented, CO_2e_{bi} and CO_2e_{mi} are the CO_2 equivalent emissions with and without the abatement measure (i) implemented. The abatement cost can either be for a particular year in the planning horizon, or the cumulative cost over a period spanning the planning horizon. If it is for a particular year, then capital costs are annualised, using the discount rate and the life times of technologies and are added to the annual operating costs (maintenance and fuel). The mitigation abatement cost is the total annualised costs incurred by the agent divided by CO_2e abated per annum.

The fundamental difference between expert-based and model-based curves is that expert- based curves do not take system-wide impacts into consideration while the model-based curves do. An expert curve considers technology's emissions reduction potential of that particular technology whereas for model-based curves the technology's emissions reduction potential is affected by what is happening upstream from the energy system. If a mitigation action is on the demand side and a particular technology is installed, expert-based curves will produce the same emissions potentials for that technology/mitigation action even when the electricity mix changes. When constructing a model-based curve, the analyst uses a model that automatically adjusts emissions intensities based on changing fuel mixes on the energy system. Examples of systems models include a Market Allocation (MARKAL) model for the energy sector and a Computable General Equilibrium (CGE) model for a national economy. Using energy systems models, two different approaches can be taken:

A. Single measures: Measures are implemented one at a time without taking interaction between the measures into consideration. Although this might be constructed using a model, the methodology is similar to expert-based curves.
B. Cumulative measures: Each measure is implemented cumulatively and the interactions between these measures are taken into account. Caution should be exercised because the order of measures' implementation changes the results (emissions potential and mitigation costs) drastically.

Examples of energy systems model-based MAC curves are those done by Criqui (2009), Kesicki (2013), Chen (2005) and Energy Research Centre (2007) in the Prospective Outlook on Long-term Energy Systems (POLES), as well as Market Allocation (MARKAL) models. Examples of GCE model-based MAC curves are those that were produced by Klepper and Peterson (2004) in the Dynamic Applied Regional Trade (DART) model, Paltsev et al. (2005) in the MIT Emissions Prediction and Policy Analysis (EPPA) model, and Buchner (2005) in Fondazione Eni Enrico Mattei –RICE (FEEM-RICE) model.

Both system-wide models (energy and economic) can be used to endogenously determine penetrations of mitigation technologies driven by CO_2 price levels or stepping down CO_2 emission levels by means of a constraint. However, it is very difficult to model all demand-side mitigation measures in such a way that the model can respond to rising CO_2 price levels or dropping CO_2 constraints endogenously, especially those that depend on behaviour change. In a CGE model, the marginal abatement is defined as a shadow cost (Klepper and Peterson, 2004) or a carbon tax produced by constraining carbon emissions. The more stringent the constraint, the higher the MAC becomes.

In both the CGE and energy systems models, the main parameter of interest is the value of a carbon tax or carbon shadow price. In an energy systems model approach, different shadow prices are levied on all areas of the model that use fossil fuel (Klepper and Peterson, 2004). Taking into account the technologies, implicit behavioural changes and energy efficiency improvements, the differing shadow prices levied on fossil fuel use lead to adjusted final energy demand. Adjusted energy demand is accompanied by corresponding levels of emissions reductions. In a CGE approach, the analyst uses high-level economic disaggregation, where the sectors are divided into factors of production (capital, labour, fuels) as inputs and output (technology, food and others) and CO_2e emissions depend on the amount of fuel used in production, i.e. $CO_2e = \alpha F$, where α denotes the emission coefficient of fuel F. Constraining CO_2e emissions is therefore equivalent to restricting the input fuel (Klepper and Peterson, 2004). The price of carbon is used to equilibrate demand with supply, hence determining the cost of reducing emissions in the economy.

Based on the above description, the fundamental difference between the expert and model-based MAC curves comes from the fact that expert-based curves are technology centred and considers one mitigation action at a time, while model-based approaches take into account system-wide implications. Irrespective of the method used to construct a MAC curve, the proposed mitigation actions are ranked in increasing order of mitigation costs. After this ordering, the mitigation actions are drawn based on cumulative CO_2e emissions saved (x-axis) versus the unit cost of each mitigation action (y-axis). The curve is constructed from individual rectangular blocks, each representing one specific abatement measure. The width of each block represents the incremental emission-reduction potential (in tonnes) relative to the reference high-carbon alternative. The abatement options are arranged in order of cost, with the cheapest on the left and the most expensive on the right. Mitigation costs are *relative* and *incremental*, rather than absolute costs. The cost will either be the incremental cost incurred by the agent affected by the mitigation action or the system-wide incremental cost per unit of mitigated CO_2.

The MAC curve can be represented in two different formats, either as a width varying histogram (bar graph) or as a curve (line graph). Both of these formats show the potentials (emissions that can be avoided) and the costs/savings (monetary value associated with such an investment). In a bar graph, the width of each block of the bar graph represents the total CO_2e savings per annum from a particular mitigation action. The height of the bar shows the average unit cost (positive scale) or savings (negative y-axis scale) of a particular abatement option. The area (height*width) of the bar represents the total cost for delivering all the CO_2 savings from the action. The sum of all bar widths shows the total cumulative CO_2 emissions saved by all abatement options. For the line graph, the height of the line graph represents the cost associated with the abatement option. The area under the line gives the total abatement costs.

MARGINAL ABATEMENT COST CURVES SHORTCOMINGS

The aim of this section is to show that although MAC curves represent a simplified tool for displaying mitigation cost-effectiveness and potentials, it has many shortcomings. Several researchers have highlighted the weaknesses of MAC curves (see Bloomberg, 2010; Ekins, Kesicki and Smith, 2011; Kesicki, 2013; Buchner, 2005). Some papers (Kesicki, 2013; Ekins, Kesicki, and Smith, 2011) discuss MAC curves from the point of cost, the main arguments being that MAC curves:

- Only show costs for a specific point in time (a snap shot)
- Are subject to inter-temporal dynamics or path dependency
- Include direct technological costs and exclude ancillary benefits and market failures
- Do not give any indication of uncertainties involved in carbon dioxide emissions reduction
- Are sensitive to assumptions (especially baseline assumptions)
- Rely on mitigation costs only, despite the fact that some of mitigation actions cannot be monetised.
- The marginal abatement cost shown on the curve does not really show the actual costs that will be incurred to implement the mitigation action (Vogt-Schilb and Hallegatte, 2012).

METHODOLOGICAL CONSIDERATIONS: ILLUSTRATIVE EXAMPLES

MAC curves can assume many forms (Kesicki, 2013). They differ with regard to regional scope, time horizon and the approach used to generate them. The final results shown on a curve will differ depending on the methodology used to construct the curve. Different approaches therefore complicate the meaning of MAC curves. A MAC curve that was constructed using CGE will differ from a MAC curve that was constructed by using a partial equilibrium model such as MARKAL, because the functionalities of these models differ fundamentally. The aim of this section is illustrate the impacts of different methodologies on the results through simple examples.

The illustration is done using a simple energy systems model of an imaginary country, similar to South Africa. The analysis spans from 2010 to 2020 and detailed assumptions are given in the appendix. Three mitigation action options were considered to illustrate the points of interest:

- **Measure 1 (LFSH):** All normal shower heads are replaced with low-flow shower heads by 2020, assuming a gradual penetration of 10% per annum
- **Measure 2 (SWH):** All electric geysers are replaced by solar water heaters, by 2020
- **Measure 3 (REN):** 50% of electricity produced comes from renewables by 2020 and the reaming 50% comes from coal.

Like in any modelling exercise, the base case assumed a scenario where electricity was produced for the customers without any energy efficiency intervention (no SWH or low-flow shower heads). The electricity scenario assumes a simplified case, where when renewable energy is added to produce electricity, the equivalent amount of coal power plants is retired.

The aim is to illustrate three fundamental weaknesses or inconsistencies with MAC curves:

- MAC curves are sensitive to baseline assumptions (both expert- and model-based)
- In model-based MAC curves, the assumed order of implementation affects the results
- MAC curves are sensitive to input assumptions (such as the type of discount rate used)

First the three mitigations are implemented in the model and assessed in isolation. This is how expert based curves are constructed, i.e. no interaction between the mitigation actions. The results of these mitigation actions are shown in Figure 2.

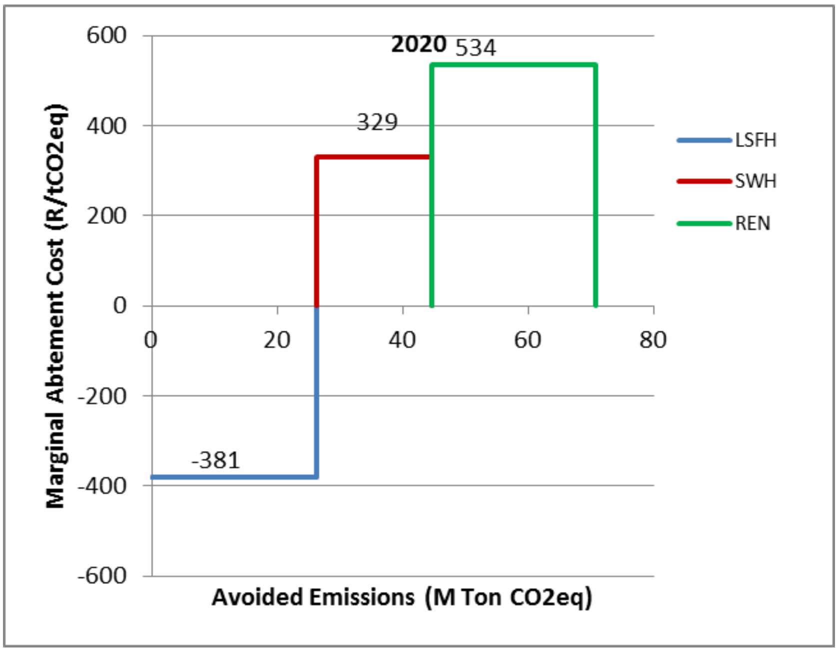

Figure 2: Expert-based MAC curve

Figure 2 shows that the abatement cost of fitting low-flow shower heads is negative (-R381/ton). This means that fitting low-flow shower heads will bring monetary savings instead of incurring a cost. The most expensive measure is the renewable energy mitigation action, costing around R534/ton. REN also has the biggest emissions reduction potential. Depending on what discount rate is used, the marginal costs change drastically, producing a very different curve. If a social discount of 30%[1] is used for all demand measures, SWH becomes the most expensive mitigation action, as shown in Figure 3. Although similar emissions were achieved, the marginal abatement costs for SWH scenario increased eight fold. It is clear that expensive demand mitigation actions are sensitive to the discount rate used.

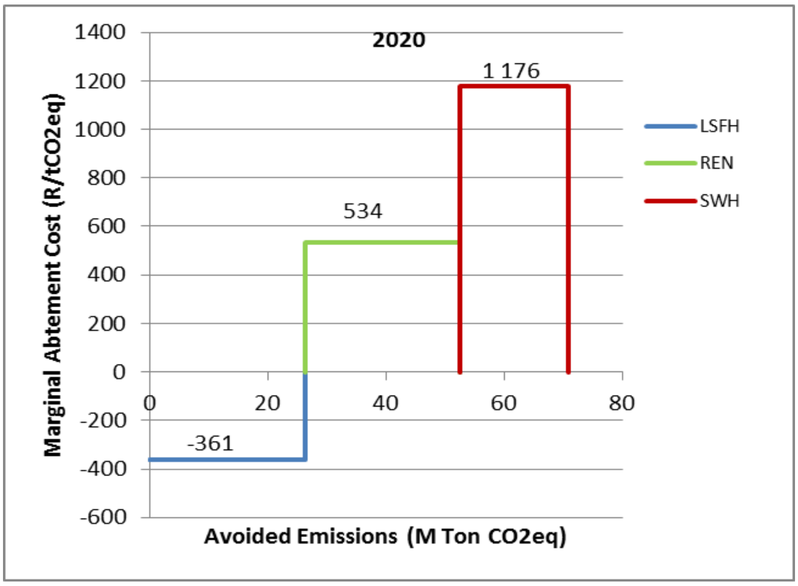

Figure 3: MAC curve's sensitivity to discount rate (social discount rate)

[1] Which is actually what consumers are charged

Next, it is assumed that the three measures interact with each other. In this manner, what happens on the energy supply side has an impact on how much emissions can be reduced. This methodology incorporates system-wide impacts. When considering system-wide impacts, the emissions from demand measures are responsive to energy supply changes. For example, a measure that reduces electricity demand will result in reduced electricity supply, hence reduced mitigation potential from that measure. Given the differing emissions reduction potentials from different mitigation actions, the order in which the measures are implemented affect the cost and emissions reduction potential of the subsequent measures. To show the impact of ordering the mitigation measures, it was assumed that LFSH is implemented first, followed by solar water heaters (SWH) retrofits and lastly renewable REN sources by 2020. This ordering is named “LSR” and the MAC curves for these are shown in Figure 4, Figure 5and Figure 6. The MAC curves look very different from Figure 2 and Figure 3.

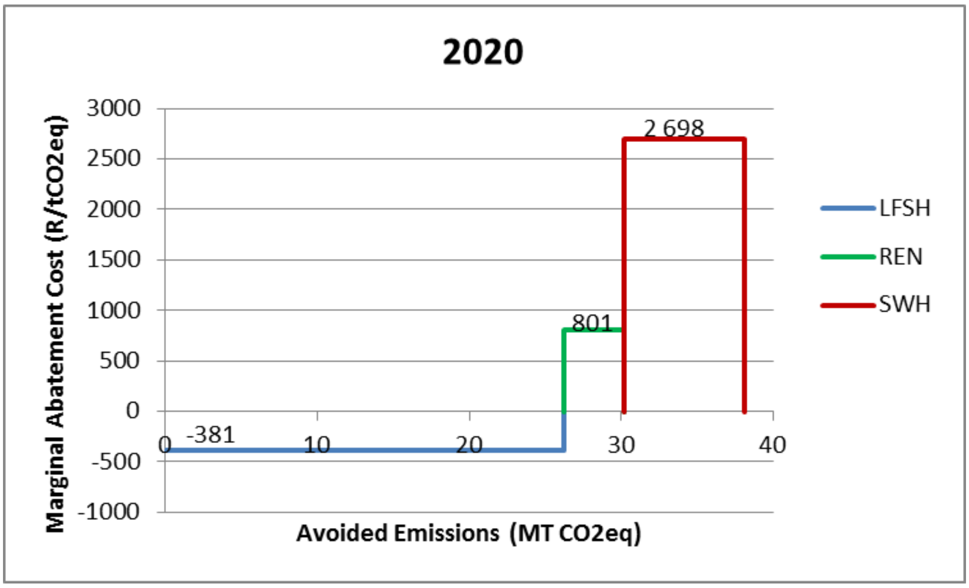

Figure 4: System Wide Impacts (LSR order, normal discount rate, 50% REN electricity is used)

It is evident that LFSH reduces a significant amount of CO_2e, followed by SWH. REN reduces the least emissions. The amount of CO_2 reduced by the LFSH when considering system-wide impacts is the same as the expert-based methodology shown in Figure 2 and Figure 3. This similar emissions reduction is achieved because subsequent mitigation actions can only abate what could not be abated by the first measure. For REN, the reduced emission reduction potential results from the fact that less electricity will need to be produced since the preceding measures reduced the demand for electricity already. A comparison between Figure 4and Figure 2shows that the emission reducing potentials of SWH and REN have reduced significantly. Economically, it is more expensive to abate a tonne of CO_2e with SWH. This simply means that installing more SWHs will not be cost effective if a prior measure already reduced a significant amount of CO_2. In Figure 4, the measures have a combined potential of reducing 40 MtCO_2e, whereas when they were implemented in isolation, they had a combined potential of 80 MtCO_2e. Ordering mitigation actions affect the cost and emissions reduction potential of the subsequent mitigation actions.

In Figure 5 we assume that solar-water heaters are installed first, followed by low-flow shower heads and lastly renewable energy. This ordering is named SLR. SWH reduced 34 MtCO_2e with a unit cost of R329 per tonne of CO_2e, similar to what it reduced when the measures were implemented in isolation. LFSH becomes an even more favourable mitigation action economically compared to when it was used as the initial measure in Figure 4 and when it was implemented in isolation in Figure 2. LFSH’s emissions potential decreased three fold, from 26 MtCO_2e to 9 MtCO_2e. In both LSR (Figure 4) and SLR

(Figure 5), the emissions reduction potential for REN mitigation action has stayed very low but the cost of mitigation is higher compared to when REN was implemented in isolation (refer to Figure 2). Figure 6 shows that LFSH is highly responsive when using a social discount rate as it changes from R3 715 to R7 587 in monetary savings. In Figure 3 and Figure 4, when LFSH was the baseline, its marginal cost was not so responsive to discount rate.

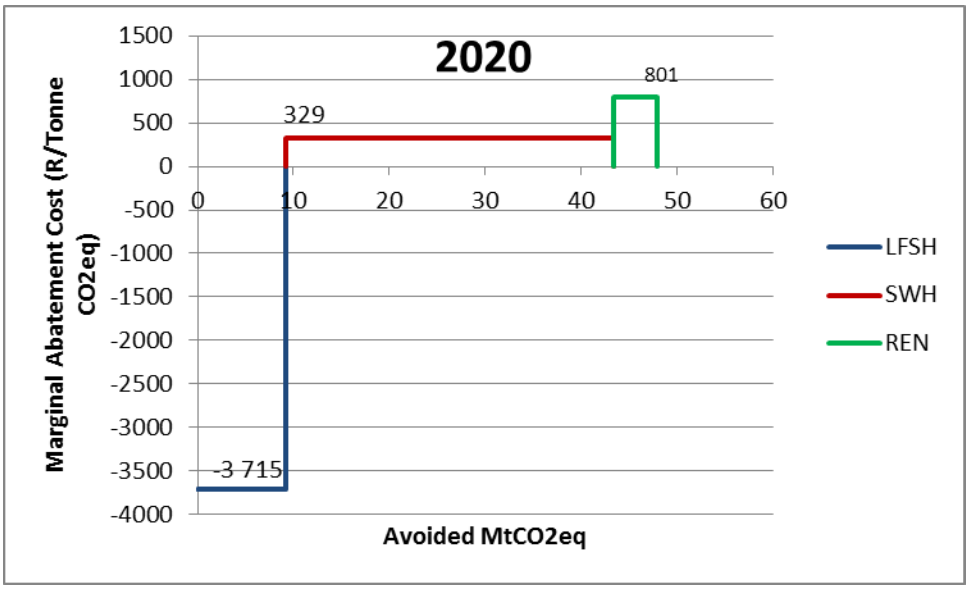

Figure 5: System-Wide Impacts (SLR order)

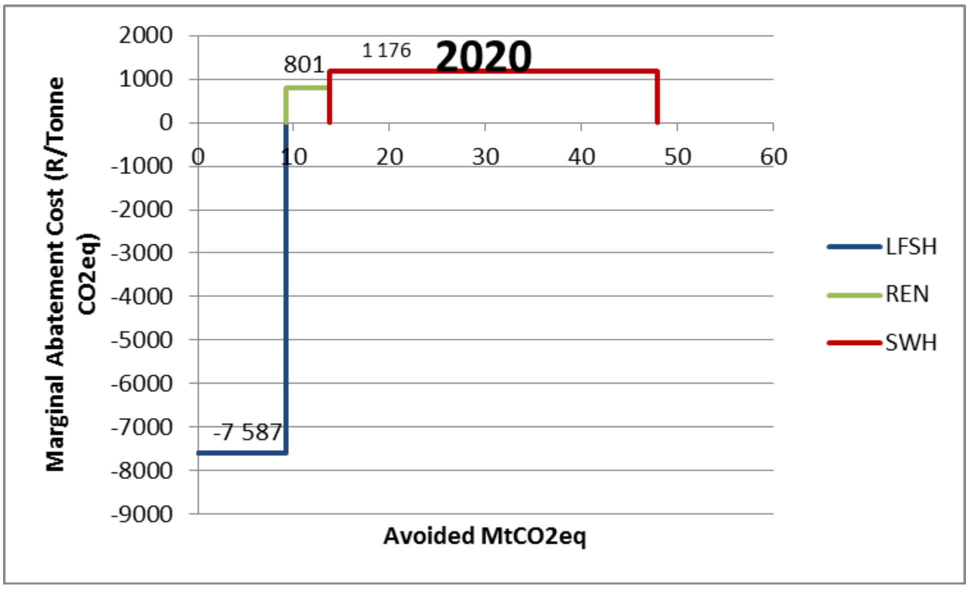

Figure 6: System-Wide Impacts (SLR order with social discounting rate)

Lastly, we assume that we start implementing REN before the demand measures, such that the demand measures will start off already using cleaner electricity. The accompanying MAC curve is shown in Figure 7. REN has the highest potential of reducing emissions and SWH is the most expensive mitigation action with the least potential to reduce CO_2e emissions. It becomes costlier to abate with SWH because all the installations that are made increase the cost but do not have a significant impact on emissions reduction because the electricity used is already clean. If an emissions reduction target was set, new installations could stop once the target was reached and SWH could cost less due to the imposed target.

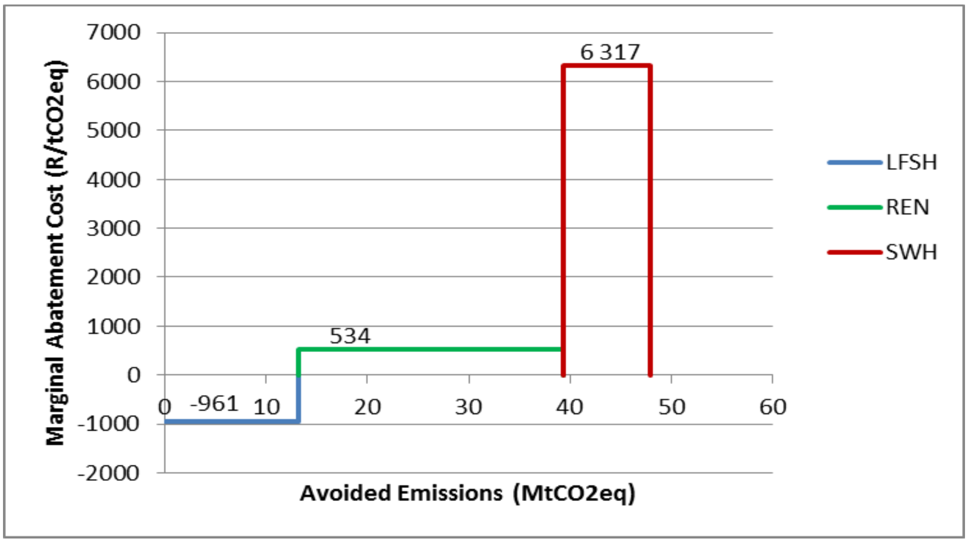

Figure 7: System wide impacts (RLS order)

CONCLUSIONS

Referring back to illustrative examples, each graph is distinct. The potentials and costs of the three mitigation actions that were used (LFSH, SWH and REN) changed dramatically with changing assumptions. Therefore there is no single MAC curve that can represent any two mitigation measures. The curves become even more complicated for interconnected systems such as the energy system. The emissions reduction potential on the supply side, affects the emissions reduction potential on the demand side. In systems such as the energy system, the order at which the mitigation actions are implemented matters because the ordering affects the emissions potential and how much the measure costs. If MAC curves are to be used for any policy-related decision-making, it is crucial for all stakeholders using the curves to be brought to the same understanding of what message the curves confer. The understanding of the curve goes hand in hand with understanding the assumptions that were used to construct the curves. For stakeholders' understanding these assumptions must be as explicit as possible. This explicitness will help with transparency and accountability, and the correct use of the curve is more likely. Without explicitness and understanding of the input assumptions, MAC curves must not be used in policy or planning processes.

A MAC curve can be useful if it is used with the understanding that it does not show how to abate, nor the economic impacts of abating. As Ekins et al. (2011) and Naucler et al. (2009) put it; MAC curves are useful as "a starting point for global discussion about how to reduce GHG emissions, showing the relative importance of different sectors, regions, and abatement measures."

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APPENDIX A: MODELLING ASSUMPTIONS

The emission factor is assumed to be 993 kgCO_2e/MWh. The cost of electricity produced using coal was assumed to be R420/MWh to the consumer and for electricity coming from renewables the cost was assumed to be 5 times more. The levelised cost of producing electricity from coal was assumed to be R143/MWh.

MITIGATION	TECHNOLOGY COST	PENETRATION RATE
LFSH	200	10% annually
SWH	15000	10% annually
REN	7 000 000[2]	50% of electricity by 2020

[2] Total cost of producing electricity.