Bloomberg
NEW ENERGY FINANCE

14 January 2010

Carbon Markets – North America – Research Note

Contents

A fresh look at the costs of reducing US carbon emissions

New analysis from Bloomberg New Energy Finance on the cost of reducing CO2 emissions in the US shows that some previous estimates of abatement costs have probably been too optimistic. To achieve a 17% reduction on 2005 levels by 2020 entirely within the US would make use of some "early wins" in energy efficiency and land-based measures, but would then require more fundamental changes to the power and transport sectors. Overall however, the costs should be affordable and can further be reduced by the use of international offsets.

Marginal abatement cost (MAC) curves show the set of options available to an economy to achieve increasing levels of emission reductions. The MAC curve analysis in this report – developed from Bloomberg New Energy Finance's new Global Energy and Emissions Model (GE2M) – seeks to address shortcomings in previous MAC studies by developing a methodology which directly links abatement potential to projections of emissions, and which explicitly shows the effect of how the private sector views and invests in energy saving measures. It also uses Bloomberg New Energy Finance's in depth knowledge of clean energy and low carbon technologies.

The study has been funded and conducted entirely by Bloomberg New Energy Finance over the course of 2009 with data drawn from hundreds of sources. Studies such as this can always be improved with more detailed data collection and modelling, and we will be looking to enhance our modelling of specific areas in 2010. However we believe this analysis sheds new and important light on the potential of the US to reduce its carbon emissions. In particular the analysis finds:

- **When assessing the potential of the US economy to limit carbon emissions, clarity of methodology is vital.** In particular it is critical that any presentation of a MAC curve is explicitly linked to a corresponding emissions projection. Different assumptions about what is included in the emissions projection produce different MAC curves. For example, adjusting the curves to reflect private sector risks and constraints (leading to shorter investment horizons) shows less abatement potential than one created from the perspective of society as a whole.
- **US carbon emissions will decrease slightly by 2030 if current trends continue and existing policies are implemented as expected.** Increased emissions from economic growth will be offset by improvements in energy efficiency, and, to a limited extent, by renewable portfolio standards (RPS) and vehicle efficiency standards (CAFE). Without the RPS and CAFE standards, 2030 emission levels will be broadly equal to 2007 levels (6.1Gt). With these policies, 2030 emissions will be 0.2Gt lower at 5.9Gt, 3.7% below 2007 levels and 2.0% below 2005 levels.
- **While significant cost effective abatement potential exists in the US, much of this is likely to happen anyway, without the need for additional policy intervention.** Previous MAC studies have suggested that a large amount of abatement potential can be captured by exploiting cost effective (negative cost) abatement opportunities such as efficiency technologies for cars, light bulbs, and building insulation. Our analysis shows that much of this negative cost abatement is likely to occur regardless of policy as the economy continues on a trend of improving energy intensity. For example, 70% of abatement projected to occur as a result of the continuation of improving energy intensity consists of negative cost opportunities.

- **Energy efficiency and land-use projects will drive abatement in the early stage, but transformational technologies will be required in the long run.** Assuming that the cheapest abatement options are used first, the analysis shows that the US is likely to initially make use of low cost energy efficiency and land use change opportunities. However, to achieve emission reductions of 42% on 2005 levels by 2030 will require more fundamental changes to the power sector and commercialisation of Carbon Capture and Storage.

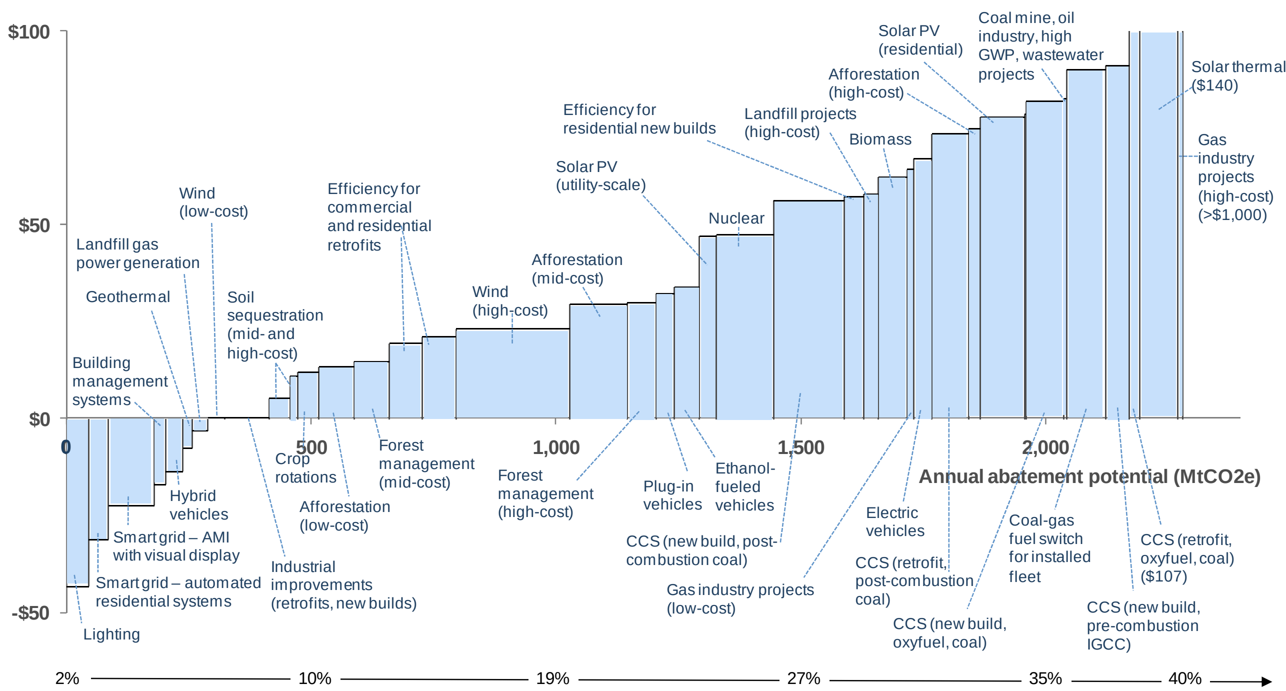
- **Using domestic abatement to achieve a 17% reduction on 2005 levels by 2020 would cost on average between $11/t and $25/t, with a carbon price of around $69/t.** From society's perspective meeting a 17% reduction from 2005 levels by 2020 (corresponding to a reduction from 6.0Gt to 5.0Gt) would cost on average around $11/t ($14/t in nominal terms). From the perspective of the private sector these costs are higher. Using private sector discount rates in key sectors, the average cost of meeting this target increases to around $25/t ($31/t in nominal terms). Under both perspectives the last unit of emissions reduced to achieve the 17% target (which in theory would set the price of carbon) would cost around $69/t ($86/t in nominal terms).

- **These costs can be significantly reduced by using international offsets.** The carbon prices suggested by this analysis ($69/t in 2020 in real terms) can be reduced by allowing the use of international offsets (low-cost abatement options from developing countries) in a US cap-and-trade programme. For comparison, Bloomberg New Energy Finance forecasts of carbon prices in 2020 under the Waxman-Markey bill (which includes a provision for international offsets) are around $19/t in real terms ($24/t in nominal terms) – a reduction of $50/t.

- **Even on the basis of these numbers, meeting a 17% reduction by 2020 could be considered affordable in the US.** With an average cost of around $11/t to $25/t the study shows that abatement could achieved without posing an insurmountable cost burden for the US economy. The cost of realizing a 17% reduction target by 2020 (and even a 30% reduction by 2030) is less than a dollar a day per US household. The analysis in this research is also relatively conservative. Steeper learning curves, more rapid exploitation of breakthrough technologies, and more radical shifts in consumer behaviour could drive costs even lower.

Figure 1: 2030 US MAC curve (accounting for improving carbon intensity, key recent policies, and sector-specific discount rates)

2009 $ / tCO2e



Source: Bloomberg New Energy Finance

1. Introduction

Marginal abatement cost (MAC) curves chart the set of options available to an economy to achieve increasing levels of emission reductions. They are valuable tools for driving forecasts of carbon allowance prices, prioritizing low-carbon investment opportunities, and shaping policy discussions around a national climate change strategy.

For example, carbon traders use MAC curves to derive the supply function for modelling carbon price fundamentals. Power companies may employ MAC curves to guide their decisions about long-term capital investment strategies to select among a variety of efficiency and generation options. Economists have used MAC curves to explain the economics of interregional carbon trading,[1] and policy-makers turn to MAC curves to show how much abatement an economy can afford and where policy should be directed to achieve the emission reductions.

Existing MAC curves for the US economy have already been influential in guiding the thinking of private- and public-sector decision-makers. Some of these analyses are by now out of date, while other more recent studies have taken a regional or sectoral focus. For example, ICF International, as well as Sweeney and Weyant, have presented MAC curves for the state of California in 2005 and 2008 respectively, while Wei and Rose developed MAC curves for Florida and states belonging to the Western Climate Initiative (WCI) in 2008.[2] Two years earlier, the EPA built MAC curves specific for sectors such as non-CO2 gases.[3] In addition, other MAC curves have been produced using interpolation of data points or computable general equilibrium (CGE) models.[4] These computational approaches draw on rich databases and may be able to accommodate sophisticated interaction effects such as energy price demand elasticities. However, their methodologies are typically opaque and they do not produce one final, easily understandable MAC curve tagged with distinct abatement categories.

Of the recent US MAC curve analyses, the most renowned has been the study published by the consulting firm McKinsey in 2007.[5] This study is comprehensive, simple to digest, and notable for some of its high-level findings, such as the claims that 3Gt of abatement may be achieved for less than $50/t or that half of this abatement could come at negative cost.

Yet this and other previous studies are also found wanting in some respects. Potential issues with MAC studies have included:

- no explicit connection is made between abatement options and the reference case: this makes it unclear what portion of the abatement curve – and especially what 'negative cost' portion of the curve – might be expected to occur regardless of the carbon policy in place
- they pay insufficient attention to the hidden and missing costs of investors' decision-making, resulting in abatement options that appear to be economically attractive but that are not adopted in practice
- they tend to oversimplify technologies ('one-size-fits-all') with a broad range of costs, resulting in 'lumpy', discontinuous MAC models which stray too far from the true abatement supply picture
- they present inaccurate estimates of the cost of the more advanced technologies, such as CCS and renewable energy.

The MAC curves presented in this report have two principal advantages. First, they follow a unique methodology, each step of which is explained below. In contrast with other studies, this methodology provides a clear link between the reference case and the incremental abatement options, and accounts for hidden and missing costs. Second, the MAC curves given here draw on Bloomberg New Energy Finance's experience with the energy industry and carbon markets. Specifically, the analyses employ our internal data on the costs and carbon intensities associated with a range of abatement options, from improved feed conversion for cattle to oxy-fuel combustion CCS retrofits on power plants. Furthermore, they draw on the company's in-house expertise on clean energy, CCS, nuclear energy, energy smart technologies, and carbon markets.

[1] See, for example: Ellerman, A.D. and Decaux, A., *Analysis of post-Kyoto CO2 emissions trading using marginal abatement curves*, 1998.
[2] ICF International, *Emission reduction opportunities for non-CO2 greenhouse gases in California*, 2005; Sweeney, J. and Weyant, J., *Analysis of measures to meet the requirements of California's Assembly Bill 32*, 2008; Wei, D. and Rose, A., *Preliminary cap and trade simulation of Florida joining WCI*, 2008.
[3] EPA, *Global mitigation of non-CO2 greenhouse gases*, 2006.
[4] See Ellerman and Decaux, op.cit.; Klepper, G. and Peterson, S., *Marginal abatement cost curves in general equilibrium: the influence of world energy prices*, 2005; and Laitner, J.A., *The positive economics of climate change policies: what the historical evidence can tell us*, 2009. Laitner, in particular, identifies important drawbacks of traditional CGE models.
[5] McKinsey, *Reducing U.S. greenhouse gas emissions: how much at what cost?*, 2007

Section 2 of the report defines the reference case. For the emissions expected to occur under business-as-usual (BAU) conditions, three scenarios are presented and compared. Section 3 explains how the MAC curve is created, by describing the methodology used to quantify abatement and by developing four MAC curves, corresponding to different BAU scenarios and discount rate assumptions. This section also explores the cost distributions and abatement themes in the 2020 and 2030 MAC curves. Section 4 presents conclusions emerging from the MAC curves and implications for policy-makers and investors. While the body of the report looks at the MAC curve in aggregate (focusing on the methodology used to produce the curve and the implications that flow from the analysis), the Appendix of the report provides further analysis and explanation of methodology and data sources used to derive sector-specific abatement quantification.

2. The reference case – what is business as usual?

2.1. Methodology

Before defining the amount and cost of abatement that can be achieved in an economy, the reference case, or business-as-usual (BAU), emission projection must be defined. Alternative MAC curve analyses have tended to pay minimal attention to this step. Unless the construction of the BAU is completely transparent and directly linked to the MAC curve, the analysis on its own is impossible to interpret meaningfully. For example, if the BAU projection is conservative in its expected use of energy saving measures, the corresponding MAC will look more optimistic and vice-versa.

This section of the report defines three scenarios for BAU. These scenarios are summarized in Table 1 and elaborated on below. Section 3 below presents MAC curves corresponding to each scenario.

Table 1: Summary of BAU scenarios

	Carbon intensity		Policy effects	
BAU scenario	Static (2007-2030 at 2007 levels)	Sector-specific historical trends (1990-2007)	Existing policies that have started to affect emissions	RPS and CAFE
1. Static carbon intensity	✓			
2. Improving carbon intensity		✓	✓	
3. Key recent policies		✓	✓	✓

Source: Bloomberg New Energy Finance

BAU scenario 1: Static carbon intensity

The first BAU scenario builds emissions growth projections assuming pure economic growth with carbon intensity fixed at 2007 levels. This scenario therefore shows how emissions would grow in the US economy if there were no further improvements in energy efficiency. The corresponding MAC curve (see Section 3) would therefore include all abatement options that would be deployed simply as a matter of course as the economy changes and becomes more efficient in its use of energy and resources, as well as those that would be implemented as a result of policy intervention.

The economy comprises six emissions-producing sectors: land-use, buildings, industry, power, transport, and waste/fugitives/high global warming potential (GWP) gases. For each sector, an underlying growth driver is identified (eg, electricity sales for power sector emissions, industrial output for industry sector emissions). The values of these drivers in 2030 are estimated by using 2007 values and projected growth rates (2007–30) of those drivers.

Carbon intensity is defined as the ratio of a sector's CO2e emissions versus the value of that sector's underlying driver (eg, tCO2e/tons of industrial output). Projected 2030 emissions in this scenario are thus the product of (i) projected 2030 values of the sector's underlying growth driver, and (ii) the carbon intensity in 2007 for that sector. This approach also takes into account the changing structure of the economy over time, for example with the relative decrease in the share of the (more carbon intensive) manufacturing sector.

BAU scenario 2: Improving carbon intensity

The purpose of this scenario is to show how actual emissions are likely to evolve in the US without additional policy intervention. In this scenario, the same underlying economic growth projections are assumed as in the first scenario, but future carbon intensity is assumed to evolve based on sector-specific historical trends (1990–2007).

This includes the effects of natural trends that change the carbon intensity of the economy through technical improvements in energy efficiency. It also includes the effects of existing policies that have started to affect emissions – such as lighting efficiency standards in the Energy Independence and Security Act of 2007 (EISA2007) and refrigerator efficiency standards at both federal and state level.

Over the past 17 years these factors have reduced the carbon intensity of the US economy by 26%.[6] In the model, the trends at the sector level are assumed to continue at the same rate to 2030.

[6] EIA, 2008. Carbon intensity measured as metric tons of carbon dioxide per GDP (real 2000 $).

For the power sector, one other element of variability is introduced in this scenario: the projected growth in electricity demand is lowered to reflect a trend of gradually declining demand growth. In the previous BAU scenario, the analysis assumes a projected growth rate equal to the average growth rate of the past five years. In this scenario, the analysis follows the Energy Information Administration's (EIA) guidance for projected growth rate to 2030, as these projections incorporate the effect of historically declining demand growth. (Changing only the carbon intensity would just capture the trend of increasingly cleaner power – eg, lower tCO_2e/MWh – while neglecting the trend of increasingly efficient end-user demand.)

BAU scenario 3: Key recent policies

The final adjustment made to the BAU emission projections is to take into account the incremental abatement that is expected to occur as a result of key policies that are a departure from previous policy initiatives and the effects of which would not show up in historical trends. Specifically, this includes the Renewable Portfolio Standards (RPS) to promote adoption of renewable energy and the Corporate Average Fuel Economy (CAFE) to encourage improved efficiency in cars and light trucks.

Quantifying the incremental abatement effects of RPS involves projecting the renewable build that is expected to be driven by these standards. The next step is to subtract the renewable build that may have occurred regardless of these standards as low-cost renewable energy sources become competitive with conventional power sources. Similarly, quantifying the incremental abatement effects of CAFE involves projecting the evolution of a more efficient vehicle fleet as required by this policy and subtracting the improvements to vehicle efficiency that would have occurred regardless of these regulations as the automotive sector follows historical trends of producing more efficient engines.

The resulting BAU projection provides an emissions estimate that is most likely to occur taking into account all existing technical and economic trends, and policies currently in place. The corresponding MAC curve therefore shows the range of carbon abatement options actually available to policy makers going forward.

2.2. Assumptions for underlying emission projections

Table 2 shows the inputs underlying the sectoral emission projections. For most sectors, the projected annual growth rate of the underlying driver is positive, as the growing US economy and population will require more electricity, cars, houses and food, and will produce more waste. On the other hand, the projected growth rate of carbon intensity for most sectors is negative, as companies and consumers pursue efficiency measures to contain costs. As a result of these inputs, in scenario 1, 2030 emissions will exceed 2007 emissions for most sectors, whereas in scenario 2, historically extrapolated efficiency improvements will outpace growth, so that emission levels for most sectors will decline between 2007 and 2030.

Table 2: Inputs used to generate 2030 BAU emissions scenarios

Sector	Emissions driver	Projected annual growth rate (2007–30)	Projected growth rate of carbon intensity (2007–30)
Power	Electricity sales	1.35% or 1.02	–0.22%
Transport	GDP and oil price	0.69%	–1.11%
Industry	Industrial output	–0.70%	–0.08%
Waste /fugitives /high GWP	Landfill waste, fuel production, industrial output	0.53%	–2.10%
Buildings	Residential dwellings, commercial space	0.90% residential, 0.20% commercial	–0.91% residential, –0.50% commercial
Land use – agriculture	Food expenditures	1.14%	–1.74%
Land use – forestry	Forestry BAU emissions not based on growth of emissions driver but rather kept as constant of historical average from 1990 to 2007	0%	0%
US territories	Analysis assumes zero abatement, and constant emissions, from US territories	n.a.	n.a.

Sources: Bloomberg New Energy Finance, EIA, EPA, Bureau of Economic Analysis, Department of Transportation, USDA Economic Research Service, BP Statistical Review of World Energy. Notes: Carbon intensity generally measured as tCO_2e per unit of the applicable driver for that sub-sector's emissions (e.g. tCO_2e / tCement). Projected growth rate in carbon intensity is assumed to equal historical growth rate in carbon intensity from 1990 to 2007 (except in certain cases where most recent accurate end point data is from 2002).

With regard to specific sectors, electricity demand growth in the power sector is modelled using two growth rates. The static carbon intensity scenario assumes 1.35% growth rate, corresponding to the five-year average of the electricity demand growth rate (2003-2007). In the improving carbon intensity scenario, 1.02% is employed, corresponding to the EIA's electricity demand projections which incorporate the effects of improved demand-side efficiency. Yet even in this improved carbon intensity scenario, electricity demand growth is expected to outstrip the rate of change of increasingly cleaner power generation. This only extrapolates the historic trend in carbon intensity improvements. Going forward the decline may be faster as the sector's focus shifts towards renewable energy, gas, and potentially nuclear.

The transport sector has made sustained improvements in efficiency which are expected to continue over the coming decades. Energy use per passenger-mile has decreased by 2% annually for aviation and by 0.6% for road transport since 1960 according to the Bureau of Transportation Statistics. Carbon intensity declined in parallel, with a 2.4%/year decrease for aviation from 1990 to 2007 and 0.8%/year for road transport.

The industrial sector is expected to experience the combined effects of depressed domestic economic growth prospects and continued efficiency investments. The projected output growth figure of -0.70% is a weighted average of the growth projections for the cement, iron and steel, aluminum, chemicals, refineries, and paper industries. Output from the iron and steel, aluminum, chemicals, and refining industries are projected to fall from 2007 to 2030, and carbon intensities of the iron and steel, aluminum, and paper industries are also projected to decline, in line with historical trends since 1991.

The waste/fugitive/high GWP sector's emissions will be driven by declining carbon intensities for waste and declining carbon intensities for some fugitive sectors and decreased production for others. Overall, the sector is projected to grow at 0.53% per year, representing a weighted average of the following categories: municipal solid waste going to landfills (waste); natural gas, coal, and petroleum production (fugitives); and refrigerator, aluminum, and semiconductor manufacturing output (high GWP). Carbon intensity of landfill waste has fallen by 1.9% annually since 1990, and this trend is expected to continue through 2030. Fugitive emissions result from the production of natural gas, coal mining, and petroleum. The carbon intensities from production of natural gas and coal mining have fallen by 1.6% and 2.8% annually, respectively. Petroleum production has actually experienced a slight increase in carbon intensity, but production has dropped from 8.9 million barrels of oil per year in 1990 to 6.8 million barrels in 2007. High GWP emissions are associated with the production of HCFC-22, magnesium, aluminium, and semiconductors. Semiconductor manufacturing has decreased since 1990, and carbon intensities of production associated with HCFC-22 and aluminium have each decreased by greater than 7% annually.

For buildings, efficiency improvements will more than offset population growth, following historical trends. Residential and commercial buildings have become more efficient since 1990, with carbon intensity dropping from 3.6tCO2e to 3.1tCO2e per residential building and from 0.037tCO2e to 0.034tCO2e per square meter of commercial building.

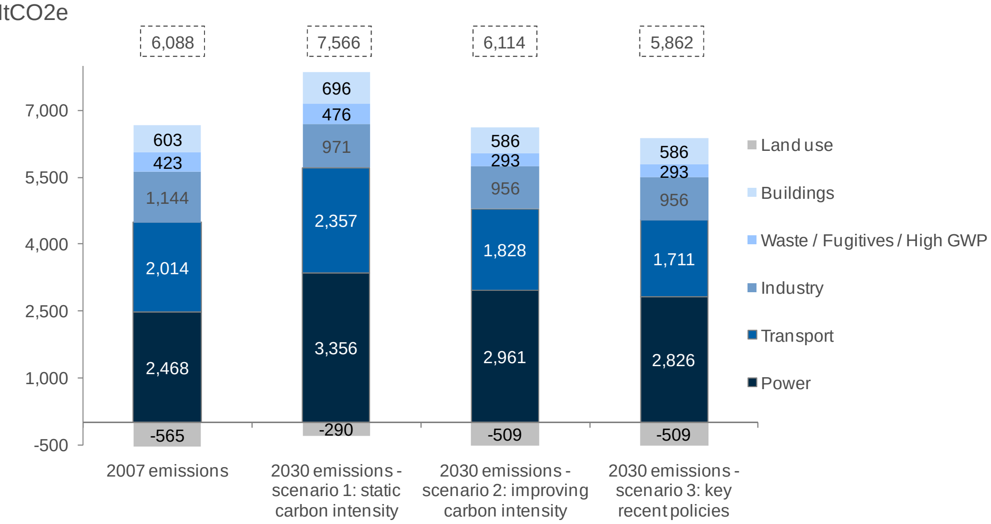
The land-use sector, a net carbon sink, will continue to adopt increasingly efficient agricultural practices. Carbon intensity in this industry – measured here as the ratio of agriculture emissions to volume of US food expenditures – has decreased by 1.7%/year. This is likely the result of cost-effective abatement measures such as low-cost conservation tillage and anaerobic digesters.

2.3. BAU emission projections

Figure 2 shows emissions for 2007 and for each BAU scenario in 2030 by sector. In scenario 1, for all sectors except industry, emissions increase between 2007 and 2030 as a result of economic growth. In scenario 2, emissions decline from 2007 to 2030 for all sectors except power – the only sector for which growth rate effects are expected to exceed efficiency improvements. Between scenarios 2 and 3, two sectors have slightly lower emission figures: the power sector as a result of RPS policy and the transport sector as a result of CAFE policy.

Figure 2: BAU emissions by sector

MtCO2e

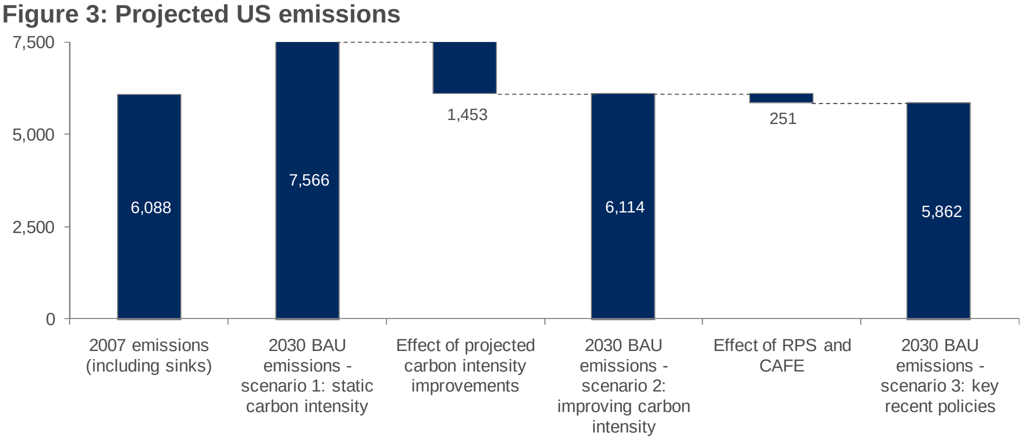


Source: Bloomberg New Energy Finance Note: Values in dashed boxes represent column totals. Totals shown here include emissions from U.S. Territories, which are assumed to stay constant (58Mt) to 2007 values.

Figure 3 shows projected BAU emissions as a snapshot in 2030 with aggregate values for each scenario. Pure growth would bring 2030 emissions to 7.6GtCO2e. Under BAU as a result of carbon intensity and efficiency improvements, abatement of 1.5Gt is expected. An additional 0.3Gt that would not otherwise have been abated will be driven by existing policy. Final 2030 projected emissions therefore amount to 5.9Gt.

The 0.3Gt value does not mean that the impact of the RPS and CAFE is limited to this quantity of abatement. Indeed, some of the effects of RPS and CAFE are also incorporated into the second BAU scenario, which captures the gradually cleaner profile of power generation and the gradually improved carbon intensity of road transport. As such, the 0.3Gt figure only represents the incremental abatement that is not otherwise captured in the 'improving carbon intensity' scenario. Nevertheless, this 0.3Gt represents only 4% of 'pre-policy' BAU emissions, demonstrating that current policy is playing only a limited role in driving *incremental* emission reductions.

Figure 3: Projected US emissions

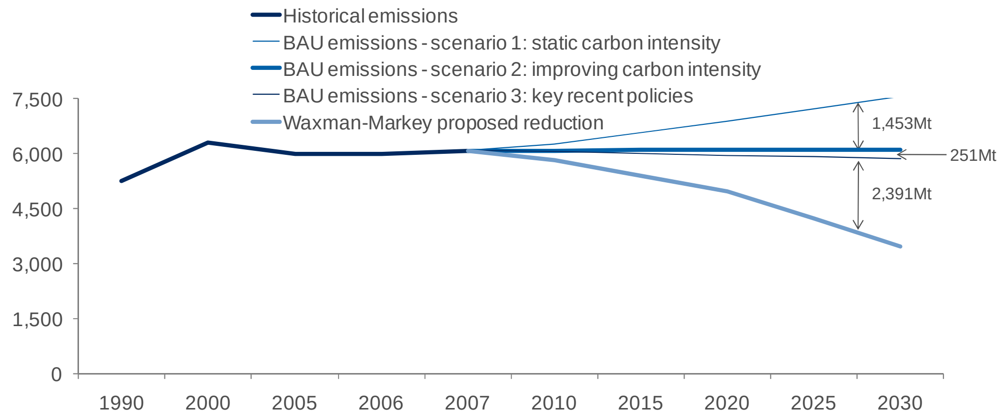


Source: Bloomberg New Energy Finance

Figure 4 shows US historical and projected emissions based on the methodology outlined above. The projections are contrasted with the emissions track proposed in the Waxman-Markey bill, which calls for a 17% reduction from 2005 levels by 2020 and a 42% reduction by 2030.[7] Our projections show that, without the RPS and CAFE standards, 2030 emission levels will be broadly equal to 2007 levels (6.1Gt). With these policies, 2030 emissions will be 0.2Gt lower at 5.9Gt, 3.7% below 2007 levels and 2.0% below 2005 levels. Yet neither the improving carbon intensity trends nor these key recent policies will be sufficient to drive the significant reductions comparable with those proposed in House legislation.

Figure 4: Historic and projected US emissions

MtCO2e



Source: Bloomberg New Energy Finance

[7] These reductions applied to covered sectors only, which represent 85% of emissions, yet other measures in the bill, such as direct regulation of some non-covered sectors, suggest that the 17% and 42% figures can be intended to be economy-wide targets.

3. Creating the US abatement cost curve

3.1. Abatement summary and calculation methodology

A summary of the options that could reduce carbon emissions in the US is shown in Figure 5. In total, the analysis includes over 2,000 abatement options covering all sectors of the economy. It focuses on available abatement measures that are, or could be, deployed at scale, and excludes measures that rely on technologies that have not yet entered the market. This approach has been taken to make the analysis a practical tool for decision-making today about long-term applicable solutions. It also excludes measures involving behavioural change, since quantifying the costs and potential of these essentially limitless opportunities would rely too heavily on assumptions.

Figure 5: Abatement option summary

	Abatement options	Data sources and methodology notes
Land use	• Soil sequestration and crop rotation • Livestock practices • Afforestation and forest management	• U.S. EPA, U.S.D.A., Winrock forestry data • Agriculture and forestry ramped-up to reflect realistic potential • Soil sequestration costs based on recent Bloomberg New Energy Finance agriculture research
Buildings	• Heating • Insulation { • Residential new builds and retrofits • Commercial new builds and retrofits }	• U.S. EIA residential and commercial survey, Energy Saving Trust • 100 potential building classes, employing combinations of 30 heating and insulation technologies
Industrials	• Process improvements • Fuel mix • CCS { • Cement • Steel • Refineries • Paper • Pulp • Ammonia }	• U.S. EIA, BEA, IEA, Oil and Gas Journal, European cement and steel groups, academic and national lab research on industrial technologies • 3-10 technologies per sector, with corresponding CAPEX, fuel mix, and carbon intensities
Power	• Renewables • Nuclear • CCS • Short-term and long-term fuel switching • Smart grid, electronics, appliances, lighting	• U.S. EIA, NREL, Platts, academic and government nuclear reports • Costs and abatement potential provided by Bloomberg New Energy Finance Lead Analysts for Clean Energy, Nuclear, CCS, Digital Energy • Fuel switching potential generated from Bloomberg New Energy Finance North American Carbon Model
Transport	• LDV fuel efficiency • Ethanol • Advanced ICE • Hybrids, plug-ins, electric vehicles	• U.S. EIA, EPA, Department of Transportation, IEA , national lab research • Vehicle mix and weighted average mpg figures for fuel efficiency based on new CAFE standards
Waste / Fugitives	• Gas, oil, coal mine, landfill abatement • High GWP (HFC, PFC, SF6) abatement	• U.S. EPA • Figures adjusted to reflect realistic, rather than technical, potential
>2,000 abatement options evaluated		

Source: Bloomberg New Energy Finance

The data sources for the analysis include government, industry and academic reports, including:

- land-use surveys and greenhouse gas inventories (Winrock and EPA)
- building efficiency analyses (EIA, Energy Saving Trust)
- industrial technology cost analyses (IEA, industry trade journals, academic research)
- energy consumption surveys and household electricity reports (EIA)
- renewable energy resource potential estimates (NREL)
- power plant databases (Platts)
- transport technology costs and trends reports (IEA, Argonne National Laboratory).

This report supplements these sources using research developed by Bloomberg New Energy Finance, including:

- land-use analyses to account for practical constraints of realizing the full technical abatement potential of agriculture and forestry opportunities
- analyses of costs and carbon intensities of building types, building efficiency technologies and industrial abatement technologies, including reports which produce MAC curves specific to the European industrial sector and consider the viability of CCS installations for these sectors
- levelized cost of energy models that compare the economics of renewable and conventional energy technologies
- bottom-up projections for nuclear build based on assessments of current applications submitted to the Nuclear Regulatory Commission
- a series of research efforts dedicated to understanding the capital and operating costs of CCS plants across each capture technology

- fuel-switching measurements derived by inputting scenarios of very low natural gas prices into Bloomberg New Energy Finance's North American Carbon Model (a proprietary application used to project emissions, abatement and carbon prices under a range of scenarios for federal or regional cap-and-trade programmes)
- capital and fuel cost comparisons for conventional versus biofuels-based transport.

The methodology for analyzing abatement generally follows the methodology used in Bloomberg New Energy Finance carbon models and Global Energy and Emissions Model (GE^2M).[8] Sectors are divided into classes (eg, 25 classes of cattle, 10 of petroleum refineries, 51 of residential buildings). The classes are distinguished by the types of technology employed – eg, one refinery class includes all the potential abatement options that could be adopted by a refinery, while another refinery class is an existing plant with no abatement underway. The abatement potential is a function of the penetration that can be achieved as low-abating classes evolve into high-abating classes.

In each case, the potential and cost of an abatement technology is calculated with reference to a substitute technology. The abatement potential is the amount of CO2e emissions avoided each year by using the new technology. A more efficient vehicle, for example, would require less gas per mile and therefore would emit less CO2 for the same number of miles travelled. The annual abatement potential is counted for each year that the original vehicle would have been on the road. The abatement cost ($ per ton of CO2e abated) is the net incremental cost of this new technology, given by the formula below:

$$\text{Abatement cost} = \frac{(\text{Annualized equivalent cost})_{\text{Abatement option}} - (\text{Annualized equivalent cost})_{\text{Reference}}}{(\text{CO2/year})_{\text{Reference}} - (\text{CO2/year})_{\text{Abatement option}}}$$

The *annualized equivalent cost* is the total cost (capital and operating costs) of the technology amortized over its useful life, taking into account financing costs.[9] The *CO2/year* is the average tCO2e reduced per year associated with the technology. In the case of the vehicle example, the annualized equivalent cost of abatement would include the capital cost of the more efficient vehicle (including a more expensive engine) amortized over the life of the vehicle, plus any net change in annual running costs, for example due to different maintenance requirements and the savings due to less gasoline required.

Measuring and amortizing costs requires assumptions about discount rates. This report develops MAC curves based on two discount rates. For one version of the MAC curve, we use a 'social discount rate': a financial concept used for cost–benefit analyses of public projects, this is a measure of society's valuation of the relative welfares of current versus future generations. We use a 6% real discount rate, slightly below the 7% used by the Office of Management and Budget, while recognizing that recent climate change research has used social discount rates as low as 0.1%[10]

For the other version of the MAC curve, we use a private discount rate that is specific to each sector, ranging from 6% for sectors with long time horizons to 40–50% for other sectors. It is through this adjustment of the discount rate that we account for the hidden and missing costs: raising the discount rate from 6% to much higher rates reflects the fact that homeowners and car buyers make economic decisions with short time horizons, and that industry executives typically make efficiency investment decisions based on very short payback periods (eg less than 2 yrs) and under the constraint of limited availability of capital.

The cost measurements also involve assumptions about the location and timing of the deployment of new technologies. For renewable energy technologies, the costs represent a weighted average of the varying costs associated with varying capacity factors of distinct locations. (A special case is made for wind, the renewable technology with the largest abatement potential; the MAC curve separates out three wind tiers, corresponding to different wind power speeds of distinct locations.) The waste/fugitive/high GWP and land-use sectors' abatement opportunities are also region-specific, based on EPA assessments of abatement opportunities by state.

[8] GE^2M integrates New Energy Finance's regional models to produce a global picture of energy and emission flows. This model is discussed further in Section 4 of this report.

[9] Costs exclude any policy-related costs or incentives, such as taxes, tax credits, or accelerated depreciation benefits, as these are regarded as transfer payments.

[10] Office of Management and Budget, Circular No. A-94; UK Treasury, *Stern review on the economics of climate change*, 2006. The debate about the social discount rate became prominent after the publication of the Stern Review. The most important critical analysis of the social discount rate concept, particularly as it is applied in the Stern Review, is found in Nordhaus, W. *A review of the* Stern review on the economics of climate change, 2007.

Finally we include effects of technology learning and economies of scale for those technologies expected to experience the most significant cost declines through 2030. Cost projections for renewable energy are based on Bloomberg New Energy Finance's levelized cost of energy models. These models examine the historical evolution of component prices and account for potential future resource constraints. Bloomberg New Energy Finance's CCS cost model projects the cost of the 'nth plant' (ie, the cost of a plant once CCS has reached a point of large-scale commercial deployment). We use these costs for the 2030 CCS cost figures, and work backwards to derive 2020 CCS costs assuming 2% annual cost decline, consistent with the range of cost declines for renewable energy. For hybrids, plug-ins, electric vehicles and ethanol-fuelled vehicles, 2020 and 2030 costs are derived from straight-line estimates based on research by Bloomberg New Energy Finance's biofuels and vehicles analysts.

3.2. Four MAC curves

As described in Section 2, it is possible to define BAU emission projections in several ways, depending on assumptions about what trends and policies are included. Each emission projection has a correspondingly different MAC curve. This section shows the MAC curves for the US associated with the three scenarios of the BAU emissions described in Section 2. We also show a fourth MAC curve that more accurately reflects the reality of how decisions on investing in abatement measures are actually made.

1) *MAC curve based on BAU scenario 1 – static carbon intensity*: this curve includes the full inventory of abatement options, including the abatement that would occur as the economy follows historical trends of improved efficiency. Costs for this curve are calculated using a 6% discount rate.
2) *MAC curve based on BAU scenario 2 – improving carbon intensity*: this curve excludes the abatement that is expected to occur as the economy pursues efficiency measures in line with historical trends. Costs for this curve are calculated using a 6% discount rate.
3) *MAC curve based on BAU scenario 3 – key recent policies*: having already excluded the abatement that occurs due to efficiency trends, this curve also excludes the incremental abatement that occurs as a result of RPS and CAFE policies. Costs for this curve are calculated using a 6% discount rate.
4) *MAC curve based on sector-specific discount rates:* this curve keeps the amount of abatement from the previous curve (MAC based on scenario 3) intact but shows a different cost picture, resulting from changing the discount rate to reflect investors' – rather than society's – perspective.

Scenario 1 MAC curve – static carbon intensity

The MAC curve produced in this scenario, shown in Figure 6, captures the full inventory of abatement options, including those which would occur as the economy follows historical trends of improved efficiency. This scenario shows 3.8Gt of abatement in 2030 at a cost of less than $143/t, of which several options should be highlighted:

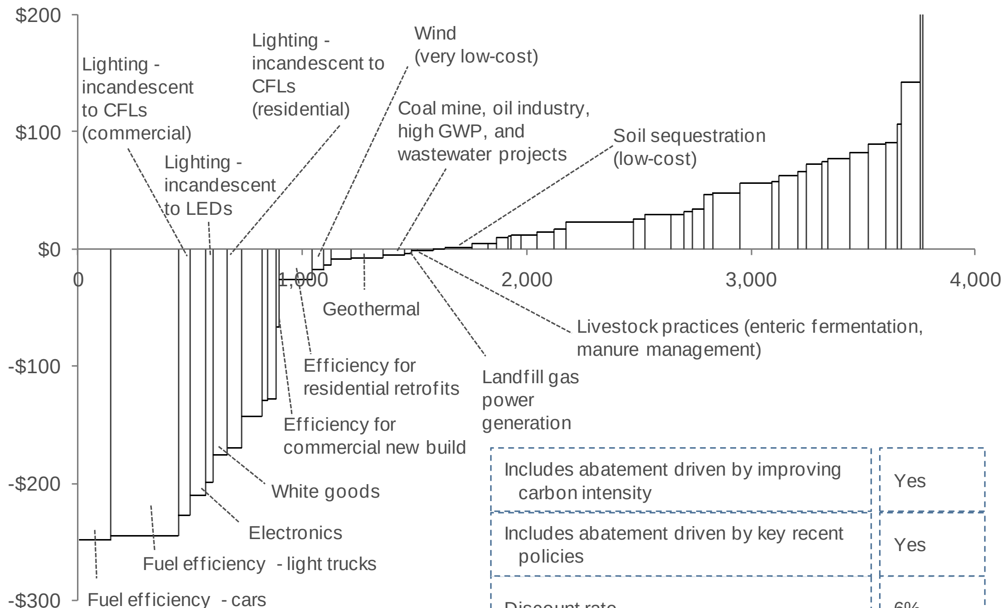
- *Vehicle fuel efficiency*: the widest negative-cost boxes correspond to the abatement options for fuel efficiency of cars (144Mt) and light trucks (300Mt) at a cost of –$240 to –$250/t. Although more efficient vehicles have higher capital costs, owners of these vehicles incur 40% lower fuel costs over the life of the vehicle. These net savings are responsible for the significantly negative abatement costs of these abatement options.
- *End-user electricity efficiency*: several other sizable options, with costs ranging from –$220/t to –$170/t, correspond to abatement resulting from changes in efficiency of end-user demand devices, including electronics, white goods, and especially lighting. Abatement from lighting includes transitions from incandescent to CFL, and from incandescent to LED, at the residential and commercial levels.
- *Building efficiency*: efficiency improvements to existing or new build structures account for 288Mt of potential abatement in this view. Improvements to existing residential structures make up the largest portion of this sector's abatement, with costs ranging from -$66/t to $0/t for commercial and -$25/t to $17/t for residential.
- *Clean power generation*: very low-cost renewable energy – especially wind, but also geothermal and landfill gas – is part of this scenario's abatement portfolio. Very low-cost wind has an abatement cost of -$16/t. Geothermal and landfill gas also have low negative costs.
- *Agriculture practices*: low-cost soil sequestration is a significant abatement opportunity (126Mt). Livestock practices largely have to do with containing emissions from cattle; the significant

technologies are enteric fermentation emission reduction methods (improved feed conversion, intensive rotational grazing, propionate precursors) and manure management (covered lagoons, complete-mix digesters).

- *Waste/fugitives/high GWP projects*: the chart highlights a set of projects in this sector linked to improved wastewater filtering; coal mine methane capture; improved operational efficiency in the oil industry; and reduction of HFC, PFC, and SF6. Together, these projects represent 102Mt of abatement at an average weighted cost of –$4.7/t.

This initial MAC curve is the starting point for the development of the other curves presented in this analysis, but it is important in its own right because it allows us to observe the full envelope of negative cost abatement potential.[11] The negative cost opportunity, according to this curve, is significant, totalling 1.6Gt of abatement potential, almost half of the full potential available in the curve. Yet, because these opportunities yield net savings, most of them are expected to be adopted even without any new legislation. The negative cost abatement potential is so large in this first MAC curve because it includes the myriad products that companies will make to offer their customers lower-cost goods (eg, efficient light bulbs, efficient cars) and the various processes that companies may adopt to lower the operating costs of their businesses (eg, low-cost power generation, NPV-positive soil sequestration).

Figure 6: 2030 US MAC curve based on BAU scenario 1 – static carbon intensity
2009 $ / tCO2e



Includes abatement driven by improving carbon intensity	Yes
Includes abatement driven by key recent policies	Yes
Discount rate	6%

Source: Bloomberg New Energy Finance

Scenario 2 MAC curve – improving carbon intensity

Transitioning from scenario 1 to scenario 2 eliminates the abatement that would occur as the economy adopts efficiency measures in line with historical trends. BAU scenario 1 represented the projected emissions due to economic growth, whereas scenario 2 took into account natural trends in improving energy efficiency and declining carbon intensity. This transition lowers the total abatement captured from 3.8Gt (scenario 1) to 2.5Gt by 2030 at a cost of less than $143/t (scenario 2).

This 1.3Gt reduction is allocated on a sector-specific basis, based on the following rule: the least-cost abatement options are removed from the MAC curve until the eliminated abatement from a particular sector matches the difference between that sector's emissions in BAU scenario 1 versus BAU scenario 2. For example, the difference between emissions in BAU scenario 1 versus scenario 2 for

[11] Negative costs are a controversial concept, as they would seem to suggest that no carbon price signal is necessary to justify the adoption of these measures. In reality, though, there will always be some measures which ostensibly make economic sense but which are just not done, partially because we have only a limited understanding of the full set of monetary and non-monetary costs (e.g. cost of inconvenience) that factor into investors' decision-making.

the land-use sector in 2030 is 217Mt. The MAC curve for scenario 2, therefore, excludes 217Mt of low-cost abatement options in the land-use sector.

Applying this rule to each sector eliminates some of the large abatement options present in the scenario 1 MAC curve:

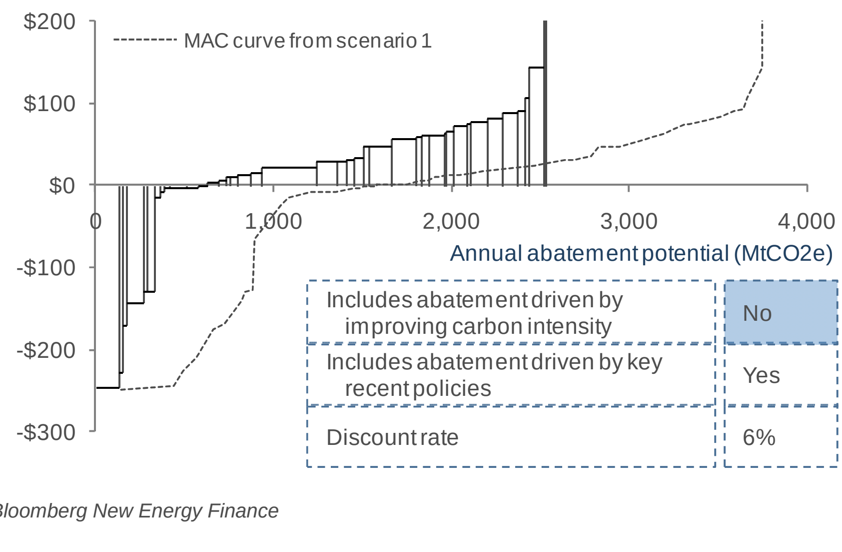
- *Vehicle fuel efficiency*: the majority of vehicle fuel efficiency abatement is expected to occur under BAU, in line with historical trends of improved efficiency for road transport.
- *End-user electricity efficiency*: lighting, electronics and white goods have historically experienced improvements in efficiency. The unit energy consumption of the average US refrigerator, for example, has declined by 2.9% annually since 1985 (some of which has been driven by the National Appliance Energy Conservation Act and state standards). Much of the projected abatement, then, will occur in line with historical trends.
- *Building efficiency*: 110Mt of building efficiency abatement is expected to occur under BAU, in line with building efficiency trends.
- *Clean power generation*: portions of cheap clean power generation are expected to arise under BAU, continuing the national power fleet's trend of –0.2% annual decrease in carbon intensity.
- *Agriculture practices*: low-cost agriculture abatement, in particular low-cost soil sequestration, will occur under BAU. Recent Bloomberg New Energy Finance research about the US agricultural sector has determined that 18% of US farmers practice no-till farming, which is already economically attractive for most farmers due to lower operating expenses and yield increases.[12]
- *Waste/fugitives/high GWP projects*: many of these projects are economically attractive without accounting for carbon and are expected to occur under BAU. Coal mine and high GWP abatement projects have negative costs (coal mine methane can be sold as fuel), and wastewater projects have roughly zero net cost.

Figure 7 shows the MAC curve based on BAU scenario 2, with the dashed line giving the curve from scenario 1. This scenario 2 curve shows the incremental abatement potential for the US economy beyond the abatement which would occur through natural economic and technological trends.

This view with the scenario 1 curve overlayed on the scenario 2 curve is useful for two reasons. One, it underscores an important theme of this report, which is that MAC curve definitions depend on assumptions about the BAU. Second, the scenario 2 curve displays the abatement potential that could be achieved by implementing policy. The difference between scenario 1 and scenario 2 defines abatement that will be driven by private-sector investments regardless of carbon policy, while the remaining curve presents the portfolio of options which policy-makers can choose to promote by implementing policy measures such as a cap-and-trade programme, efficiency standards, or renewable energy tax credits.

Figure 7: 2030 US MAC curve based on BAU scenario 2 – improving carbon intensity

2009 $ / tCO2e



Source: Bloomberg New Energy Finance

[12] New Energy Finance, *Carbon trading, what's in it for farmers?*, Nov 2009

Scenario 3 MAC curve – Key recent policies

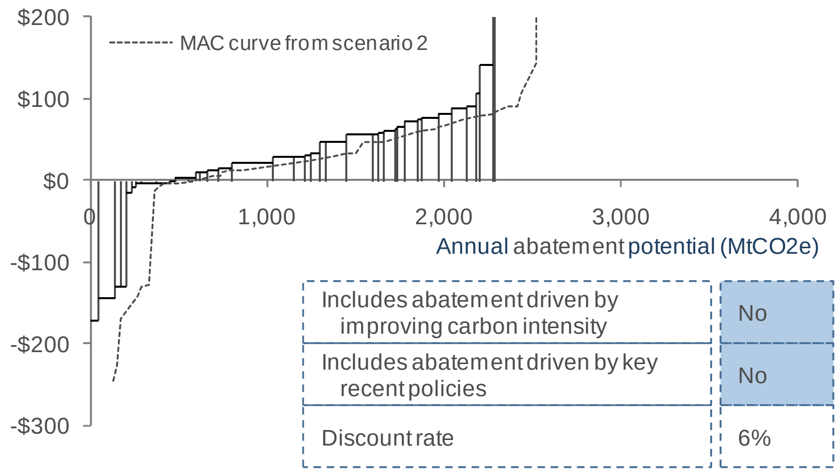
BAU scenario 3, as explained in Section 2, includes abatement driven by two key existing policies that would not be captured simply through historical trends – the RPS and CAFE standards.

Introducing these policies into the BAU projection eliminates 251Mt of abatement (Figure 8). The CAFE standards will ensure that the remaining opportunity for fuel efficiency (115Mt) will be captured, above and beyond the historic improvement of transport efficiency. State RPSs will mandate the build-out of 133GW of renewable energy, of which 99GW will be wind, as projected by Bloomberg New Energy Finance's Renewable Energy Credits (REC) Model. Some portion of this new build will have occurred regardless, in line with the power sector's gradual movement towards a cleaner fleet, as explained in scenario 2. The remaining abatement specifically as a result of RPS accounts for 136Mt; this is therefore eliminated. As a result, 2.3Gt of abatement potential in 2030 at a cost of less than $143/t remains.

This view highlights the relatively small effect of the RPS and CAFE policies compared to the trends that we would expect to occur anyway. Out of the 2.5Gt of potential incremental abatement that could be addressed through some form of policy by 2030, only 10% is expected to be implemented by these two regulations. Furthermore, the view demonstrates how these policies are somewhat selective, targeting only specific sectors and discrete portions of the MAC curve. More comprehensive policy would alter the curve. A cap-and-trade programme, for example, would absorb abatement from the left part of the curve, as compliant entities with low-cost abatement options at their disposal invest in these measures and sell their credits to entities which would only be able to invest in high-cost abatement options.

Figure 8: 2030 US MAC curve based on BAU scenario 3 – key recent policies

2009 $ / tCO2e



Source: Bloomberg New Energy Finance

Scenario 4 MAC curve – sector-specific discount rates

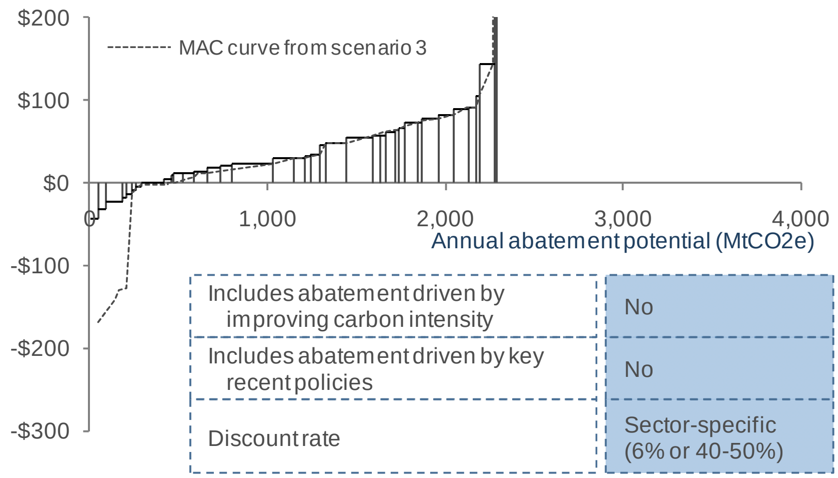
This scenario keeps the abatement potential of scenario 3, but changes the discount rates used to calculate the costs of abatement measures to reflect not society's perspective – but rather the perspective of investors undertaking these abatement measures in key sectors. The important net effect of this scenario is a curve with a much reduced negative cost abatement opportunity, as shown in Figure 9, where the dashed line is the curve produced in the previous scenario.

For industry, a 50% discount rate is used, as the industrial sector often faces constraints on the availability of capital and tends to use payback periods rather than net present value to evaluate investment decisions. Previous analyses have shown that energy savings projects adopted by small and medium US enterprises had an average projected payback of 1.1 years, underscoring the short payback period required of efficiency investments. The 50% discount rate corresponds to a two-year payback period and captures this important characteristic.

For efficiency improvements related to buildings (eg, insulation retrofits), demand-side power use (eg, residential smart grid equipment), and transport, a 40% discount rate is employed, aligned with the 2–3-year payback period implicitly employed by homeowners and car buyers. In each case, raising the discount rate reflects an understanding of the limited capital availability and opportunity costs faced by these decision-makers.

For all other sectors (agriculture, forestry, power generation, and waste/fugitive/high GWP), costs are kept the same, reflecting the longer-term view adopted by decision-makers in these sectors. With these adjustments, the height of most of the remaining negative cost boxes, and some of the positive cost boxes, is reduced. Scenario 4, then, represents what we consider to be the best perspective on the US MAC curve.

Figure 9: 2030 US MAC curve based on scenario 4 – accounting for improving carbon intensity, key recent policies, and sector-specific discount rate adjustments
2009 $ / tCO2e



Source: Bloomberg New Energy Finance

3.3. Exploring the 2030 US MAC curve

The 2030 MAC curve as derived from scenario 4 is shown in more detail in Figure 10.

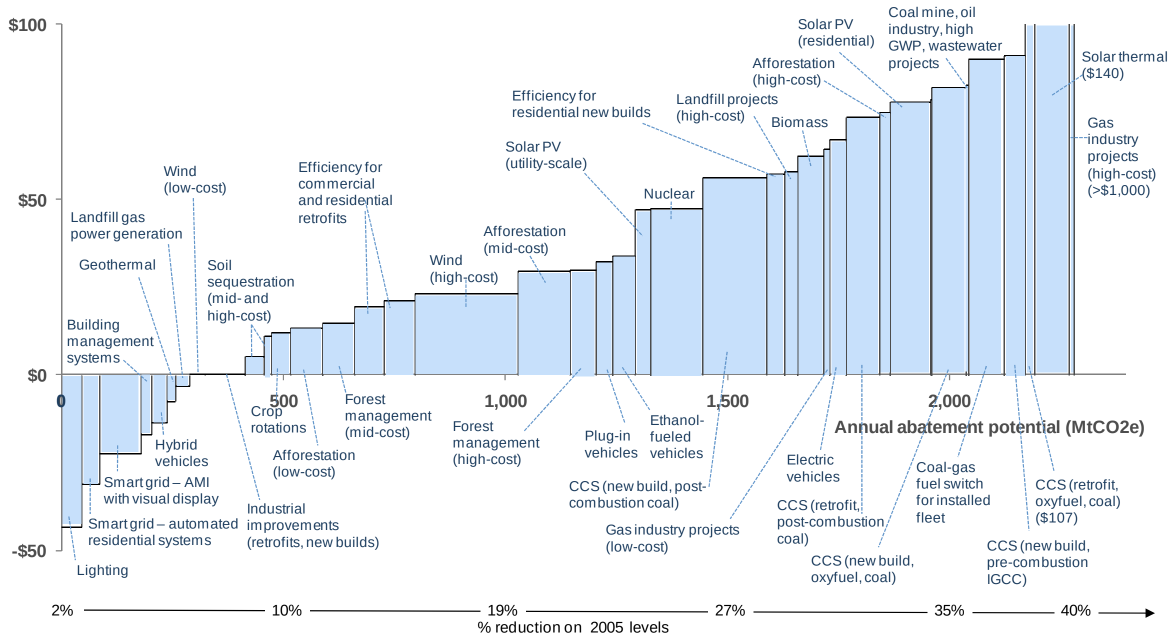
The analysis captures 2.3Gt of annual abatement potential by 2030 at a cost of less than $143/t. The bottom of the diagram shows the gradual percentage reduction on 2005 BAU emissions, before accounting for the effects of RPS and CAFE. These policies would produce an incremental 2% reduction, and each additional 500Mt of abatement would lower the reference case by an additional 8%.

The curve presents the cost distribution of abatement: 1.4Gt of abatement will involve a cost less than $50/t of which 290Mt (13%) is cost-effective even without a carbon price and accounting for short payback periods. 730Mt (32%) incurs a cost of less than $20/t, roughly corresponding to the prevailing price of allowances in the EU ETS today, and almost all of it (2.2Gt) would incur a cost less than $100/t. Drawing a straight line from the 290Mt mark to the 2.2Gt mark, as the price rises from zero to nearly $100/t, shows a slope of 21. As such, on average, each dollar increase on the carbon price theoretically makes roughly 20Mt of incremental abatement economical.

Two sectors account for almost 80% of the abatement potential: land use (19% of the 2.3Gt of total abatement potential) and power (59%), but no single option stands out. CCS is the largest abatement option (16%), but even this abatement category consists of a multitude of options, spread across retrofits and new builds, and segmented into post-combustion, oxy-fuel combustion, and pre-combustion applications.

Figure 10: 2030 US MAC curve (scenario 4 – accounting for improving carbon intensity, key recent policies, and sector-specific discount rate adjustments)

2009 $ / tCO2e



Source: Bloomberg New Energy Finance

The 2030 MAC curve can be further characterized by dividing the abatement options into four cost bands, with a key theme corresponding to each band.

1) Efficiency band (–$43 to $0/t)

This band features options concerning lighting, smart grid, and building management systems, which appear to make economic sense regardless of a carbon price. To some extent, they have been or will be initiated without a carbon market, but the promise of a carbon price (ie, avoided carbon cost) may be just the tipping point required to overcome investors' inertia in implementing these measures.

Importantly, while this band presents compelling investment opportunities, it only accounts for 13% of the final abatement curve. This is because many of the abatement opportunities that would have otherwise fallen into this band are expected to be adopted by the economy regardless of carbon policy, as per BAU scenario 2. The relative scarcity of negative cost abatement is an important source of differentiation between this MAC curve and previous analyses which have identified a wide band of negative abatement opportunities.

2) Land-use band ($0 to $15/t)

A cluster of abatement options concerning land use fall within a band that ranges from $0 to $15. 66% of abatement in this band relates to agriculture or forestry, including medium- and high-cost soil sequestration (either through conservation tillage or fertilizer management); crop rotations (including winter cover crops); low-cost afforestation; and medium-cost forest management (low-cost forest management is expected to occur under BAU). Agriculture and forestry projects, as evident from this analysis, could deliver abatement at far lower cost than many covered sector abatement options. This explains why the admissibility and governance of these projects as domestic offset opportunities have become such critical points in Senate negotiations for a federal US cap-and-trade programme.

3) Transformational technologies band I ($15 to $50/t)

In this band sit several power generation and transport technologies that have received significant investor attention over the past decade – propelled by a combination of venture capital backing, government stimulus funding, and government loan guarantees – and are now at the point, or on the brink, of wide-scale commercialization and adoption. They include 'high-cost' wind (ie, wind farms in areas with mean wind speed less than 7.0m/s), plug-in vehicles, ethanol-fuelled vehicles, and utility-scale solar photovoltaics (PV). Nuclear energy also falls within this band, which, in terms of new build, has been a largely dormant industry for the past 30 years.

4) Transformational technologies band II (>$50/t)

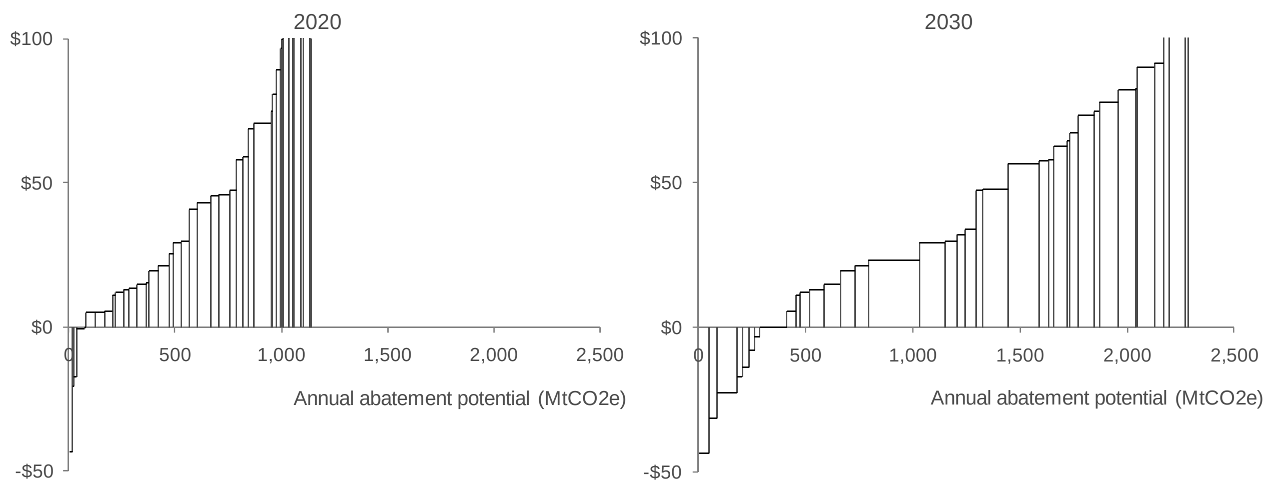
At an abatement cost above $50/t, CCS proliferates, accounting for 44% of the abatement potential above this price. Other abatement options in this band tend to be more expensive versions of abatement technologies seen at lower price points, including high-cost waste and fugitive projects, higher cost solar energy, and electric vehicles.

3.4. The shorter-term MAC curve: 2020

The 2020 MAC curve is naturally steeper and more compressed than the 2030 curve (Figure 11) showing fewer abatement options – 1.1Gt compared with 2.3Gt. Additionally, most abatement options are expected to be more costly, in real terms, in the former as the 2030 case has incorporated the economic benefits achieved through learning curves and economies of scale. Yet the cost distributions, on a percentage basis, are comparable. In 2030, 1.4Gt – or 63% of abatement potential – incurs a cost of less than $50/t, while in 2020, 790Mt – or 69% – fall under this cost.

Figure 11: Comparison of 2020 vs. 2030 US MAC curves (scenario 4)

2009 $ / tCO2e



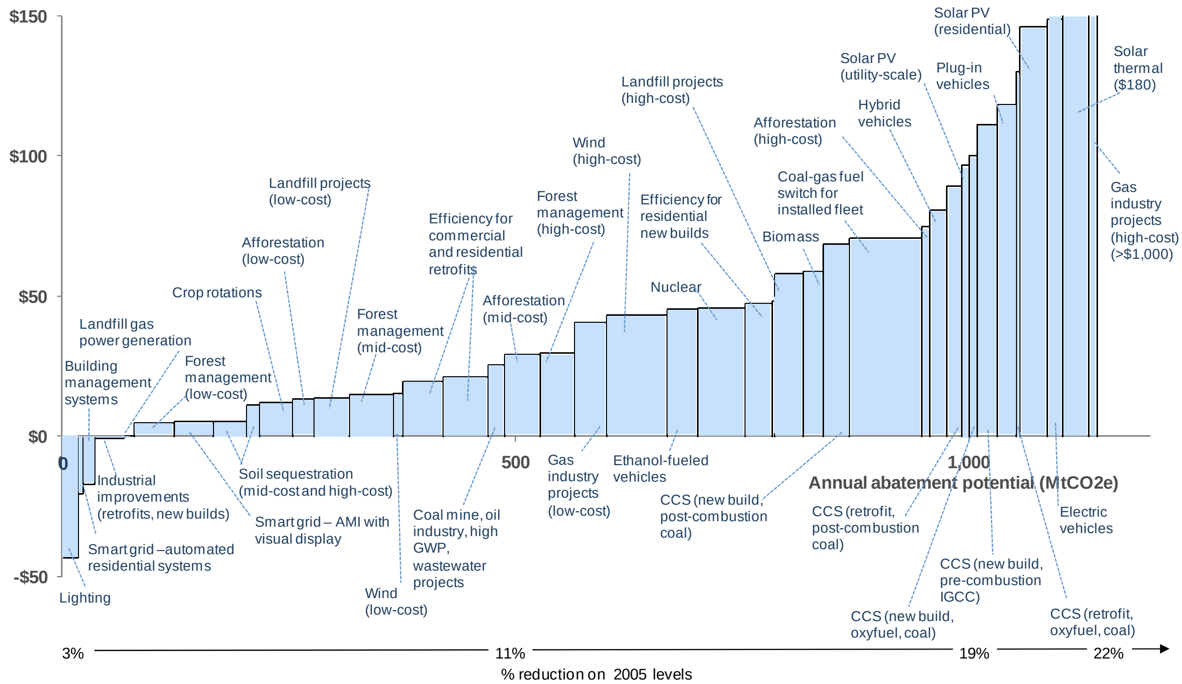
Source: Bloomberg New Energy Finance

A magnified view of the 2020 MAC curve for the US, as per scenario 4 in the methodology, is shown in Figure 12. The 2020 MAC curve has several important key characteristics.

- *Incomplete exploitation of land-use abatement opportunities*: the analysis of land-use-related opportunities includes a ramp-up factor that bridges existing practical potential with technical potential. Given projected rates of adoption by land-use constituents such as farmers, the abatement potential is projected to grow each year towards its technical potential.
- *Solar energy remains highly expensive*: solar energy is currently far from competitive compared with conventional power on a levelized cost basis, with coal and gas at $57-$59/MWh, and solar at $215-$285/MWh for PV and $254/MWh for solar thermal. With rapidly declining costs (led by a high rate of decline in module prices in the case of solar PV), solar energy will eventually become more competitive. Yet by 2020, the cost decreases will only have brought solar to a range of $97–$175/t, compared with $47–$143/t in 2030.
- *Narrower scope for blockbuster technology*: CCS, the most highly represented technology in 2030, accounts for only 7% in 2020. The injection dates for the first large-scale CCS demonstration projects are scheduled for 2013-5. Projections in the 2030 MAC curve assume that these demonstrations successfully meet cost targets and assuage safety concerns. Only then would the coal industry evolve towards a more mainstream adoption of this technology.
- *The 2030 curve captures some cost reversals compared with 2020*: two abatement opportunities – smart grid AMI systems with visual display, and hybrid vehicles – which appear below the x-axis in 2030 have a positive abatement cost in 2020. Projected declines in capital costs are responsible for this effect.

Figure 12: 2020 US MAC curve (scenario 4 – accounting for improving carbon intensity, key recent policies, and sector-specific discount rate adjustments)

2009 $ / tCO2e



Source: Bloomberg New Energy Finance

At a more general level, the contrast between the 2020 and 2030 MAC curves can be summarized by comparing their sector distributions, as shown in Figure 13 and Figure 14. In both cases, power generation is the primary contributor, but it accounts for a larger proportion in 2030, when big technologies such as wind, solar, CCS and nuclear energy have achieved much wider scale. On a percentage basis, the roles of waste / fugitive / high GWP projects, and of agricultural soil projects, decline as their ramp-up is not as significant as the expected growth of other abatement measures.

Figure 13: Sector distribution in 2020 MAC curve

% of annual abatement potential

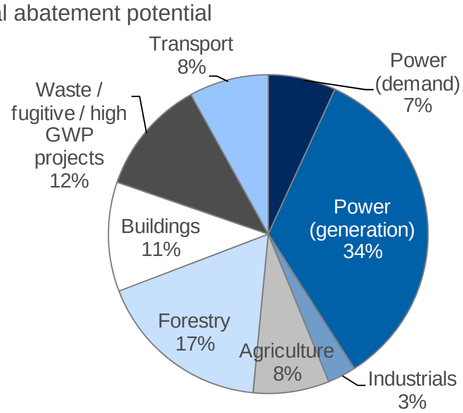
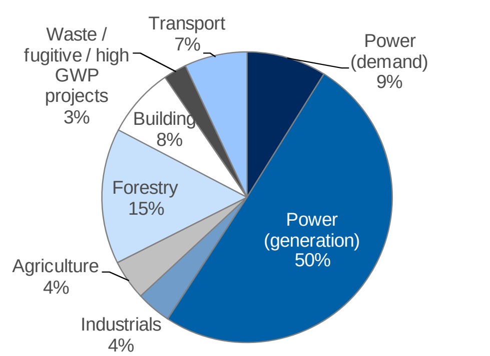


Figure 14: Sector distribution in 2030 MAC curve



Source: Bloomberg New Energy Finance

4. Conclusions and implications

4.1. Conclusions

Based on the MAC curves presented above, several conclusions can be drawn about the economics of US carbon emissions over the next two decades.

Clarity of methodology

MAC curves must be explicitly linked to a BAU scenario and must be defined in terms of a cost perspective. Section 3 demonstrated how the breadth and shape of MAC curves varied based on different assumptions about BAU emissions. These MAC curves paint alternative pictures for the marginal cost of abatement, the types of abatement options, and the most appropriate policies that can induce their adoption. Without a clear definition of the underlying assumptions about BAU, and the relationship between abatement under BAU versus abatement in the MAC curve, MAC studies may lead to potentially misleading implications.

Our methodology also showed how the MAC curve's profile changes based on assumptions about discount rates. These discount rate assumptions correspond to the different cost perspectives used by society versus investors. Adjusting discount rates to match investors' decision-making habits is an attempt to capture hidden and missing costs. As a result, it produces a curve that more closely matches private-sector abatement adoption patterns compared with a curve that uses a uniform social discount rate. A social discount rate is appropriate for considering the cost of public projects to society but may produce deceptive interpretations about how much abatement will be delivered by a particular carbon price.

This is one reason why carbon taxes tend to be less favoured by policy-makers – it is impossible to know how much abatement will be delivered by a given level of tax.

Limited *incremental* negative cost abatement potential

Previous MAC studies have suggested that a large amount of abatement potential (up to half of the MAC curve) can be captured by exploiting negative cost abatement opportunities. This analysis argues otherwise. We project 1.5Gt of abatement – of which 1.0Gt (70%) has a negative abatement cost – to happen without additional policy intervention, ie in line with historical trends of improved energy efficiency and declining carbon intensity. This abatement therefore cannot be considered to be incremental. An additional amount of negative cost potential actually has a positive cost when viewed from the perspective of investors.

This point highlights the MAC curve's sensitivity to the choice of methodology, as highlighted in the first conclusion. The MAC curve for the most pessimistic BAU scenario (ie, the scenario with the highest 2030 emissions) features 1.6Gt of negative cost abatement, whereas the MAC curve for the most optimistic BAU scenario (ie lowest 2030 emissions) features 440Mt of negative cost abatement.

Evolution of the US domestic abatement strategy

Section 3 characterized the 2030 MAC curve using four cost bands: the efficiency band, the land-use band, and transformational technologies bands I and II. Together, these cost bands suggest a likely evolution for a US domestic abatement strategy. The cost of abatement is projected to rise over time as easy and affordable options are adopted first, leaving the more capital-intensive, uncertain and costlier options for later. Therefore, US domestic abatement will likely draw heavily on offset projects and higher take-up of efficiency measures in the short term and in the long term will turn to transformational technologies for power generation and transport.

Some short-term options are cost effective in their own right, but these negative cost opportunities only account for 13% of the curve's abatement potential. To achieve more ambitious emission reductions will require fundamental long-term changes to the power sector (representing 59% of abatement potential) and widespread adoption of land-use measures (19% of abatement potential). Of these long-term options, CCS will be vital, representing 16% of the abatement potential, spread across various combinations of installation types and capture technologies.

The diversity of these bands also underlines the necessity for a comprehensive domestic abatement strategy, incorporating multiple technologies and abatement options in parallel. This can be contrasted with the circumstances around the US SO2 cap-and-trade programme for which only two abatement options existed: fuel switch from high-sulphur to low-sulphur coal, or installation of capital-intensive scrubbers.

Costs of national emission targets

The Waxman-Markey bill proposed a 42% reduction from 2005 levels by 2030[13]. With 2005 emission levels of 6.0Gt, a 42% reduction would require abatement of 2.7Gt, towards which existing policy will only contribute 0.3Gt. The remaining abatement need – 2.4Gt – almost exactly matches the total abatement potential in the final 2030 MAC curve presented in this report. This shows 2.3Gt of abatement at a cost of less than $143/t by 2030 – a relatively steep cost compared to our projections for carbon allowance prices. We estimate that a 30% reduction by 2030 could be achieved with domestic options (with the remaining 12% to be met by international offsets) and would entail a cost of $60/t ($91/t in nominal terms assuming 2% inflation).

In the shorter term, a 17% reduction from 2005 levels by 2020, consistent with reduction targets proposed by President Obama in Copenhagen, would require emissions to be cut to 5.0Gt. In BAU scenario 3 (which includes the effect of improving carbon intensity trends and key recent policies), 2020 emissions are projected to be 5.8Gt. According to the 2020 MAC curve which reflects the perspective of investors using a private discount rate, the gap of 0.8Gt (5.8–5.0Gt) would incur an average cost of $25/t ($31/t in nominal terms) and a marginal cost of $69/t in real terms ($86/t in nominal terms). From the perspective of society, meeting this 17% target would incur the same marginal cost but a lower average cost of $11/t ($14/t in nominal terms) because this perspective includes a larger amount of negative cost abatement potential. The average cost figures can be used to calculate the total costs of abatement to the economy or per household, and the marginal cost figures set the price of carbon allowances (if a market exists).

Need for international offsets

The carbon prices suggested by this analysis ($69/t in 2020 in real terms) are higher than projected carbon allowance prices. International offsets, which are carbon credits derived from low-cost abatement measures implemented in developing countries, are an essential cost containment tool. The EPA comes to the same conclusion in its analysis of the costs of meeting Waxman-Markey, noting that allowance prices would be 96% higher without international offsets.[14] Our North American Carbon Model, which assumes international offsets eligibility as specified by the Waxman-Markey bill, projects a $19/t price by 2020 in real terms ($24 in nominal terms).

Economic viability of abatement

While this analysis has demonstrated that free abatement does not exist in the quantities that had been suggested by other studies, an important finding that emerges from this report is that combating climate change does not pose an insurmountable challenge to the US economy.

A 17% reduction by 2020 would cost the US economy $22 billion ($27 billion in nominal terms) in 2020, or $170 per household ($211 in nominal terms). In 2030, a 30% reduction from 2005 levels would cost $33 billion ($49 billion in nominal terms), or $237 per household ($360 in nominal terms). The average US household spends $1,810 on energy per year.[15] Carbon emission abatement using purely domestic measures, therefore, would represent a 9-12% increase in energy spend per household. Some studies have claimed that abatement will cost as much as $3,100 per household on average, yet this MAC curve analysis indicates that these cost estimates are overstated. We calculate the cost of meeting a target of 17% reduction by 2020, and even 30% reduction by 2030, to be less than a dollar a day per family.

These total abatement costs are comparable with previously published government estimates. An April 2009 EPA analysis of the Waxman-Markey targets (17% by 2020) estimated total abatement costs of $30 billion,[16] and the Congressional Budget Office (CBO) calculated total abatement costs for these targets to be $22 billion annually, or $175 per household.[17] However, both government analyses differed in two significant ways from our analysis. First, both used a higher reference case for BAU emissions in 2020 (official EIA emission projections have tended to be higher than Bloomberg New Energy Finance projections). Second, both allowed for international offsets whereas this analysis purely examines domestic abatement options. Therefore, the volume of abatement required to achieve a 17% reduction was likely higher in their analyses, but the cost certainly lower due to their incorporation of low-cost international offsets (eg, EPA projects $17-$33/t allowance

[13] This reduction applied to covered sectors only, which represent 85% of emissions, yet other measures in the bill, such as direct regulation of some non-covered sectors, suggest that the 42% figure can be intended to be an economy-wide target.
[14] EPA, *Preliminary analysis of the Waxman-Markey discussion draft*, April 2009
[15] 2005 EIA Residential Survey
[16] EPA, *Preliminary analysis of the Waxman-Markey discussion draft*, April 2009
[17] Congressional Budget Office, report submitted to Congressman Dave Camp analysing potential effects of H.R. 2454, June 2009

price, and CBO projects $28/t allowance price). This contrast demonstrates once again the significance of linking MAC curves to precise definitions of the BAU.

The cost estimates produced from these curves are conservative, and the actual cost in 2030 may well turn out to be lower than projected here. If pursued aggressively, with sufficient government backing, technologies such as electric vehicles, solar energy, and CCS could experience sharper learning curves than assumed in this analysis. Breakthrough technologies that are in their infancy today and not included in the MAC curves could emerge and flourish, or American consumers could begin to exhibit behavioural changes related to energy consumption. The MAC curve analysis has suggested where the upper bound of abatement cost might lie; scientific innovation, entrepreneurial ambition, and consumer resolution could dictate how far down the lower bound may fall.

4.2. Implications

Policy-makers

The analysis presented above suggests that policy-makers should recognize the economic viability of abatement, the limited contribution of existing policy and therefore the need for additional policies, and the importance of international offsets.

Meeting the climate change challenge through domestic abatement is economically viable. Proposed climate change legislation is invariably countered with arguments stressing the onerous cost burden that this would create for the economy. This analysis demonstrates that, even by conservative measures, the costs are manageable. But acting with urgency is imperative. Waiting ten years before we begin to act on 2030 abatement measures will leave us with a 2030 MAC curve that is as steep as the 2020 curve we face today.

Existing policy for energy efficiency standards, vehicles and renewable power generation will contribute to emission reductions but will be far from sufficient to achieve the large-scale reduction pursued by the current Administration. To make adoption of abatement measures an economically rational decision by companies and investors, additional policies will be needed.

In the short term, a carbon price under a cap-and-trade programme would incentivize the adoption of domestic offsets such as waste/fugitives/high GWP projects and agriculture and forestry projects. Adoption of these projects would ‘buy time’ for the pursuit of the long-term solutions required to drive sustained, massive change – the transformational technologies that need carbon prices beyond $50/t for economic viability and that are likely to only start delivering large-scale results after 2020. Preparing these technologies for large-scale deployment will initially require government support. As such, nuclear energy will seek government loan guarantees; renewable energy will continue to rely on economic incentives and RPS; CCS will require DOE grants; and electric and ethanol-fuelled vehicle technologies will benefit from fuel mandates and stimulus funds.

Nevertheless, even with the portfolio of abatement options available to the US, the associated cost could still be too high for society, particularly at the onset. The role of international offsets as a low-cost opportunity is therefore crucial for any domestic carbon reduction strategy. Indeed, the House bill and proposed Senate bills have already recognized the valuable role played by these options and have included these measures prominently in their proposals.

Investors

As to investors, the analysis suggests that they should prioritize domestic offsets, recalibrate the market potential of ‘negative cost’ opportunities, and understand that future carbon prices may not be sufficient to rationalize investments in new capital-intensive technologies.

In particular, the MAC curve produces lessons about prioritization and timing. Domestic offsets will be vital and immediate contributors to US abatement; of these, waste/fugitives/high GWP projects have begun to be exploited, especially those with negative costs, but there are opportunities in the land-use sector. These would, however, only have value if a regional or national cap-and-trade programme would be put in place.

Efficiency options are attractive, but *incremental* abatement may not be as sizable as had been previously suggested. As indicated above, many of these options are likely to be taken up regardless of any additional policy. Moreover, the analysis shows how payback periods can sometimes stymie adoption of these measures.

For other technologies, the analysis demonstrates that future carbon prices may be helpful but not entirely adequate for opening the commercial floodgates. Neither nuclear, solar nor CCS technologies are economically viable on their own at carbon prices of $27/t in 2030 (or $41/t in nominal terms, equal to price projections in our North American Carbon Model in real terms). Investors deciding on these technologies should count on additional incentives such as tax benefits, think about broader geographies, or calculate with long time horizons.

4.3. Looking ahead

The sizing and costs of the elements that comprise the country's marginal abatement cost curve will increasingly become matters of vigorous debate. We have developed our analysis to inject our voice into this debate. At the same time, we are sensitive to the limitations of our own analysis; our comprehensive examination of a national abatement portfolio is not perfect. Rather, we present these results to share our methodology and current perspective on this problem, and to invite the response and comments of experts and vested parties.

Several parts of the analysis will continue to be refined. We will continue to deepen our understanding of demand-side abatement (efficient appliances, smart grid), abatement potential from coal-to-gas fuel switching, and process abatement for US industrial sector companies (our analysis here has to some extent drawn on knowledge of European processes). We are in the process of developing our own model to better understand ramp-up of land-use opportunities. We will also improve our tracking of the take-up of abatement opportunities that appear to be economical without a carbon price, to test our assumption that much negative cost abatement will occur under BAU conditions.

The final motivation for presenting this analysis is to provide an insight into Bloomberg New Energy Finance's Global Energy and Emissions Model (GE^2M). Among GE^2M's outputs are region-specific MAC curves; among its inputs are region-specific, granular assessments of carbon intensities and costs of technologies that span the six sectors presented here, as well as algorithms that project the likely adoption and evolution of those technologies.

GE^2M is Bloomberg New Energy Finance's global model. It is an integration of the regional carbon models that we have developed to understand the movements in carbon prices in the EU ETS, regional North American programmes, the markets around the Kyoto programme, and the voluntary markets. In this sense, it is both the latest extension of our work as well as a new and exciting platform that sheds light on the entangled picture of the world's diverse carbon policies, economic growth patterns, land-use trends, energy relationships, emission sources, and abatement opportunities. GE^2M is scheduled to be released in March 2010.

Appendices

Appendix A. Sector-specific analysis and data

This appendix provides further analysis and explanation of methodology and data sources used to derive sector-specific abatement quantification.

A.1 Land use

The land-use sector includes both agriculture and forestry abatement measures. Agriculture includes livestock practices and agricultural soil projects.

For livestock practices, the prominent classes are dairy and non-dairy cattle; the technologies that contribute most towards abatement in these classes are enteric fermentation emission reduction methods (improved feed conversion, intensive rotational grazing, propionate precursors) and manure management (covered lagoons, complete-mix digesters). Quantifying the abatement potential and cost for this sub-sector involves examining carbon intensities and capital and labour costs associated with application of these technologies, and projecting evolution of class mix from the current state to a future state based on adoption of these technologies.

The projects that comprise agricultural soil and forestry-related abatement are described in Table 3.

Table 3: Description of agricultural soil and forestry sub-sectors

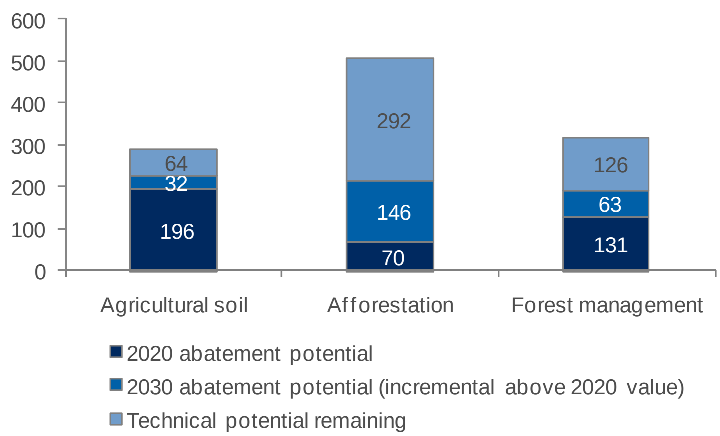
Sub-sector	Description
Agricultural soil	Conservation tillage to increase carbon sequestration; better fertilizer management to mitigate N2O emissions; crop rotations (including winter cover crops, such as legumes) to annually restore nitrogen to the soil
Afforestation	Conversion of agricultural lands (pastureland and cropland) to forest, which has higher carbon storage potential
Forest management	Passive forest management (lengthened timber harvest rotation, forest preservation, avoided deforestation) and active forest management (fertilization, controlled burning, and thinning to increase forest and carbon productivity)

Source: Bloomberg New Energy Finance, EPA

Abatement potential and costs for these sectors come from EPA and Winrock.[18] However, we temper the abatement potentials derived from these reports. We include a 20% risk buffer to account for concerns about permanence, and we implement a ramp-up methodology that consists of straight-line growth from 2020 to 2050, such that the abatement potential reached in 2050 for these sub-sectors equals the technical abatement potential as defined by the EPA and Winrock. The extent of abatement captured through this ramp-up is presented in Figure 15.

Figure 15: Ramp-up of land-use abatement options

MtCO2e



Sources: Bloomberg New Energy Finance, EPA, Winrock

[18] Winrock *International, Carbon supply from sequestration activities on agriculture and forest lands for the SECARB partnership*, 2005. EPA, *Greenhouse gas mitigation potential in U.S. forestry and agriculture*, 2005. Importantly, the EPA report relies heavily on outputs produced from the Forest and Agriculture Sector Optimization Model with Greenhouse Gases (FASOMGHG), a partial equilibrium economic model of the U.S. land-use sector.

A.2 Buildings

Abatement opportunities for buildings consist of heating efficiency applications to existing buildings or to new buildings that may be erected between now and 2030, in classes spread across the residential and commercial sectors. The technologies that were considered in evaluating abatement opportunities for building efficiency were the following:

- roof insulation
- cavity wall filling
- wall insulation
- floor insulation
- double-glazing and triple-glazing of windows
- heat pumps
- local embedded generation
- gas-fired central heating with or without a condensing boiler
- centrally-controlled district heating
- locally-run CHP generation

Table 4 below identifies the abatement potential and costs for significant selected opportunities from each subsector and type combination (ie, residential vs. commercial, new build vs. improvements to existing buildings).

Table 4: Building classes, abatement opportunity, abatement potential, and costs (for significant opportunities)

Sector	Type	Original class	Opportunity	Abatement potential (MtCO2e)[19] in 2030	Cost ($ / tCO2e)
Residential	Improvements	Brick built house	Upgraded roof insulation, cavity walls filled, heating by gas-fired central heating with condensing boiler	33.6	8.5
Residential	Improvements	Brick built house	Same as above, plus double-glazed windows	21.8	20.9
Commercial	Improvements	Building with high heating and cooling requirements, gas as primary heating fuel	Upgraded roof insulation, improved wall insulation, triple-glazed windows, heat pump	8.1	4.5
Residential	New build	n.a.	Ultra-modern flat with condensing boiler	25.3	(2.0)
Commercial	New build	n.a.	Heat pump, single glazing	3.6	16.3

Sources: Bloomberg New Energy Finance, EIA, Energy Saving Trust (UK), websites of home improvement suppliers

The largest opportunities in the residential sector are for retrofits to existing brick modern homes (130Mt of potential abatement by 2030, of which 33.6Mt can be achieved through a combination of technologies listed in the first row in the table above) and erection of ultra-modern homes (38Mt, of which 25.3Mt represent ultra-modern flats with condensing boiler). Brick modern homes may have existing carbon intensity as high as 5.5tCO2e/structure/year. Applying combinations of the various technologies listed above can lower emissions for these homes by as much as 60%. In comparison with average existing homes which have carbon intensity of 3.1tCO2e/structure/year, ultra-modern homes have the potential to have achieve carbon intensity lower than 0.4tCO2e/structure/year. In the commercial sector, improvements to existing buildings with high heating and high cooling requirements represent the biggest opportunities (49Mt, of which 8.1Mt can be achieved by applying a combination of roof, wall, window, and heating technologies to buildings with high heating and cooling and which use gas as the primary heating fuel).

Changing the cost perspective, from the cost to society to the cost to investors, has a notable effect in this sector. Figure 16 and Figure 17 compare the MAC curves for the building sector under the different scenarios for discount rates. Raising the discount rate from a social discount rate of 6% to a 40% discount rate that reflects the 2–3-year payback period guiding most building improvement

[19] Abatement potential is calculated as the product of (a) number of dwellings projected to make the given class transition and (b) change in carbon intensity (tCO2e / dwelling / year) achieved through this transition. In the case of commercial sector, we use square meters rather than dwellings.

decisions changes the shape of the curve. Most negative cost abatement measures in the 6% scenario, such as brick modern home upgrades, have a small positive cost in the 40% scenario.

Figure 16: Building sector MACC (6% discount rate)

2009$ / tCO2e

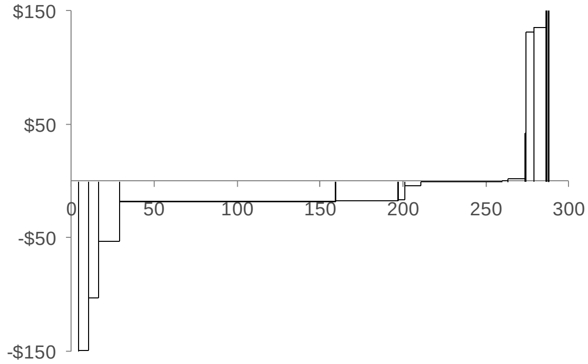
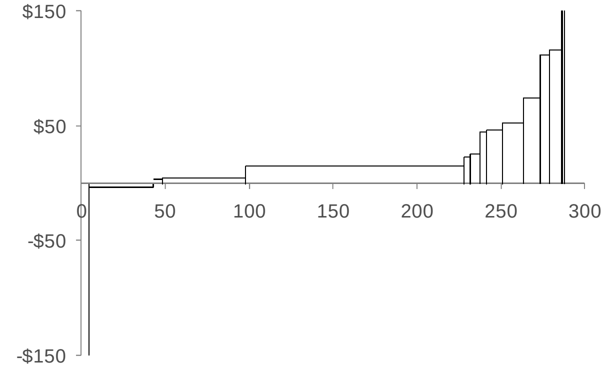


Figure 17: Building sector MACC (40% discount rate)



Source: Bloomberg New Energy Finance

A.3 Industry

Table 5 describes classes and abatement technologies evaluated in the industry sector.

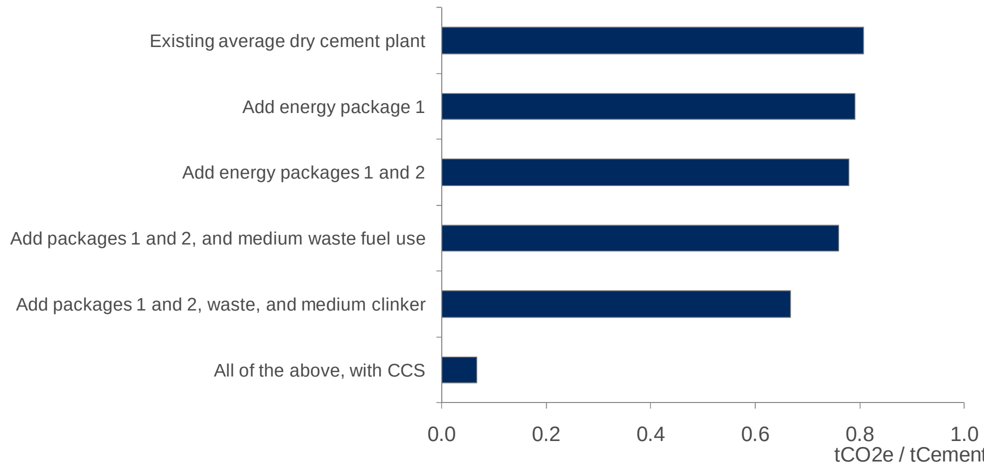
Table 5: Industry classes and technologies evaluated

Sector	Classes	Technologies
Cement	• Existing dry plants • New dry plants	• Preventative maintenance • Improved kiln combustion • Shell heat loss reduction • Indirect firing • New grate cooler • Process control and automation • Medium waste fuel • Medium clinker substitute • CCS (retrofit and new build)
Steel	• Existing BOF route plants • New BOF route plants	• Energy monitoring and management system • Preventative maintenance • Hot blast stove automation • Sinter plant heat recovery • Coal moisture control • Blast furnace pulverised coal injection • BOF gas + sensible heat recovery • CCS (retrofit and new build)
Ammonia	• Existing ammonia plants	• Improved CO2 removal • Energy management
Pulp and paper	• Existing pulp plants • Existing paper plants	• Waste heat recovery • Process controls and pinch analysis
Refining	• Hydroskimming (HSK) refineries • HSK with fluid catalytic cracking (FCC) • HSK with hydrocracking units (HCU) and on-site hydrogen production • 'Complete': Refineries with HSK, FCC, HCU, on-site hydrogen production	• Pumps motors and compressed air • Waste heat recovery • Energy management • Fouling mitigation • Advanced catalysts • Improved process controls • Process integration / change • CCS (retrofit and new build)

Sources: Bloomberg New Energy Finance; IEA; Lawrence Berkeley Laboratory; European Cement Research Academy; Entec; European Steel Technology; Oil and Gas Journal; Szklo, A. and Schaeffer, R., Fuel specification, energy consumption, and CO2 emission in oil refineries*, 2007; Holmgren, K. and Sternhufvud, C.,* CO2 emission reduction costs for petroleum refineries in Sweden*, 2008; Petrick, M. and Pellegrino, J.,* The potential for reducing energy utilization in the refining industry*, 1999.*

In the long run, CCS will play a critical role in reducing industrial emissions as there are thermodynamic limits to what industrial plants can do to reduce emissions. As outlined above, each of the analyzed industries could adopt a range of new technologies from process controls to enhanced fuel mixes to more efficient equipment. Yet most of these abatement options cannot impact the process emissions that are involved in producing cement, steel, refined petroleum, and the other industrial products. Process emissions are often a floor on carbon intensity, and best practices across industries have been approaching this theoretical limit asymptotically with only a few additional percent gains achieved through each new implementation. CCS, which is capable of reducing process emissions, is the exception. The carbon intensity gains afforded through implementation of other technologies is small relative to the massive gains achieved with CCS, as demonstrated in Figure 18 below, using the cement industry as an example.

Figure 18: Cement industry abatement measures



Source: Bloomberg New Energy Finance Notes: 'Energy package 1' consists of preventative maintenance, improved kiln combustion, and shell heat loss reduction; 'energy package 2' consists of indirect firing, new grate cooler, and process control and automation.

In practice, CCS is expected to first be implemented in the power sector, given the conservative nature of the industrial sector companies. Eventually, however, industrial sector companies facing carbon constraints may require CCS, in which case we would expect post-combustion CCS to be the primary technology choice given that it is capable of capturing process emissions (unlike pre-combustion) and can be most easily adjusted to fit existing production processes (unlike oxy-fuel combustion).

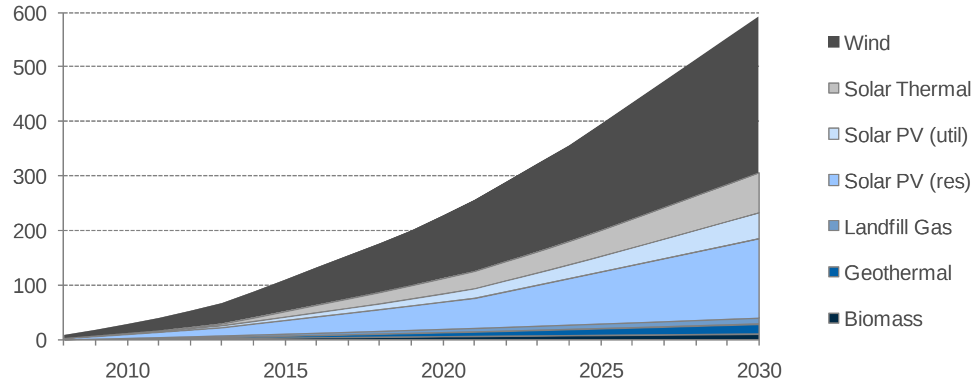
A.4 Power (supply-side)

Renewable energy

Abatement potential for renewable energy was based on estimations by Bloomberg New Energy Finance for each of the technologies about potential new capacity build, respecting constraints such as resource and transmission availability. The potential new build by technology over time appears in Figure 19, which shows potential new build of 590GW, a majority of it being wind, by 2030.

Figure 19: Potential build-out of renewable technologies

GW of installed capacity (cumulative potential)



Source: Bloomberg New Energy Finance, NREL

A portion of this renewable build-out will be driven by RPS: 133GW, of which 99GW will be wind, as projected by our Renewable Energy Credits (REC) Model. The remaining amount is considered to be incremental and qualifies as part of our MAC curve. The costs for the renewable technologies are based on our most recent levelized cost research,[20] and the levelized cost of each renewable technology is compared against the levelized cost of new build, high-efficiency coal plants (0.8tCO2e/MWh).

The most important of these renewable technologies is wind power, which represents 271Mt, or 46% of the renewable abatement opportunity. The MAC curve disaggregates this wind abatement, as explained in Table 6 below.

Table 6: Wind abatement opportunity tiers

	Applicable wind power class	Mean wind speed (m/s)	2009 levelized cost ($/MWh)	2030 abatement expected in BAU (MtCO2e)	2030 incremental abatement potential (MtCO2e)
Wind tier 1	6 and above	>8.0	68.6	49.8	-
Wind tier 2	5	7.5	88.5	10.3	36.7
Wind tiers 3-4	3 and 4	6.4-7.0	116.5	65.8	233.8

Source: Bloomberg New Energy Finance, NREL Wind Energy Resource Atlas of the US

Nuclear energy

Based on Bloomberg New Energy Finance's analysis of all nuclear plants under construction and of the viability and timing of all applications for combined construction and operating licenses (COL) submitted to the US Nuclear Regulatory Commission, we project 10GW of new nuclear build in US by 2020 in a base case, which would increase the installed capacity of the existing nuclear base by 10%. Assuming a similar rate of growth in the following decade, total new build from nuclear would be 21GW by 2030. However, in a high case, this number could be as much as 46GW by 2030. It is this incremental 25GW that drives abatement volumes in our MAC curve analysis. Because we have attached these installed projections through 2020 to specific COLs, we are able to define the states where this new build would occur, and therefore the likely mix of coal and gas that might be replaced with cleaner nuclear technology: we project that 44% of the new nuclear fleet would replace coal and 56% would replace gas, measured in terms of capacity.

Our costs for nuclear energy are on the high end of published sources. Table 7 presents the levelized cost estimates provided by seven research studies, and underneath some of the key assumptions that drove these estimates. Our observation of costs are on the high end of those cited below, as recent industry estimates suggest a cost of $9 billion for a new 1,600MW reactor. We therefore take the highest of these levelized cost estimates, $96/MWh, which translates into an abatement cost of $46/t. This abatement cost is in line with estimates by the US Congressional Budget Office.

[20] New Energy Finance, *Q3 levelized cost of energy outlook*, Oct 2009

Table 7: Comparison of nuclear cost estimates, and corresponding assumptions, from various sources

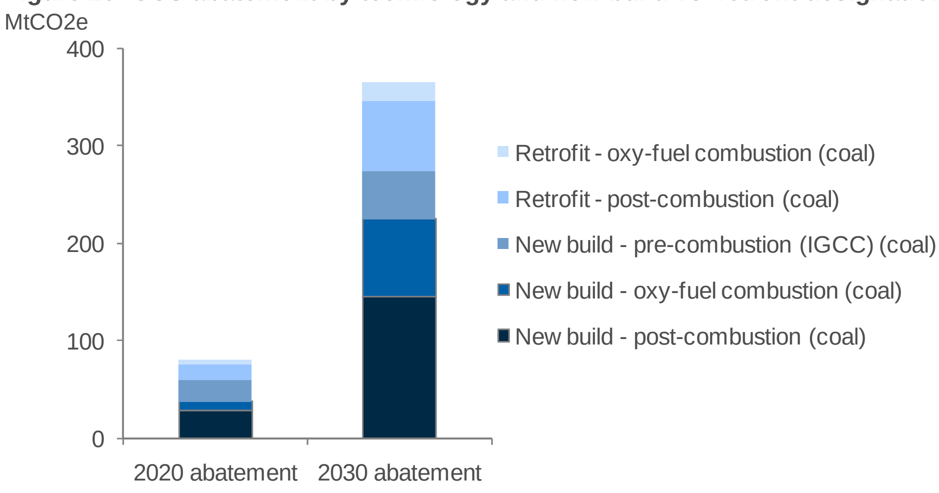
	DGEMP (2003)	MIT (2003)	U. of Chicago (2004)	RAE (2004)	NEA / IEA (2005)	Keystone Center (2007)	MIT updated (2009)
Levelized cost ($/MWh)	48	73	68	52	53	96	75
Discount rate (%)	5–11	10–11.5	12.5	7.5	10–11.5	5–10	10–11.5
Debt finance / cost of debt (%)	–	50 / 8	50 / 10	–	–	50 / 8	50 / 8
Equity finance / cost of equity (%)	–	50 / 12–15	50 / 15	–	–	50 / 12–15	50 / 12–15
Load factor (%)	85	85	85–95	85	85	75–90	85
Construction overnight cost (2007$ / kW)	1,600	1,800–2,400	1,400–2,200	2,500	1,200–3,000	3,000	4,100

Sources: General Directorate for Energy and Raw Materials (DGEMP), study of reference costs for power generation, 2003; MIT Energy Initiative, The future of nuclear power*, 2003; University of Chicago,* Economic future of nuclear power*, 2004; Royal Academy of Engineering,* Costs of generating electricity*, 2004; OECD / IEA Nuclear Energy Agency,* Projected costs of generating electricity – update*, 2005; Keystone Center,* Nuclear power joint fact-finding*, 2007; MIT Energy Initiative,* Update of the MIT 2003 future of nuclear power*, 2009. Results of these research studies were collected by F. Leveque of Mines ParisTech and presented on the EU Energy Policy website. Levelized costs shown in this table are based on Leveque's analysis of these studies and on an average exchange rate for 2007 ($1.37/€).*

CCS

CCS has the potential to play an enormous role in power generation abatement. In the high case, we project 55GW of potential new build by 2030, corresponding to almost 25% of new build coal plants over the next 20 years. The distribution of this new build is presented in Figure 20. The distributions for 2020 are based largely on the distribution of funding that has been allocated to date to specific projects, including the 225MW FutureGen project in Illinois, the 120MW Beulah project in North Dakota, the 350MW HECA project in California, the 540MW Tenaska project in Texas, the 200MW AEP project in Oklahoma, and the 300MW Duke Energy project in Indiana. Capital allocation for CCS has so far been skewed towards post-combustion new build coal plants and pre-combustion new build IGCC coal plants. By 2030, this mix will likely evolve, with an even higher weighting towards post-combustion new build coal and potentially higher representation for oxy-fuel combustion.

Figure 20: CCS abatement by technology and new build vs. retrofit designation



Source: Bloomberg New Energy Finance

Cost estimates for CCS are based on Bloomberg New Energy Finance's recently developed CCS Cost Model, which look at the cost for building the 'nth plant' across a variety of technologies. On the low end is post-combustion technology, for which the CCS Cost Model estimates an abatement cost of $57/t. On the high end is pre-combustion at a cost of $91/t. The cost for retrofits is 30% higher than for new builds, given that the cost is amortized over a shorter lifetime. The abatement potential and costs are also both dependent on the capture rate, which is highest for oxy-fuel (99%).

Fuel switching

Calculation of the cost of short-term fuel switching involves comparing the efficiencies (energy supply input required to achieve MWh of electricity output), carbon intensities (tCO2e/MWh), and fuel price inputs (2020 and 2030 forecasted spot prices of the relevant commodities) of natural gas and coal plants. This calculation produces an abatement cost of $71/t in 2020 and $90/t in 2030. The abatement potential is pulled from running our North American Carbon Model under a scenario with very low natural gas prices; in this situation, unused natural gas capacity would be expected to be fired in lieu of portions of baseload coal. Our model indicates an abatement potential of roughly 80Mt, although in a situation with extremely depressed gas prices – which is not inconceivable if shale production greatly exceeds current market estimates – the abatement potential could be much more.

With regard to long-term fuel switching, an additional abatement option that we considered was new build of CCGT plants, which are cleaner than new build coal but more carbon-intensive than renewables, nuclear or CCS. Because our levelized cost estimates of natural gas and coal plants are almost equal ($57.6 for natural gas, $58.3 for coal), the abatement cost of new build CCGT would be nearly zero. In the final presentation of our MAC curve, however, we have excluded this as an abatement option. Had we included CCGT new build as an option, its abatement potential would be defined as all new build that might occur between now and 2030 as electricity demand grows and as old plants get retired. Our electricity demand analysis projects the US to be at 4,800TWh by 2030, of which 2,800TWh will be delivered by sources installed before 2007. The remaining 2,000TWh will be supplied by a combination of new build renewables, new build nuclear, and new build CCS. We could have chosen, instead, to have this entire remaining need satisfied by new build CCGT, which means that all of these power generation options that show up in our MAC curve would otherwise have been crowded out. In practice, we expect new build CCGT to be a central element of the US abatement strategy. This will dampen the abatement potential that could have been realized by these cleaner technologies but will serve as a functional, financeable, cleaner-than-conventional-coal bridge between the present and future states of US electricity power generation.

A.5 Power (demand-side)

Smart grid

As outlined by EPRI in its June 2008 *Green grid* report, abatement from smart grid technologies will come from measures such as improved operational efficiency (including reduced line losses and voltage control), enhanced demand response (including peak demand reductions and reduced operation of peaking plants), integration of intermittent renewables, and transformed customer energy usage behaviour. Of these, EPRI has quantified that the most significant contribution will come from transformed customer energy usage behaviour driven by systems that provide direct feedback to the customer.[21] This, then, is the focal point of our smart grid analysis. We analyzed two residential smart grid options, presented in Table 8 below.

Table 8: Smart grid abatement options

Abatement option	Energy savings from option (%)	tCO2e abatement per household per year	Equipment cost ($)	2020 Penetration (number of US households, million)
Changes in energy usage behaviour driven by advanced metering infrastructure (AMI) with visual displays	8.7	0.84	462	51
Automated energy reduction using smart plugs and optimized thermostats	6.1	0.70	150	8.7

Sources: Bloomberg New Energy Finance, AlertMe and GoodEnergies "Residential Smart Energy Savings" white paper, US ARRA grant awards information, EIA Residential Energy Consumption Survey, 2005 Note: Assumes average US household electricity spend per year of $1,969.

Lighting, building management, electronics, white goods

CFL and LED lighting are more efficient alternatives than incandescent lighting which dominates the market today. Table 9 emphasizes the efficiency and lifetime benefits of these options. We envision adoption in two stages: the rise of CFLs, followed by the rise of LEDs. The maximum abatement that could occur would represent a complete shift from incandescent to LEDs, leapfrogging CFLs, yielding 170Mt of abatement. However, as CFLs are expected to be part of the solution, we project 147Mt of

[21] EPRI, *Green grid* report, June 2008: The total avoided CO2e emissions from smart grid measures were 211MtCO2e in the high case, of which 68MtCO2e came from "Direct Feedback on Energy Usage". If we remove the abatement measures that are related to renewable energy and electric vehicles, then this abatement option represents 60–70% of total smart grid-driven abatement opportunity.

abatement, assuming 80% share for CFLs. CFLs represented about 10% of light bulb sales in 2007, according to the EIA. As this share rises, average bulb lifetimes will increase, reducing turnover.

Table 9: Lighting abatement options

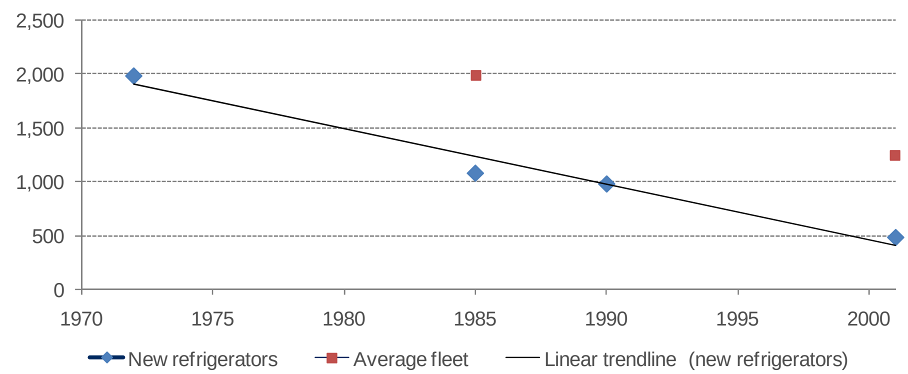
Lighting type	Power per bulb (W)	Lifetime (hours)	Abatement potential assuming 100% transition from incandescent to new type	Expected market share in 2030 (%)
Incandescent	75	1,000	n.a.	0
CFL	19	10,000	141Mt	80
LED	7.5	50,000	170Mt	20

Source: Bloomberg New Energy Finance, EIA Annual Energy Outlook 2008. Note: Abatement potential includes residential and commercial, and is driven from EIA projections of electricity end-use (460TWh in 2010)

Other power sector demand-side abatement measures relate to building management systems and more efficient devices (electronics and white goods). For building management systems, a study conducted by TIAX evaluated the energy savings that might come from control systems for US commercial buildings; an aggregation of the diagnostics and controls could address much of the 'faults' which represent 11% of energy consumed by HVAC, lighting, and larger refrigeration systems in commercial buildings.[22] For white goods and electronics, we evaluated electricity savings by reducing annual electricity usage for these sub-sectors by efficiency improvements in line with historical improvements. Of special relevance are refrigerators, which have huge electricity consumption needs but which have also experienced significant efficiency improvement over the past 30 years, driven partially by state and federal standards. Figure 21 shows the pattern of unit energy consumption decline for new US refrigerators. Due to refrigerators' long lifetimes, however, there is a long lag before these improvements are manifested in efficiency levels of the average fleet.

Figure 21: History of US refrigerator efficiency improvements

Unit energy consumption (kWh per refrigerator)



Source: Bloomberg New Energy Finance, EIA Household Electricity Report, 2005

A.6 Transport

In the transport sector, we look at both new vehicle technologies as well as advances to the internal combustion engine (ICE) to make vehicles more fuel-efficient. Hybrid, plug-in hybrid, electric, and ethanol-fuelled vehicles each have the potential contribute more than 30Mt of abatement by 2030, with hybrids coming at a negative cost and the other alternatives at a cost of low $30s/t for plug-ins and ethanol-fuelled vehicles, and $67/t for electric vehicles. By 2030, we project that these new vehicle technologies together have the potential to claim 23% market share, led by 10% for ethanol-fuelled vehicles.

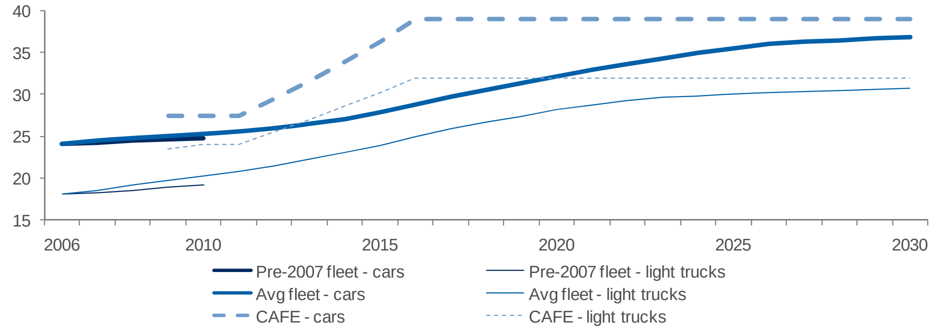
For ICE vehicles, abatement will be driven primarily through CAFE standards. Current standards require efficiency of 27.5mpg for new cars and 23.1mpg for new light trucks. By 2016, at the federal level, US cars will be required to achieve 39mpg and light trucks 32mpg. As a result, based on vehicle

[22] TIAX LLC, *Energy impact of commercial building controls and performance diagnostics: market characterization, energy impact of building faults and energy savings potential*, 2005. Report prepared for the U.S. Department of Energy.

turnover rates, fuel efficiency of the average fleet in 2030 is expected to approach the regulations for vehicles with 2016 model year, as shown in Figure 22.

Figure 22: US fuel efficiency projections

Miles per gallon

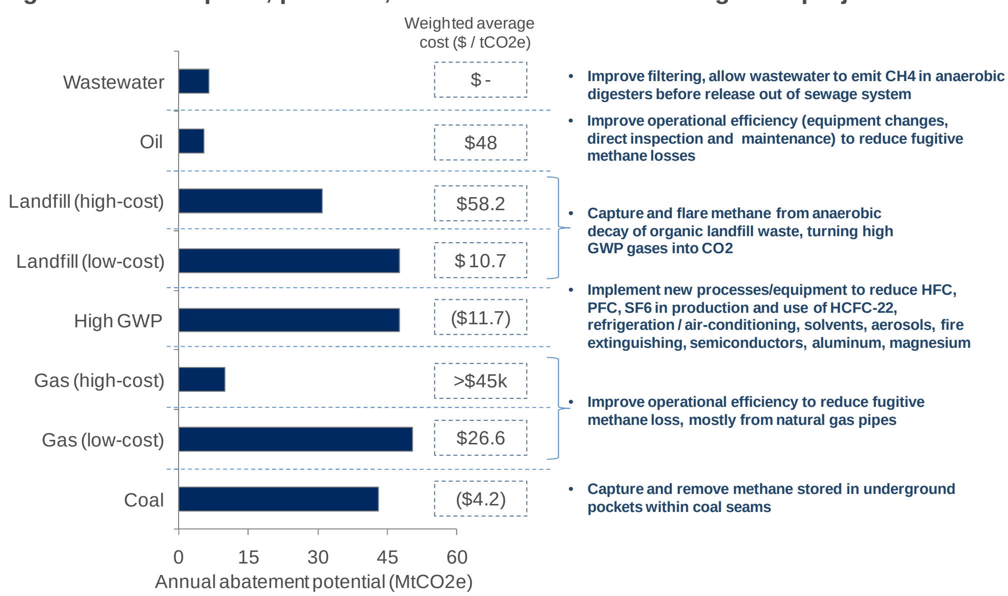


Source: Bloomberg New Energy Finance; White House Office of the Press Secretary press release, May 2009

A.7 Waste and fugitives

Figure 23 summarizes the abatement options available in the waste and fugitive sector.

Figure 23: Description, potential, and costs for waste and fugitives projects



Source: Bloomberg New Energy Finance, EPA

Abatement in some facilities will be an inexpensive proposition. Emission reductions in manufacturing processes that produce high global warming potential gases, methane capture and flaring from landfill waste, and methane capture from coal mines fall into this category. These are among the types of projects that will likely qualify for domestic offsets under a federal cap-and-trade programme.

Appendix B. Related recent analysis from Bloomberg New Energy Finance

Because construction of a MAC curve is necessarily interdisciplinary, this exercise draws on expertise and workstreams from across our firm. Table 10 below provides a list of representative Research Notes, all from the past 12 months and relevant to the analysis presented here, to give some examples of how each of these topics can be explored in more depth.

Table 10: Related recent analysis from Bloomberg New Energy Finance

Sector	Examples of relevant representative reports from Bloomberg New Energy Finance
Land use	• Carbon Markets, *Carbon trading, what's in it for farmers?,* Nov 2009 • Carbon Markets, *Forestry offsets – paradox or panacea*?, Nov 2009
Buildings	• Energy Smart Technologies, *Financing energy efficiency*, June 2008
Industry	• Carbon Markets, *Will cap-and-trade be the final push for the already declining industrial sectors?,* Oct 2009 • Carbon Markets – EU ETS, *Industrial installations should look to CCS in the long term*, Nov 2009 • Carbon Markets – EU ETS, *CO2 abatement potential in European industry*, Dec 2009
Power	• Clean Energy, *Q3 Levelized cost of energy outlook*, Oct 2009 • Nuclear, *US power generation: will nuclear rebound?* Nov 2008 • CCS, *Capturing costs: the economics of CCS*, Oct 2009 • Energy Smart Technologies, *Mapping the value chain: opportunities in digital energy*, Dec 2009
Transport	• Clean Energy, *US next generation biofuels: off target*, Aug 2009 • Carbon Markets, *Does Waxman-Markey mean a turning point for the oil and gas sector?,* Sep 2009 • Carbon Markets, *Electric vehicles – a good idea, but little impact to be seen before 2020*, Dec 2009
Waste/fugitives/high GWP	• Carbon Markets, *Investment opportunities for US-based offset projects*, Apr 2009

About Us

Subscription Details Carbon Markets – North America sales@newenergyfinance.com

Contact Details

Guy Turner
Director, Carbon Markets
guy.turner@newenergyfinance.com
+44 20 7092 8829

Milo Sjardin
Head of Carbon Markets, North America
milo.sjardin @newenergyfinance.com
+1 646 214 6166

Michel Di Capua
Associate, North America
michel.dicapua@newenergyfinance.com
+1 646 214 6205