

Marginal abatement cost curve for NO_x incorporating controls, renewable electricity, energy efficiency and fuel switching

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ABSTRACT

A marginal abatement cost curve (MACC) traces out the relationship between the quantity of pollution abated and the marginal cost of abating each additional unit. In the context of air quality management, MACCs typically are developed by sorting *end-of-pipe* controls by their respective cost effectiveness. Alternative measures, such as renewable electricity, energy efficiency, and fuel switching (RE/EE/FS), typically are not considered as it is difficult to quantify their abatement potential. In this paper, we demonstrate the use of an energy system model to develop a MACC for nitrogen oxides (NO_x) that incorporates both end-of-pipe controls and these measures. We decompose the MACC by sector, and evaluate the cost-effectiveness of RE/EE/FS. RE/EE/FS are shown to produce emission reductions after end-of-pipe controls have been exhausted. Furthermore, some RE/EE/FS are shown to be cost-competitive with end-of-pipe controls.

INTRODUCTION

Nitrogen oxides (NO_x) are emitted when fossil fuels are combusted. In the atmosphere, NO_x reacts with volatile organic compounds (VOCs) to produce tropospheric ozone (O₃), a component of photochemical smog. Strategies for reducing O₃ typically focus on placing NO_x emission control devices on power plants, industrial sources and vehicles. In some locations, however, these “end-of-pipe” control measures may not be sufficient to achieve the National Ambient Air Quality Standard (NAAQS) for O₃¹. Instead, additional controls will need to be developed or non-traditional measures for reducing emissions will need to be explored.

Energy system models can facilitate examination of non-traditional measures such as renewable electricity, energy efficiency, and fuel switching (RE/EE/FS). We apply one such model to develop a Marginal Abatement Cost Curve (MACC) for NO_x that incorporates both end-of-pipe controls and RE/EE/FS. We decompose the curve to examine the relative cost-effectiveness of RE/EE/FS. Questions we address here include: “Can RE/EE/FS produce additional reductions beyond end-of-pipe controls?” and “Are RE/EE/FS cost-competitive with end-of-pipe controls?”

BACKGROUND

A MACC depicts the relationship between pollution abatement and cost². A MACC is often represented as a curve on an X-Y plot. In the context of air quality management, the x-axis typically represents tons of emissions reduced, while the y-axis represents the cost of reducing the last ton. Moving from left to right on the x-axis yields higher marginal costs, producing a monotonically increasing curve. Knowing the shape of the curve can help decision makers identify cost-effective reduction targets, as well as thresholds above which control costs increase dramatically. MACCs also can be integrated into a cost-benefit analysis to identify the optimal abatement level at which marginal costs equal marginal benefits³.

The U.S. EPA uses the Control Strategies Tool (CoST) to estimate the costs of reducing emissions from specific emissions sources⁴. CoST includes a comprehensive database of end-of-pipe control measures⁵ such as low NO_x burners and select catalytic reduction (SCR) devices. CoST has limited options for reducing emissions via fuel switching, however, and does not include measures such as energy efficiency, renewable electricity, or vehicle electrification. In the research presented here, we explore an approach that combines the traditional end-of-pipe measures characterized in tools like CoST with RE/EE/FS to estimate regional MACCs that incorporate a broad portfolio of pollution abatement measures.

Our empirical approach relies on the U.S. EPA MARKet ALlocation (MARKAL) modeling framework. The framework consists of the MARKAL energy system model⁶ and the EPAUS9r_2014_v1.2 MARKAL nine-region database⁷. MARKAL is an optimization model that identifies the energy technologies and fuels that meet the specified energy demands and performance constraints over the modeled time period at least cost. The EPA MARKAL database allows MARKAL to be applied to the U.S. The database includes current and projected characterizations of U.S. energy demands, renewable and fossil resources, and energy production, transformation and end-use technologies. The database also includes emission factors for a range of traditional air pollutants and greenhouse gases. For a given U.S. energy system scenario, the EPA MARKAL framework produces fuel use, technology penetration, and emission estimates through 2055 for each U.S. Census Division.

The EPA MARKAL Base Case scenario has been calibrated to approximate the technology assumptions and fuel use estimates of the U.S. Energy Information Administration's 2014 Annual Energy Outlook⁸. In addition, the baseline incorporates approximations of state-level renewable portfolio standards and "on-the-books" air pollution regulations, such as the Clean Air Interstate Rule⁹ and the Tier 3 mobile source emission standards¹⁰. The Clean Power Plan¹¹ is not included as that regulation had not yet been finalized at the time this work was conducted. Emission factors are derived from a number of sources, including the EPA's WebFIRE¹², Greenhouse Gas Inventory¹³, and the MOtor Vehicle Emission Simulator (MOVES)¹⁴.

METHODOLOGY

For this application, we data drawn from CoST to characterize NO_x end-of-pipe controls in the industrial, residential, commercial and off-highway transportation sectors. These controls were then added to the MARKAL database, complementing the electric sector NO_x controls already represented.

Next, we examined the MARKAL Base Case to identify baseline regional NO_x trajectories over the modeling time horizon. We then iteratively executed MARKAL, forcing increasingly stringent regional NO_x constraints with each iteration. These constraints reduced 2035 NO_x emissions from each region, starting at 2.5 % from baseline levels and decreasing in 2.5% increments to a 50 % reduction. The constraints were implemented linearly from 2015 and held constant after 2035. The year 2035 was selected as the end point for the trajectories, as well as year for which MACCs are calculated for several reasons: (i) 2035 is at the far end of the range of years for which regulatory impact assessments typically have been conducted, (ii) 2035 is far enough into the future that significant technological turnover can occur, and (iii) there is less uncertainty in factors such as population growth, economic growth and technological development that would be expected in later years, such as 2050.

Figure 1 illustrates baseline emissions in Region 5, the South Atlantic, and those of several emission reduction constraints.

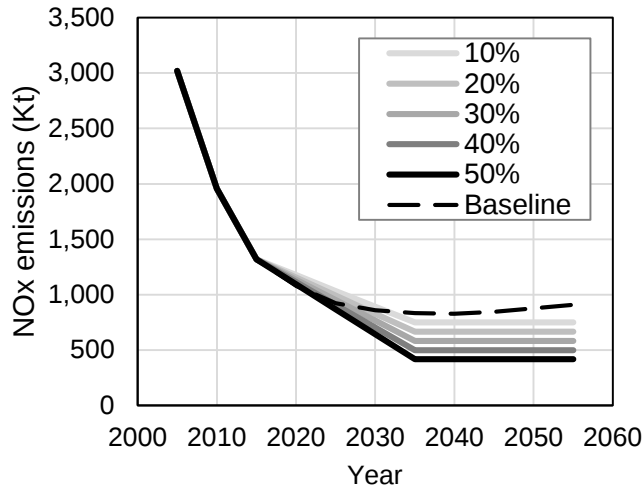


Figure 1. Example of incrementally more stringent regional NO_x constraints for Region 5, the South Atlantic.

In total, twenty one MARKAL runs were conducted, including the Base Case and alternative NO_x percent reduction targets. For each run, a wide range of outputs was recorded, including

technology penetrations, fuel use, application of control technologies, sectoral emissions, and marginal NO_x abatement cost.

RESULTS AND DISCUSSION

Figure 2 depicts the resulting MACC for NO_x at the national level. This MACC includes both end-of-pipe controls and RE/EE/FS. Base Case NO_x emissions in 2035 are approximately 6,000 kTonnes, so 1,500 kTonnes would constitute reduction of approximately 25 %.

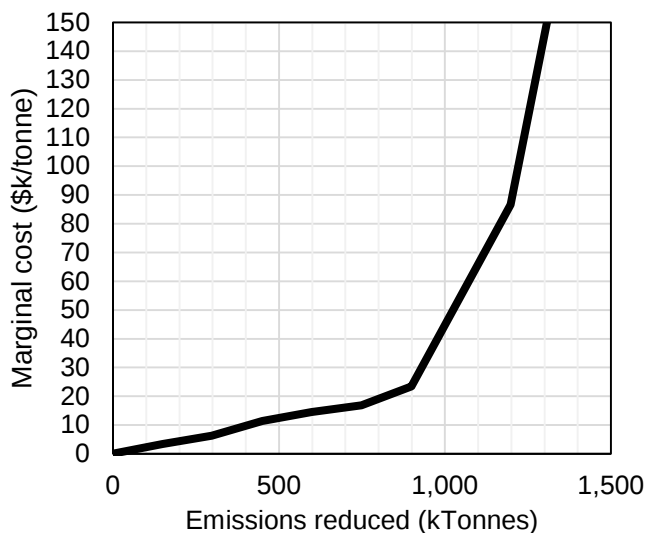


Figure 2. National MACC for NO_x for 2035.

We also estimate the sectoral contributions to this curve. Figure 3 indicates emission reductions are achievable from each sector at costs below \$20k/tonne, with the industrial, electric generating units (EGU), and transportation sectors providing the greatest reduction opportunities, respectively. The costs of additional reductions appear to increase rapidly beyond that point.

Figure 4 augments Figure 2 by adding curves for end-of-pipe controls and RE/EE/FS. These results point to an important finding: RE/EE/FS are typically able to produce approximately 40 % reduction beyond end-of-pipe controls, up to \$50k/tonne, and a greater share thereafter.

While the overall MACC is monotonically increasing, as expected, the curve formed from the underlying contribution of end-of-pipe controls to the MACC has an inflection point, after which it doubles back.

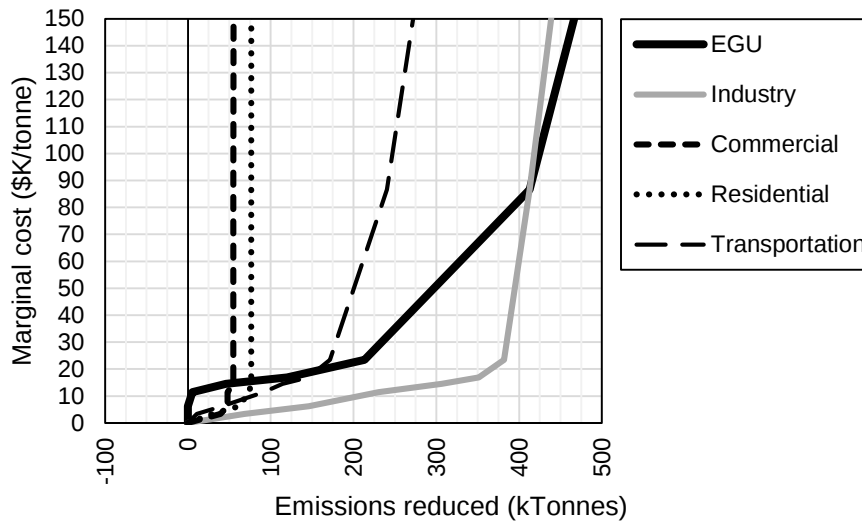


Figure 3. National MACC for NO_x for 2035, as well as MACCs for reductions attributed to end-of-pipe controls and RE/EE/FS beyond their Base Case levels.

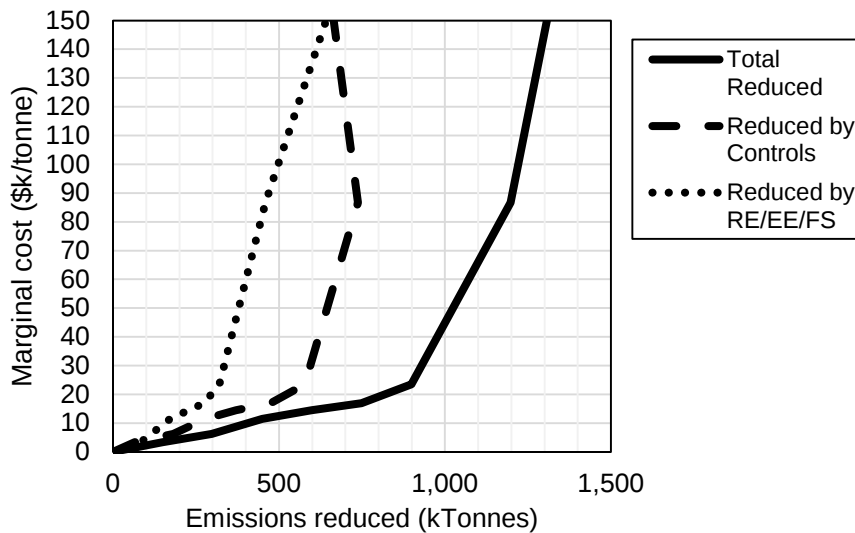


Figure 4. National MACC for NO_x for 2035, as well as MACCs for reductions attributed to end-of-pipe controls and RE/EE/FS beyond their Base Case levels.

We generated Figures 5 and 6 to investigate this outcome further. Figure 5 shows the electric sector MACC and its components, inverted so that we can more readily visualize how NO_x reductions respond to increasing marginal costs. Similarly, Figure 6 shows how electricity production responds to increasing marginal costs.

A number of observations surface. First, in the electric sector, 55 % of the end-of-pipe controls are applied at a marginal cost of less than \$20k/tonne. The remaining control-related reductions are incrementally applied through costs up to \$80k/tonne. Above this marginal cost, the control-related reductions diminish. RE/EE/FS have an increasing share of NO_x reductions from approximately \$15k/tonne, with the rate of application of RE/EE/FS increasing after \$80k/tonne. Figure 6 highlights the underlying drivers. As the marginal costs increase, MARKAL is transitioning away from coal and to a lesser extent, from biomass. Simultaneously, output from natural gas and wind is increasing. An overall increase in electricity production is indicating some degree of fuel switching in end-use sectors. From the results, we can deduce that the model can no longer benefit from end-of-pipe controls on coal plants when a more cost-effective approach is to switch to lower NO_x-emitting fuels.

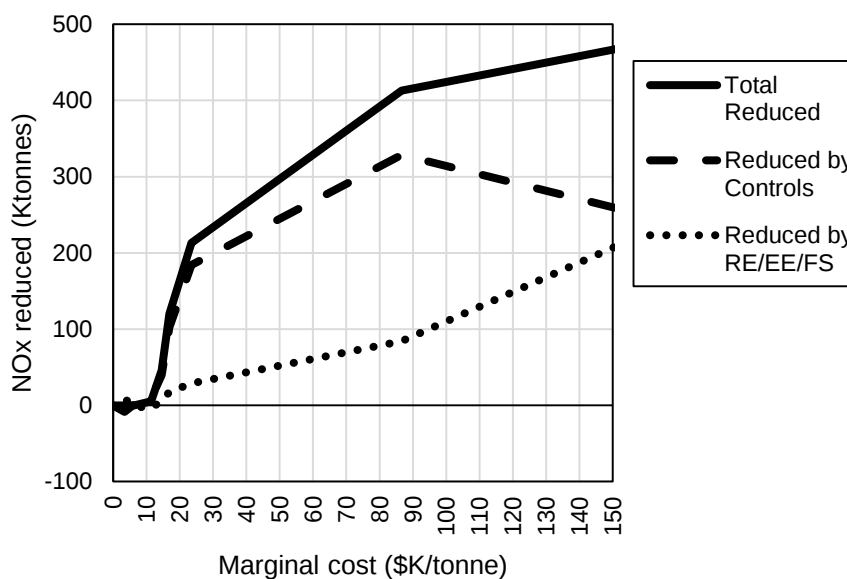


Figure 5. National electric-sector MACC for NO_x for 2035, oriented with marginal cost on the X-axis.

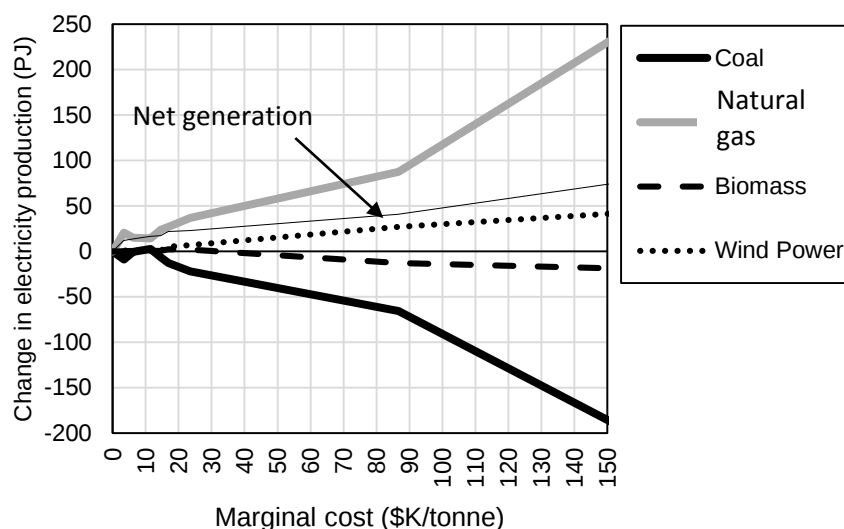


Figure 6. Change in electricity production by fuel in 2035 as a function of marginal cost. For reference, total Base Case electricity production in 2035 is approximately 33,000 PJ, with one-third from coal and one-third from natural gas.

The results in Figure 6 are also notable based upon what does not appear. For example, MARKAL does not find introduction of additional nuclear power plants to be a cost-effective means of reducing NO_x , at least up to a marginal cost of \$150k/tonne. Similarly, solar technologies do not play a major role in these results, at least at the national scale.

SUMMARY

In this extended abstract, we demonstrate the use of the EPA MARKAL energy system framework in developing national MACCs for NO_x that incorporate both end-of-pipe controls and nontraditional measures, such as renewable electricity, energy efficiency, and fuel switching. We show that RE/EE/FS have the potential to increase emission reductions considerably beyond what is possible with end-of-pipe controls alone. Furthermore, a portion of RE/EE/FS are shown to be competitive with some end-of-pipe controls. Modeling suggests that the emission reductions from RE/EE/FS and end-of-pipe controls are not always additive: fuel switching away from coal, for example, means that the reduction potential for controls on coal plants decreases. This result demonstrates the value of integrating a broad suite of abatement possibilities into a single decision-analysis framework.

Some RE/EE/FS do not appear in modeling solutions at marginal costs of less than \$150K/tonne, implying that technologies such as solar PV and advanced nuclear power may not be particularly cost-effective for NO_x reductions alone. However, these technologies are carbon free, so their attractiveness, as well as the attractiveness of other low-carbon RE/EE/FS, could be increased if

their GHG mitigation co-benefits are considered. In subsequent work, we will explore how the competitiveness of RE/EE/FS changes when one considers co-benefits.

Another important consideration is how the potential role of RE/EE/FS in reducing NO_x differs by region of the country. In ongoing work, we are analyzing MARKAL results to develop regional NO_x MACCs. Furthermore, we are disaggregating the resulting sectoral fuel and technology choices to identify the most cost-effective strategies for introducing RE/EE/FS in various regions of the country.

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DISCLAIMER

While this document has been reviewed and cleared for publication by the U.S. EPA, the views expressed here are those of the authors and do not necessarily represent the official views or policies of the Agency. Mention of software, models and organizations does not constitute an endorsement.

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