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A wedge-based approach to estimating health co-benefits of climate change mitigation activities in the United States

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DISCLAIMER

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NOTE

This article was originally published as "A wedge-based approach to estimating health co-benefits of climate change mitigation activities in the United States" in Climatic Change, Volume 127, Issue 2, pp .199-210, 14 October 2014. DOI 10.1007/s10584-014-1262-5. An Erratum Statement was issued on 6 February 2015 (http://link.springer.com/article/10.1007/s10584-015-1336-z), which read:

Immediately after online publication of our article, the authors recognized that an error had been made in the calculation of the health co-benefits associated with the "wedge" obtained from greater efficiency for direct fuel end-use in buildings. The error changes the upper bound reported for potential benefits from $30 Billion to $14 Billion under our baseline scenario and from $56 Billion to $24 Billion under our optimistic rapid implementation scenario. The estimates of benefits from the remaining wedges are unchanged, and conclusions of this paper that potential co-benefits are substantial and that it is informative to compare the health benefits of equal amounts of carbon dioxide emissions reduction from different strategies remain the same.

This wedge differed from the other wedges in being an "area source" rather than associated with air pollution from electric generating units or mobile sources. To provide a corrected estimate we used an alternative estimation method for health co-benefits associated with one wedge of CO_2 reductions from direct fuel end-use in buildings, based on data from the National Emissions Inventory for direct fuel combustion in residential and commercial/institutional buildings, and using the economic benefits per ton calculated for area sources by Fann et al. (2012). This method resulted in an estimate of $3.6 billion of health benefits with the baseline scenario and $6.8 billion with the optimistic scenario in 2020, without adjusting population (from 2005) or emissions (from 2008) to 2020. Because of the differences in methods, these figures are not directly comparable to the figures for the other wedges in the manuscript. Nonetheless, they demonstrate potential benefits in the same order of magnitude as the other wedges. The authors regret this error but stand by the methods and assumptions used in generating estimates of health co-benefits for the remaining nine wedges.

What follows is a modified version of the original article, including Supplementary Materials, which incorporates these revisions.

ABSTRACT

While it has been recognized that actions reducing greenhouse gas (GHG) emissions can have significant positive and negative impacts on human health through reductions in ambient fine particulate matter ($PM_{2.5}$) concentrations, these impacts are rarely taken into account when analyzing specific policies. This study presents a new framework for estimating the change in health outcomes resulting from implementation of specific carbon dioxide (CO_2) reduction activities, allowing comparison of different sectors and options for climate mitigation activities. Our estimates suggest that in the year 2020, the reductions in adverse health outcomes from lessened exposure to $PM_{2.5}$ would yield economic benefits in the range of $6 to $14 billion (in 2008 USD), depending on the specific activity. This equates to between $40 and $93 per metric ton of CO_2 in health benefits. Specific climate interventions will vary in the health co-benefits they provide as well as in potential harms that may result from their implementation. Rigorous assessment of these health impacts is essential for guiding policy decisions as efforts to reduce GHG emissions increase in scope and intensity.

1 INTRODUCTION

The serious threat posed by climate change to human health and well-being is leading to new national and international policies and programs aimed at reducing greenhouse gas (GHG) emissions. Most of the debate surrounding these new policies and programs focuses on the magnitude of GHG reductions achievable and the associated economic costs. However, discussions of costs often fail to recognize the co-benefits that GHG reduction activities may provide through reductions in harmful air pollutants such as particulate matter (PM).

The health co-benefits of climate change mitigation activities may be substantial, but to date, co-benefits studies have had limited usefulness in policy decision making because of variability in methods used, health outcomes assessed, the limited number of sectors evaluated, and uncertainty regarding climate change related damages (Bell et al., 2008, Nemet et al., 2010; Jack and Kinney, 2010, Groosman et al., 2011).

Our study assesses the gross health co-benefits of climate change mitigation activities through use of an integrative framework, proposed by Pacala and Socolow (2004), that facilitates comparison of different sectors and mitigation options oriented towards stabilization of CO_2 emissions. The framework describes a "wedge-based" approach to demonstrate the current technical feasibility of reducing global CO_2 emissions to the degree necessary to stabilize atmospheric concentrations. The authors identified 15 available technologies that could each deliver 1/7 of the total CO_2 reduction needed to keep emissions constant at the 2004 level—then estimated to be ~26 billion metric tons of CO_2 per year ($GtCO_2$/yr)[1]—over the next 50 years, putting the world on a path toward stabilizing CO_2 concentrations around 500 parts per million (ppm) in the beginning of the 22nd century. The concept of "wedges" arises from considering a graph of projections of future CO_2 emissions under a "business-as-usual" (BAU) scenario, drawing the horizontal or

[1] Pacala and Socolow defined a wedge in terms of metric tons of carbon (tC) rather than tCO_2, but most researchers now express CO_2 emissions in terms of tCO_2. The conversion ratio is 1 tCO_2 = 44/12 tC, or ~3.7:1. Global CO_2 emissions since publication of this paper have exceeded even these pessimistic projections; global emissions were 29 $GtCO_2$/yr in 2004, and reached 34 $GtCO_2$/yr in 2010 (Boden et al., 2011).

negatively sloped line from the present level of emissions to the emissions level necessary to achieve the desired climate outcome, and then dividing the triangular space between the BAU line and the desired line into "wedges," each of which represents the phased-in implementation of a CO_2 reduction activity over the 50-year time frame. We note that inclusion of the technologies described by Pacala and Socolow was based solely on technical feasibility, e.g., activities were excluded if they were deemed unable to scale up quickly enough or lacked sufficient global potential to reduce CO_2 emissions by ~3.7 $GtCO_2$/yr in 2054. The authors were not concerned with economic feasibility, cost-effectiveness, or any other measures of net benefits from their specified wedge technology investments.

Pacala and Socolow's (2004) wedge-based approach provides a unique framework through which to perform a health co-benefits analysis for the U.S. We apply this framework to estimate the expected health co-benefits associated with reductions in ambient $PM_{2.5}$ concentrations from implementation of specific, technically feasible GHG mitigation options over a defined time. Our purpose is not to present an array of GHG mitigation options that are individually scaled in terms of pace and degree of implementation by similar cost effectiveness or technical feasibility. Rather, as Pacala and Socolow have done, we start with an assumption of equal GHG reductions from each GHG mitigation option and estimate the associated health benefits that result from those equal "wedges" of CO_2 reduction. Our results are discussed within a larger policy context of information needs for decision-making and are used to illuminate the types of analyses necessary to fully understand both the costs and benefits of climate change mitigation actions. A full assessment of the technical feasibility and cost-effectiveness of each mitigation option was outside of the scope and purpose of this paper.

2 METHODS

Our analysis consisted of four main parts: 1) determination of CO_2 reduction scenarios; 2) estimation of future changes in PM pollution; 3) calculation of health co-benefits; and 4) economic valuation of health endpoints.

2.1 Determination of CO_2 Reduction Scenarios

2.1.1 Identification of Wedge Activities

Pacala and Socolow identified technically feasible technologies for reducing CO_2 emissions. From their list, we chose activities that could have been implemented in the U.S. in the year 2010, were associated with emissions of PM or PM precursors (NOx and SOx), and for which adequate baseline data were available. Nine specific activities were identified, including increased efficiency of vehicles, buildings, and power plants, and fuel substitution for vehicles and electricity generation (Table 1 provides the complete list of wedges included in the analysis). We also added one new wedge, which was not identified by Pacala and Socolow, but which had sufficient CO_2 reduction potential and would result in significant PM reductions: heavy-duty vehicle (HDV) fuel efficiency.[2] The activities included in our analysis fall into three main sectors: transportation, buildings, and power plants.

[2] Assumed in this wedge is the rapid commercialization of highest-efficiency engines, improved aerodynamics, lighter-weight vehicles, more efficient onboard components, early retirement of inefficient vehicles, increased logistics efficiency, and shifting a portion of freight transport to more efficient modes (ship and rail) wherever possible.

TABLE 1 Potential Reductions in Levels of Activity Corresponding to One Wedge of CO_2 Reduction

Wedge Activity	Baseline Levels of Activity (Projections) 2010	2020	2030	2060	Percentage Reduction in Activity for One Wedge 2020	2030	2060
Transportation[a,b]							
Efficient Vehicles		Million barrels/day					
1) Increase light-duty vehicle fuel efficiency	9.00	10.43	12.15	19.24	11%	19%	29%
2) Increase heavy-duty vehicle fuel efficiency	2.86	3.33	3.98	6.80	30%	50%	73%
Reduce Vehicle Miles Traveled		Billion miles/year					
3) Reduce light-duty vehicle miles traveled	2799	3474	4226	7616	11%	19%	29%
Buildings[a]							
Efficient buildings		Terawatt-hours/year					
4) Increase electric end-use building efficiency	2882	3395	3958	5642	8%	13%	26%
		Quads/year					
5) Increase direct fuel end-use building efficiency	10.88	11.72	12.22	13.69	23%	44%	98%
Power Plants[a]							
Efficient Coal Plants		Quads/year					
6) Increase efficiency of baseload coal plants	22.13	25.05	31.14	39.65	6%	10%	21%
Coal Baseload Power Substitutions		Terawatt-hours/year					
7) Substitute natural gas	2090	2418	3191	4765	11%	19%	52%
8) Substitute nuclear power	2090	2418	3191	4765	6%	10%	21%
9) Substitute wind power	2090	2418	3191	4765	6%	10%	21%
10) Substitute solar photovoltaic power	2090	2418	3191	4765	6%	10%	21%

Sources: [a]EIA 2007 [b]EPA 2007

2.1.2 Defining CO_2 Wedges

Pacala and Socolow defined a global wedge as an activity that avoids emissions of ~3.7 $GtCO_2$ per year after 50 years. Because wedges are defined as triangles depicting avoided emissions that grow linearly with time, cumulative avoided emissions are equal to ~90 $GtCO_2$. These global wedge definitions can be scaled to a particular sector or region. For this analysis we define one "U.S. wedge" as about one-fifth of a global wedge (750 $MtCO_2$/yr after 50 years, or ~19 $GtCO_2$ cumulatively), as U.S. fossil fuel CO_2 emissions comprised about 20% of global emissions between 2005 and 2010 (EIA, 2011). The pace of implementation of these wedges is consistent with assessments of feasibility in the U.S. (DOE, 2006; EPA, 2007; Duke et al., 2008; Eaken and Goldstein, 2008), although some wedges may require more aggressive policies than others.

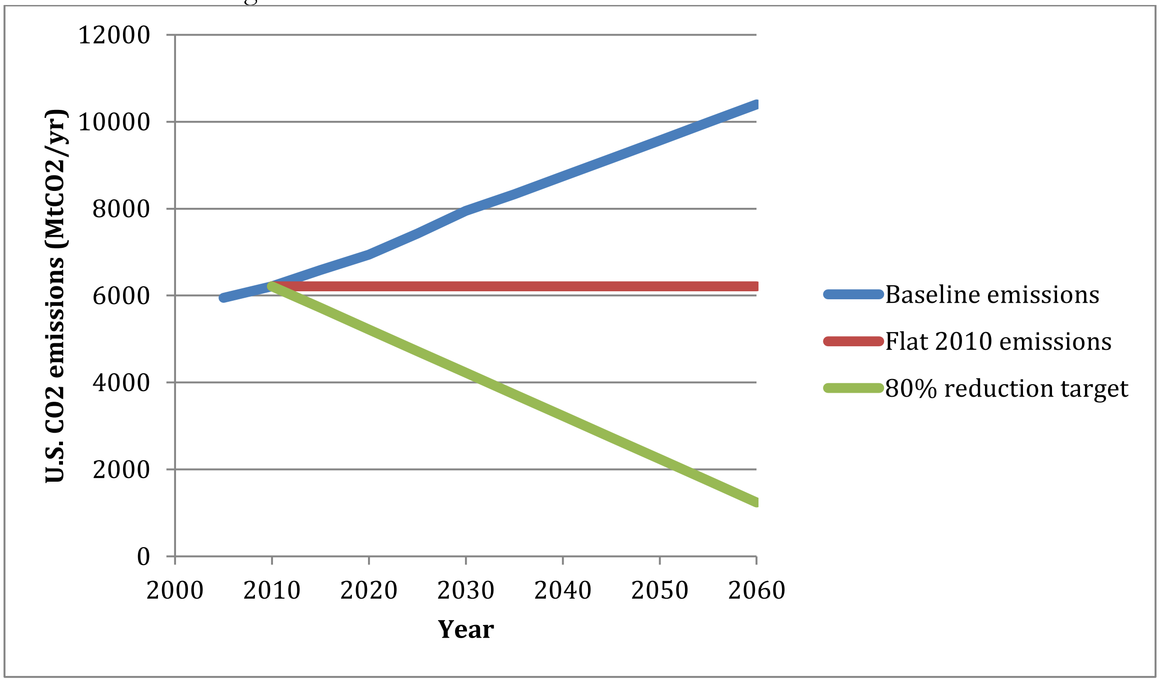
2.1.3 Determining CO_2 Reductions

The reduction in activity or amount of substitution needed to achieve one full U.S. wedge of CO_2 reduction by 2060 was estimated for each of the ten wedge activities.[3] We assumed that implementation of the wedge activities listed in Table 1 would have started as early as 2010. Implementation for the baseline case was assumed to be linear, such that 20% of the needed reduction or substitution would occur by the year 2020. For the "optimistic" case scenario, it was assumed that implementation accelerated by ten years initially such that 40% of the needed reduction or substitution occurred by 2020. For direct fuel use in buildings (wedge 5), the required GHG reductions by 2060—nearly 100%—could only be achieved if aggressive electrification of building heat was pursued in tandem with increased efficiency, replacing nearly all direct fuel use appliances by 2060.

Table 1 provides a summary of the baseline projected levels of activity (in appropriate units) for each wedge and the corresponding reduction in activity for one wedge of CO_2 reduction for the years 2020, 2030 and 2060. Given the projected rate of increase of U.S. CO_2 emissions, ~6 wedges would be needed to keep emissions flat at the 2010 level of ~6 $GtCO_2$/yr. To reduce emissions to 80% below the 2010 level—consistent with IPCC recommendations for developed countries (Fisher et al., 2007), President Obama's stated goal for the United States (The White House, 2009) and similar to long-term California GHG policy (CDOT, 2005)—would require ~12 wedges. See Figure 1.

[3] All projections are based on 2007 data.

FIGURE 1 Projected U.S. CO_2 emissions scenarios, showing baseline emissions, flat 2010 emissions, and an 80% reduction target



2.2 Estimating Future Changes in PM Pollution

For wedges 3-8, reductions in the emission of conventional air pollutants were assumed to scale proportionally with reductions in CO_2 for each time point. For example, if energy efficiency for power plants was estimated to reduce CO_2 emitted by 10%, an identical reduction was assumed for PM and its precursors. PM reductions were assumed to affect all populations and regions equally and were applied for each activity and activity combination to the total future year estimated PM and PM precursor emissions.

Improvements in LDV efficiency (wedge 1) could be decoupled from conventional pollutant emissions as vehicle PM standards are not directly benchmarked to fuel use. An additional concern is that, historically, fuel efficiency policies only applied to new vehicles, delaying fleet-wide efficiency improvements until old vehicles are retired. We used a simple fleet turnover model to estimate future fleet-wide fuel and PM reductions over time given new vehicle efficiency standards (see Appendix A). With current LDV fleet turnover rates, adopting new LDV efficiency standards soon (e.g., in 2015) would affect almost all vehicles by 2030, but only ~50% of the fleet in 2020. Because older vehicles emit more PM per kg of fuel burned compared to newer vehicles, a LDV standard that improves efficiency (and PM emissions) by 30% for vehicles produced in 2015 and after would reduce fleet-wide PM by ~10% by 2020 and close to 30% by 2030. Thus, standard efficiency policies could achieve fleet-wide CO_2 and PM reduction targets by 2030; in fact, recently the U.S. Environmental Protection Agency (EPA) effectively doubled fuel efficiency requirements for new LDVs by 2025. However, to achieve the same CO_2 and PM reductions by 2020 would require increased fuel efficiency of new vehicles and early retirement of a portion of older vehicles.

Among HDVs (wedge 2), a larger portion of fleet-wide GHG and especially PM emissions are attributed to older vehicles compared to LDVs, as HDVs generally have longer useful lifetimes than LDVs and stringent emissions controls were implemented for new HDVs more recently than similar controls for LDVs. A 30% improvement in efficiency (and PM emissions) for new HDVs starting in 2015 would reduce fleet-wide PM emissions by only 2% in 2020 and 9% in 2030 (see Appendix A). Thus, standard new vehicle efficiency regulations would not achieve GHG reduction targets and would generate little co-benefits by 2030. To obtain the 50% GHG reductions targets in wedge 2 by 2030, a policy to increase new vehicle efficiency would need to be coupled with policies to support early retirement of a portion of older vehicles.[4] Policies to support early retirement of HDVs are technically feasible, but costly.

Variable renewables (wind and solar—wedges 9 and 10) can offset fossil power generation. As the supply of renewables increases some regions will begin to intermittently curtail baseload supply resources such as coal power. Zhai et al. (2012) used an hourly energy system model to investigate technical feasibility and simulate deployment of 10% solar photovoltaic power into 10 regions across the United States. They found that the introduction of variable renewables like solar would reduce a proportional amount of coal power in regions with specific prior generation resource mixes characterized by high dependence on coal and nuclear power.

[4] Another way to increase sector-wide GHG reductions would be to couple fuel efficiency improvements with strategies to reduce vehicle miles travelled (VMT), such as better logistics and switching to more efficient transportation modes (ship and rail) wherever possible.

Much of the area from the Dakotas through West Virginia has a generation mix that fits the profile described by Zhai et al. (2012), and that area contains roughly 60% of the country's coal power generation (see Appendix B). Thus, to achieve the full co-benefits from wedges 9 and 10, deployment would need to be targeted to these regions.

As EPA rules (such as the Propose Rule on Carbon Pollution Emission Guidelines for Existing Stationary Sources: Electric Utility Generating Units, EPA, 2014) may reduce future conventional pollutant emissions from power plants, the determination of an appropriate baseline for co-benefits estimation is critical. Legal proceedings surrounding EPA rulings introduced significant uncertainty for predicting a co-benefit baseline, thus we chose a moderate baseline reflecting some EPA mandated controls but not the full suite of controls possible if the EPA faced no legal challenges. The baseline is derived from EPA estimates of national emissions for 2020 primary PM, SOx, and NOx for coal-fired power plants developed for the Clean Air Interstate Rule (CAIR) Regulatory Impact Assessment (RIA) (EPA 2005). These estimates are similar to estimates from the Energy Information Administration (EIA 2007). We note that although recent expansion of natural gas and wind power has displaced some coal power generation, we chose a baseline developed prior to this shift and explicitly specify increased use of natural gas and wind power as wedges.

2.3 Calculation of Health Co-benefits

2.3.1 Health Impact Function

Health impact functions relate changes in health outcomes to changes in ambient $PM_{2.5}$ concentrations. Health impact functions typically consist of four components: a concentration-response (CR) function derived from epidemiological studies, a baseline incidence rate for the health effect of concern, the affected population, and the projected change in ambient $PM_{2.5}$ concentrations. CR functions are a standard approach for estimating health burdens associated with an exposure; they estimate the extent of impact by level of exposure. The majority of the studies used to estimate CR functions assume the relationship between adverse health outcomes and concentrations of $PM_{2.5}$ is best described as log-linear, where the natural logarithm of the health response is a linear function of $PM_{2.5}$ concentrations; this assumption is based on a rich literature base (EPA 2006).

For all wedges except wedge 5 (increased direct fuel end-use building efficiency), intake fractions are used to calculate the exposure concentration of $PM_{2.5}$ associated with a given amount of emissions in the year 2020. An intake fraction is the fraction of $PM_{2.5}$ released from a source (such as motor vehicles or power plants) that is eventually inhaled or ingested by a population. It is dimensionless and can be defined as the ratio of the time-averaged mass of pollutant inhaled by a population to the time-averaged total amount of pollutant emitted (Levy et al. 2002). For more information, see Appendix D, section 1.

Wedge 5 differed from the other wedges in being an "area source" rather than associated with air pollution from electric generating units or mobile sources. To provide an estimate, we used an alternative estimation method for health co-benefits associated with one wedge of CO_2 reductions from direct fuel end-use in buildings, based on data from the National Emissions Inventory for direct fuel combustion in residential and commercial/institutional buildings, and using the economic benefits per ton calculated for area sources by Fann et al. (2012). Health functions are based on Krewski et al (2009). Because of the differences in methods, results using this method are not directly comparable to results for other wedges. Nonetheless, we include results for this method to demonstrate that potential benefits are of the same order of magnitude as those of other wedges (see section 3).

2.3.2 Health Endpoints and CR Functions

Our analysis relied on the EPA's Regulatory Impact Analysis (RIA) for $PM_{2.5}$ for identification of relevant health endpoints as well as the primary studies to derive CR functions (EPA 2006). EPA identifies four categories of health endpoints: premature mortality, chronic illness, hospital admissions, and a category of other. EPA's choice of endpoints is based on a weight-of-evidence approach, taking into account factors such as biological plausibility of effects, availability of CR functions, cohesiveness of results across peer-reviewed studies, and public health impact (e.g. hospital admissions). For greater detail, readers are referred to the $PM_{2.5}$ RIA (EPA 2006).

In general, selection of studies included considerations of the study design and location, characteristics of study populations, study endpoints, and whether studies were peer-reviewed. For endpoints where greater than one primary study was identified, we pooled CR coefficients via fixed effects inverse weighting. Fixed effects pooling weights each CR estimate in proportion to the inverse of its variance; studies with lower standard errors are given greater weight in the final pooled estimate. Appendix D, section 2 provides a summary of the health endpoints included in our analysis, the peer-reviewed studies used to generate CR coefficients, and the age group targeted in each study.

2.3.3 Baseline Health Incidence Rates

Baseline incidence rates for each health endpoint are needed to translate the relative risk of health effect derived from the CR function to the absolute change in health effect, or the number of avoided cases per year. Table D2 in Appendix D provides a summary of baseline incidence rates and their sources. Whenever possible, average baseline incidence rates for different age groups were determined from national survey data. For those endpoints with survey data, we chose the most recent incidence rate available to include in the analysis. We also analyzed the previous 5 years of survey data to assess trends and ensure comparability of incidence rate estimates between years. Most data came from publicly available Centers for Disease Control and Prevention databases (age- and cause-specific mortality, respiratory- and cardiovascular-related hospital admissions, emergency-room visits for asthma, and acute bronchitis, work-loss days, and minor-restricted activity days). For other endpoints, the only incidence data for the population of concern comes from the primary study itself. In these cases, the incidence in the study population is assumed to represent the incidence in the national population. More detail on incidence data is presented in Appendix D, section 3.

2.4 Economic Valuation of Health Endpoints

To estimate the gross economic benefits of reductions in $PM_{2.5}$ concentrations due to CO_2 wedge activities, we relied on economic valuation estimates provided by EPA's $PM_{2.5}$ RIA and through guidance provided for BenMap, EPA's benefits mapping and analysis program (EPA 2006, 2008). In general, EPA applied Value-of-Statistical-Life (VSL), willingness-to-pay (WTP), or direct cost approaches to health endpoints to generate a Year 2000 U.S. dollar (USD)-adjusted monetary value associated with their reduction. Details of the valuation of benefits can be found in Appendix D, section 4.

2.5 Uncertainty Analysis

The change in health and economic outcomes associated with different wedge activities for the year 2020 depends on five main analysis inputs: change in $PM_{2.5}$ emissions, CR functions, baseline health incidence rates, 2020 population projections, and intake fractions (to relate emissions of $PM_{2.5}$ to concentrations). Each is uncertain to a different degree and we characterized the total uncertainty surrounding final health and economic outcomes through Monte Carlo uncertainty propagation of the inputs. For more information on the uncertainty analysis, see Appendix D, section 5.

3 RESULTS

GHG reduction activities have the potential for substantial, near-term health co-benefits related to subsequent reductions in PM air pollution. Table 2 shows the total economic benefits (in discounted Year 2008 USD) associated with reduction in adverse health outcomes from one wedge of CO_2 reduction for the year 2020. Benefits under the various activity options (not including wedge 5; see section 2.3.1) range from approximately \$6 to \$14 billion under the baseline implementation scenario. The more optimistic, rapid implementation scenario yielded total benefits ranging from \$10 to \$24 billion. For comparison, our estimate for wedge 5 resulted in $3.6 billion of health benefits with the baseline scenario and $6.8 billion with the optimistic scenario in 2020. Note that these results were obtained without adjusting population (from 2005) or emissions (from 2008) to 2020. While not directly comparable to results for other wedges, they nonetheless demonstrate potential benefits in the same order of magnitude.

TABLE 2 Risk Reduction and Economic Benefit Estimates of Implementing Single Wedge Activities

	Economic Benefit in 2020 (All Endpoints Combined) (Millions/U.S.$)	
Wedge Activities	**Baseline Scenario**	**Optimistic Scenario**
1. Increase light-duty vehicle fuel efficiency	$5,900	$10,000
2. Increase heavy-duty vehicle fuel efficiency	$7,700	$13,000
3. Reduce light-duty vehicle miles traveled	$6,000	$10,000
4. Increase electric end-use building efficiency	$10,300	$17,000
5. Increase direct fuel end-use building efficiency	$3,600*	$6,800*
6. Increase efficiency of baseload coal plants	$7,700	$13,000
7. Substitute natural gas for coal power	$14,000	$24,000
8. Substitute nuclear power for coal power	$7,600	$13,000
9. Substitute wind power for coal power	$7,800	$13,000
10. Substitute solar photovoltaic power for coal power	$7,700	$13,000

*Not directly comparable to other wedges (see section 2.3.1)

The magnitude of health co-benefits varied significantly among wedge options. A wedge of natural gas substitution for coal power resulted in $14 billion in health co-benefits, while a wedge of improved LDV fuel efficiency or reductions in VMT resulted in around $6 billion. These differences reflect the ratio between CO_2 and conventional pollutant emissions for a given source and the percentage reduction in the baseline activity of the source needed to produce one U.S. wedge, or 750 $MtCO_2$ of reductions in 2060. Natural gas combustion leads to relatively fewer emissions of conventional air pollutants for a given amount of CO_2 emissions, and therefore substitution of enough coal to achieve a full wedge of CO_2 reductions results in substantial reductions in conventional air pollutant emissions. Conversely, one wedge of end-use efficiency in buildings results in less health co-benefits than one wedge of power plant efficiency. This is because the reductions in electricity generation and associated air pollution emissions were assumed to be proportionally spread among all different sources of electric power in assessing building efficiency, whereas the efficiency improvements in coal-fired power plants result directly in reductions in air pollution emissions from that source alone.

We performed an additional sensitivity analysis to assess what parameters contributed the greatest amount to the overall variance. In all analyses, the CR function for the health endpoint and the percentage reduction associated with the wedge activity were the two greatest contributors. In general, the CR function was the greatest contributor for mortality endpoints, while the percentage reduction was the dominant source of variability for asthma.

4 DISCUSSION

This study offers a framework for comparing the health co-benefits for U.S. climate change mitigation activities across multiple sectors. Pacala and Socolow (2004) demonstrated how selection among 15 "wedges," or specific technological activities, could achieve sufficient CO_2 reductions to stabilize global emissions. We defined an appropriate "wedge" for the U.S. and identified benefits to human health through reductions in secondary PM emissions. While other considerations are important to decision making on climate change mitigation policy, including net costs of implementation, equity and social justice implications, and technical feasibility, our intent is to demonstrate a method to estimate the gross economic value of health benefits and encourage that these analyses be incorporated into climate policy decision making processes.

Comparison with other studies reveals that our results are of similar magnitude, with many thousands of premature deaths avoided and gross economic benefits in the tens of billions of dollars associated with reducing GHG emissions. Expressed in terms of dollars of benefits per ton of CO_2 reduced, this study, with individual wedges offering between \$40 and \$93 per tCO_2 in health benefits, overlaps with the range of other studies. Values from the review by Nemet et al. (2010) for the U.S. ranged from \$4 to \$116 per tCO_2, while Groosman et al. (2011) reported values of \$1 to \$77 per tCO_2.

To place our calculated gross economic health benefits in context, estimated implementation costs for wedge activities from the recent literature are summarized in Table E2 in Appendix E. For most wedges, the range in cost is spanned by –\$90 and \$62 per tCO_2.[5] The exceptions are wedge 1 (increased LDV fuel efficiency), wedge 6 (increased efficiency of baseload coal plants), and wedge 8 (substitution of nuclear power for coal baseload power) that have much higher upper-bound cost estimates (between \$292 and \$818 per tCO_2), but lower-bound cost estimates (between –\$108 and \$88 per tCO_2) that are nearly within the range of the other wedges. The interpretation of these results is that all wedges might be implementable at a cost of ≤\$88 per tCO_2 (and possibly zero or negative cost), but three wedges (1, 6 and 8) could become cost-prohibitive if their upper-bound estimates reflect future reality. Together with our estimates of the health co-benefits of wedges between \$40 and \$93 per tCO_2, the net implementation cost of most wedges could be significantly lower than \$88 per tCO_2 (or even negative), but the uncertainty range is still large.

In carrying through the analysis to the economic valuation of reduced adverse health outcomes, a number of critical assumptions and methodological choices were made. Because our analysis assessed relative differences among reductions from specific sources, a method of estimating population-level exposures based on specific source reductions in primary pollutant emissions was necessary. We chose intake fractions as an initial approach in order to provide computationally simple yet still scientific way of estimating dispersion of emissions. The use of intake fractions involves several major assumptions, including spatially uniform reduction of emissions, continued validity of distribution of sources and dispersion modeling upon which the intake fractions were originally based for 2020, and similar spatial distribution of the U.S. population in 2020. Models that take into account individual power plants and model air concentrations more directly would allow greater confidence in the results.

[5] Negative values indicate a net cost savings over the life of the system (vehicle, building, power plant, etc.).

In this paper, PM and precursor emissions reductions are assumed to occur in direct proportion to CO_2 emissions. This assumption might be violated if any sources are regulated by flexible market-based programs, such as allowance trading. Specifically, binding CO_2 limits may cause some plants to retire, thus lowering overall SO_2 and/or NO_x emissions. If SO_2 and/or NO_x were not also subject to binding caps, sources of those pollutants other than CO_2 producing coal-fired plants may increase their emissions. (Groosman et al., 2011). In this situation, the co-benefits associated with reductions in coal-fired power generation capacity would be diminished.

We have used health cost data developed by EPA for air pollution regulatory impact assessment. This assumes that these willingness-to-pay and health cost data remain valid in 2020. We have neither applied discount rates to these values nor attempted to estimate future values adjusted for inflation of health care costs and other economic values due to added uncertainty introduced by these extra steps and the intention to facilitate comparisons among options rather than provide specific economic benefit predictions.

While evaluating the efficacy of individual wedge activities is useful, an evaluation of multiple activities implemented at one time would be important in assessing the full array of policy options. The combined impacts of wedges that address sequential factors in the chain of emissions production would likely be less than additive for both carbon dioxide and particulate matter. For instance, either a 50% improvement in fuel efficiency for light-duty vehicles (LDVs) or a 50% reduction in vehicle-miles traveled (VMT) would individually result in a 50% reduction in CO_2 emissions for the LDV transportation sector. However, when combining these two activities, the net reduction in CO_2 emissions (and PM, if assumed to track linearly) is 75%, rather than 100%, because the emission reductions from reduced VMT will be smaller if the vehicles are also more fuel-efficient. Conversely, if the analysis is constrained to maintaining a full wedge of CO_2 reduction from both activities after combination, the PM reductions would also be additive. Additional analysis of combined wedges can be found in Appendix C and Appendix E.

In conclusion, avoided adverse health outcomes related to reduced PM exposures from climate change policies can be anticipated to offset the costs of implementing such policies. Our estimates suggest that the economic benefits from one wedge of PM reductions would be in a range from $6 to $14 billion per year in 2020. Specific climate interventions will vary in the health co-benefits they provide as well as in potential harms that may result from their implementation. Rigorous assessment of these health impacts is essential for guiding policy decisions as efforts to reduce GHG emissions increase in urgency and intensity.

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6 REFERENCES

Bell, M. L., Davis, D. L., Cifuentes L. A., Krupnick, A. J., Morgenstern R. D., and Thurston, G. D.: 2008, 'Ancillary human health benefits of improved air quality resulting from climate change mitigation', Environ Health. Jul 31;7:41.

Boden, T.A., Marland, G., Andres, R.J.: 2011, Global, Regional, and National Fossil-Fuel CO_2 Emissions. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tenn., U.S.A. doi 10.3334/CDIAC/00001_V2011.

CDOT (California Department of Transportation): 2005. 'Executive Order S-3-05 by the Governor of the State of California,' Available online: http://www.dot.ca.gov/hq/energy/ExecOrderS-3-05.htm [Accessed March 14, 2013].

DOE (Department of Energy): 2006, Roadmap and Technical White Papers, 21st Century Truck Partnership, Office of Energy Efficiency and Renewable Energy, 21CTP-0003. Available online: http://www1.eere.energy.gov/vehiclesandfuels/pdfs/program/21ctp_roadmap_2007.pdf [Accessed March 8, 2013].

Duke, R., Lashof, D., Dornbos, B., Bryk, D., Greene, N., Hwang, R., Lovaas, D., Mugica, Y., Spencer, T., Steelman, J., Tonachel, L.: 2008. The New Energy Economy: Putting America on the Path to Solving Global Warming, Natural Resources Defense Council Issues Paper. Available online: http://www.nrdc.org/globalWarming/energy/eeconomy.pdf [Accessed March 8, 2013].

Eaken, A. M., Goldstein, D. B.: 2008, 'Quantifying the Third Leg: The Potential for Smart Growth to Reduce Greenhouse Gas Emissions,' ACEEE Summer Study on Energy Efficiency in Buildings. Available online: http://www.aceee.org/files/proceedings/2008/data/papers/11_607.pdf [Accessed March 8, 2013].

EIA (Energy Information Administration): 2007, Annual Energy Outlook 2007: With Projections to 2030. U.S. Department of Energy, DOE/EIA-0383(2007). Available online: http://www.eia.gov/oiaf/archive/aeo07/index.html [Accessed October 27, 2008].

EIA (Energy Information Administration): 2011, International Energy Outlook 2011, U.S. Department of Energy, DOE/EIA-0484(2011). Available online: http://www.eia.gov/forecasts/ieo/ [Accessed March 8, 2013].

EPA (U.S. Environmental Protection Agency): 2005, Regulatory Impact Analysis for the Final Clean Air Interstate Rule. EPA-452/R-05-002. Office of Air and Radiation, Air Quality Strategies and Standards Division, Emission, Monitoring, and Analysis Division and Clean Air Markets Division, Washington DC.

EPA: 2006, Regulatory Impact Analysis. National Ambient Air Quality Standards for Particle Pollution. Office of Air Quality Planning and Standards, Office of Air and Radiation, Washington DC.

EPA: 2007, A Wedge Analysis of the U.S. Transportation Sector. EPA 420-R-07-007. Transportation and Climate Division, Office of Transportation and Air Quality, Washington DC. Available online: www.epa.gov/otaq/climate/420r07007.pdf [Accessed October 27, 2008].

EPA: 2008, BenMap: Environmental benefits mapping and analysis program. User's Manual Appendices. Prepared for Office of Air Quality Planning and Standards. Prepared by Abt Associates.

EPA: 2014, Part II: Environmental Protection Agency, 40 CFR Part 60: Carbon Pollution Emission Guidelines for Existing Stationary Sources: Electric Utility Generating Units; Proposed Rule, Federal Register, 79(117):34830–34958. Available online: http://www.gpo.gov/fdsys/pkg/FR-2014-06-

18/pdf/2014-13726.pdf.

Fann N, Baker KR, Fulcher CM. Characterizing the $PM_{2.5}$ -related health benefits of emission reductions for 17 industrial, area and mobile emission sectors across the U.S. Environ Int. 2012 Nov 15;49:141-51.

Fisher, B.S., N. Nakicenovic, K. Alfsen, J. Corfee Morlot, F. de la Chesnaye, J.-Ch. Hourcade, K. Jiang, M. Kainuma, E. La Rovere, A. Matysek, A. Rana, K. Riahi, R. Richels, S. Rose, D. van Vuuren, R. Warren: 2007. Issues related to mitigation in the long term context (Chapter 3), In: Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Inter-governmental Panel on Climate Change [B. Metz, O.R. Davidson, P.R. Bosch, R. Dave, L.A. Meyer (eds)], Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. Available online: http://www.ipcc.ch/publications_and_data/ar4/wg3/en/ch3.html [accessed March 14, 2013].

Groosman B., Muller N.Z., O'Neill-Toy E.: 2011, "The Ancillary Benefits from Climate Policy in the United States, Environ Resource Econ 50, 585-603

Jack, D., Kinney, P.: 2010, 'Health co-benefits of climate mitigation in urban areas', Current Opinion Environ Sustain 2, 172-177.

Krewski D., Jerrett M., Burnett R.T., Ma R., Hughes E., Shi Y., Turner M.C., Pope C.A. III, Thurston G., Calle E.E., Thun M.J., Beckerman B., DeLuca P., Finkelstein N., Ito K., Moore D.K., Newbold K.B., Ramsay T., Ross Z., Shin H., Tempalsk B.: 2009. Extended Follow-up and Spatial Analysis of the American Cancer Society Study Linking Particulate Air Pollution and Mortality. Research Report 140, Boston: Health Effects Institute. http://www.healtheffects.org/Pubs/RR140-Krewski.pdf [accessed 13 November 2014].

Levy, J. I., Wolff S. K. and Evans J. S.: 2002, 'A Regression-Based Approach for Estimating Primary and

Secondary Particulate Matter Intake Fractions', Risk Anal. 22(5), 895-904.

Nemet GF., Holloway T., Meier P.: 2010, 'Implications of incorporating air-quality co-benefits into climate change policymaking', Environ Res Lett 5, 014007

Pacala, S. and Socolow, R.: 2004, 'Stabilization wedges: Solving the climate problem for the next 50 years with current technologies', Science. 305, 968-972.

The White House (2009) Remarks by the President at the Morning Plenary Session of the United Nations Climate Change Conference. Available online: http://www.whitehouse.gov/the-press-office/remarks-president-morningplenary-session-united-nations-climate-change-conference.

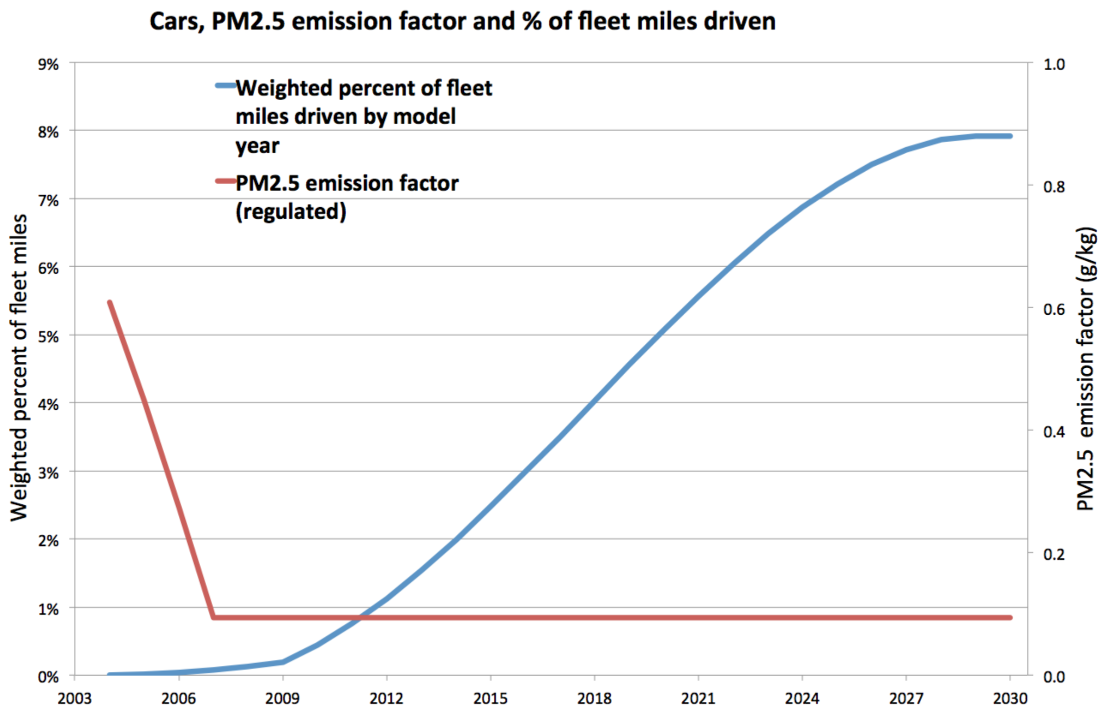
Zhai, P., Larsen, P., Millstein, D., Menon, S., Masanet, E.: 2012, 'The potential for avoided emissions from photovoltaic electricity in the United States', Energy 47, 443-450 doi:10.1016/j.energy.2012.08.025

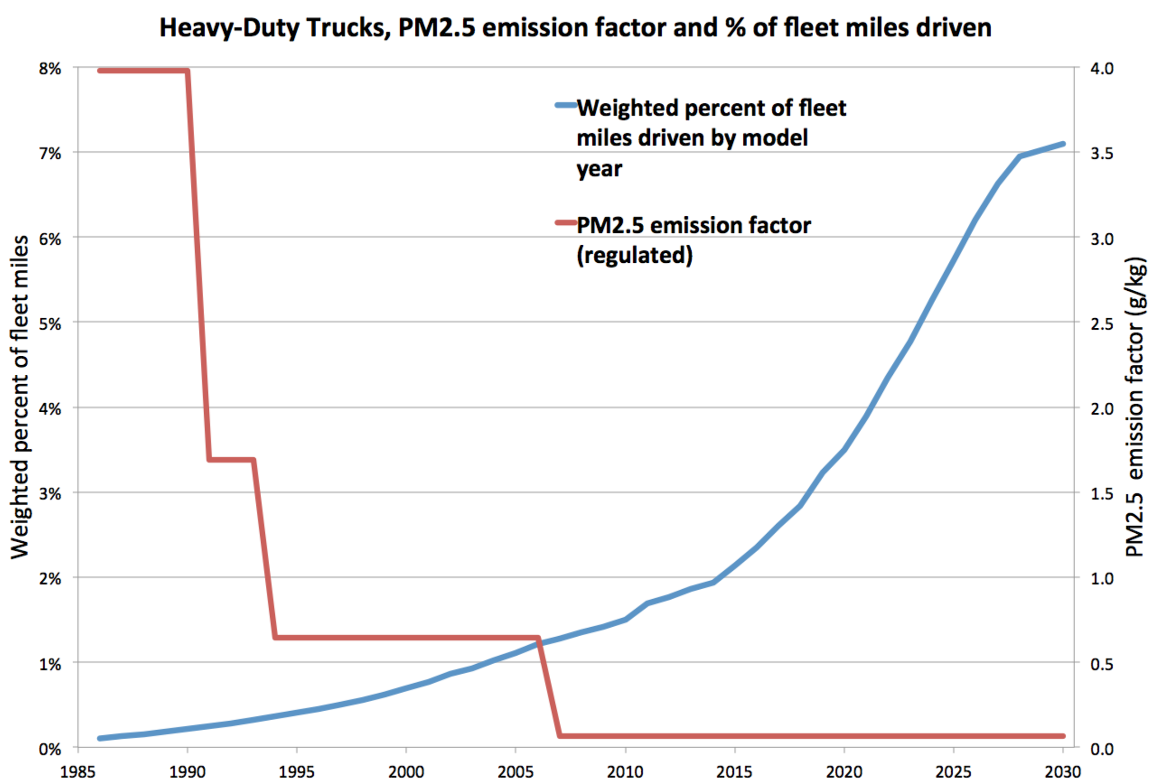
7 APPENDICES

7.1 Appendix A: Fleet turnover analysis

The magnitude of co-benefits achieved from enhancing the fuel economy of the light-duty and heavy-duty vehicle fleet strongly depends on whether new or old vehicles are replaced. Historically, fuel economy regulations have focused on new vehicle requirements due to the difficulties and cost associated with retrofitting or early replacement of used vehicles. Given recent changes to $PM_{2.5}$ and NO_x emission regulations for cars and especially trucks, a GHG reduction policy focusing exclusively on new vehicles would have significantly less co-benefits than one that required replacement of older vehicles. For example, Figure A1 shows projected relative emission factors (g $PM_{2.5}$/ g fuel) and relative fuel-use by model year of cars (top) and trucks (bottom). One key difference between the light-duty and heavy-duty vehicle sectors is that heavy-duty trucks are operated for longer than light-duty vehicles, so the total fleet average emissions for cars respond to reduced new vehicle emission regulations in a shorter time frame than trucks.

Figure A1 Projected relative emission factors (g $PM_{2.5}$/ g fuel) and relative fuel-use by model year of cars (top) and trucks (bottom)





We estimate the reduction of $PM_{2.5}$ emissions from fuel economy improvements in new vehicles starting in 2015 by holding emissions per fuel burned from model years before 2015 constant and applying a factor to fuel-use for each future model year starting in 2015. We then weight the model year emission factor by the relative fuel use expected from each model year (model year % of vehicle fleet * model year % of total miles driven) and sum to find an average fleet emission factor for a future year. The relative age distribution of vehicles is assumed to stay constant over time and is based on separate age distributions for light and heavy-duty vehicles reported by Davis et al. (2011). Emission factors (emissions/g fuel were converted from grams per brake horsepower-hour (gbhp-hr)) are simply based on the allowable emission limit for each model year depending on the regulations at the time (EPA maintains a history of emission regulations, see for example: *http://www.epa.gov/otaq/standards/allstandards.htm*). By comparing the future fleet emission factors we can find the expected magnitude of $PM_{2.5}$ reductions from fuel economy improvements to new vehicles scenarios.

Table A1 shows expected $PM_{2.5}$ reductions from 30, 50 and 100% fuel economy improvements to new vehicles beginning in 2015. Table A1 indicates that by 2030, a 30% fuel economy improvement for new cars starting in 2015 would yield 28% fleet-wide fuel savings and achieve a 23% reduction in $PM_{2.5}$ emissions from cars. By 2030 a 30% fuel economy improvement for new trucks starting in 2015 would yield 23% fleet-wide fuel savings but only achieve a 9% reduction in $PM_{2.5}$ emissions from trucks. Table A1 indicates that requiring new trucks to improve fuel economy starting in 2015 would achieve only marginal co-benefits by 2020. These results show that in order to realize co-benefits from a fuel economy program for heavy-duty trucks a policy must drive early replacement of older trucks as opposed to simply increasing new vehicle fuel economy standards.

Table A1 Expected $PM_{2.5}$ reductions from 30, 50 and 100% fuel economy improvements to new vehicles beginning in 2015

	Fleet-wide fuel reductions				**Fleet-wide PM2.5 reductions**			
	Light-duty		**Heavy-duty**		**Light-duty**		**Heavy-duty**	
Model-year fuel economy improvements (≥2015)	**2020**	**2030**	**2020**	**2030**	**2020**	**2030**	**2020**	**2030**
30%	14%	28%	12%	23%	9%	28%	2%	9%
50%	23%	47%	21%	38%	15%	47%	3%	15%
100% (no combustion)	46%	94%	41%	76%	30%	94%	6%	30%

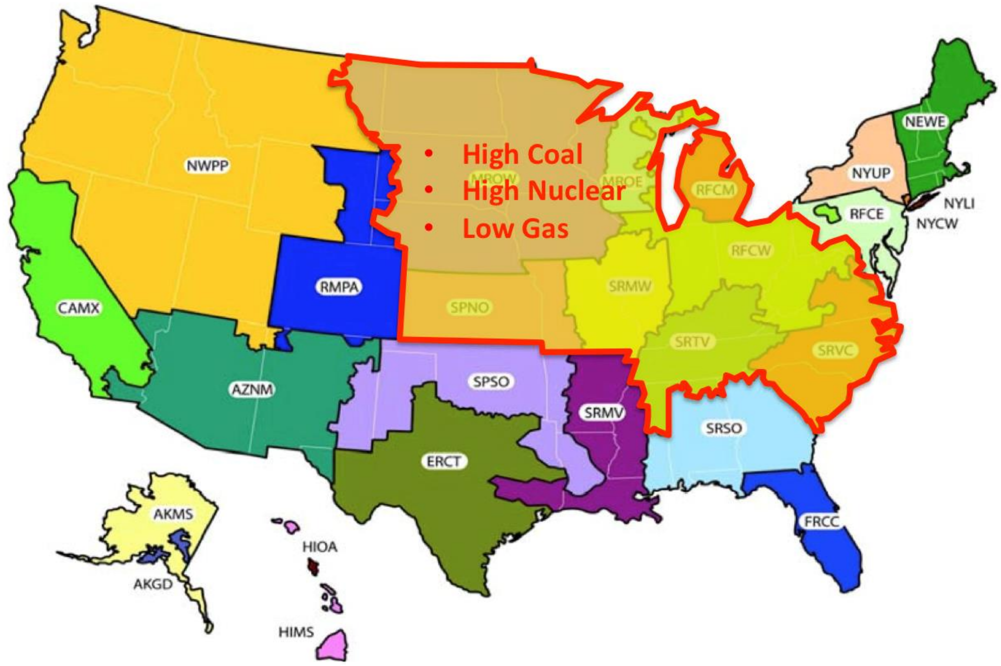
7.1.1 References

Davis, Stacy C., Diegel, Susan W., Boundy, Robert G. "TRANSPORTATION ENERGY DATA BOOK: EDITION 30" Center for Transportation Analysis, Energy and Transportation Science Division, Oak Ridge National Laboratory. June 2011. cta.ornl.gov/data

7.2 Appendix B: Integration of variable renewables

Introduction of variable renewables (wind, solar power) into the power grid can offset fossil generation. The type of fossil generation offset by variable renewables will often be natural gas, as nuclear and coal power plants are often designed to supply primarily base load power. As the supply of renewables increases, some regions will begin to intermittently curtail base load supply resources such as coal power. Zhai et al. (2012) used an hourly energy system simulation model to simulate the deployment of 10% solar power into 10 regions across the United States showing how GHG and local pollutants reductions varied across different regions. Zhai et al. (2012) found that when solar power provided 10% of total energy generated, regions with greater than ~70% of total energy generated from coal power would see reductions in emissions of SO_2, NO_x, and $PM_{2.5}$ from coal power generation. However, the simulation indicated that regions generating less than 60% of their energy from coal power would see little reduction in coal power use with the introduction of 10% solar power generation. The 60-70% threshold for reducing coal power generation discussed above is reduced if a region has energy generated from nuclear power as well. Based on Zhai et al. (2012) we identify regions of the U.S. where coal power generation would be sensitive to 10% penetration of variable renewables (Figure B2). Based on the generation mix described for NERC subregion tabulated by EPA in eGRID (EGRID 2012), much of the area from the Dakota's through to West Virginia has a prior generation mix similar to the generation mix that was identified by Zhai et al. (2012) to show reductions in emissions of pollutants and GHG associated with coal power generation. Areas with lower levels of coal generation, such as Colorado or Texas would see little reductions in coal use from the introduction of 10% variable renewables. The states highlighted in Figure B2 account for roughly 60% of national net coal generation in the U.S. in 2011 (EIA 2013).

Figure B2. NERC sub-regions with areas highlighted where prior generation mix would likely allow for reduced coal power emissions from the integration of 10% variable renewables on an energy basis. (Sub-regions are mapped from EPA's EGRID 2012).



7.2.1 References

EIA, "Electric Power Annual 2011" (2013). Independent Statistics and Analysis, US Energy Information Administration.

EGRID 2012, "eGRID2012 Version 1.0 Year 2009 Summary Tables", US EPA, created April 2012. http://www.epa.gov/cleanenergy/energy-resources/egrid/index.html.

Zhai, P., Larsen, P., Millstein, D., Menon, S., Masanet, E.: 2012, 'The potential for avoided emissions from photovoltaic electricity in the United States', *Energy* **47**, 443-450 http://dx.doi.org/10.1016/j.energy.2012.08.025.

7.3 Appendix C: Combination wedges

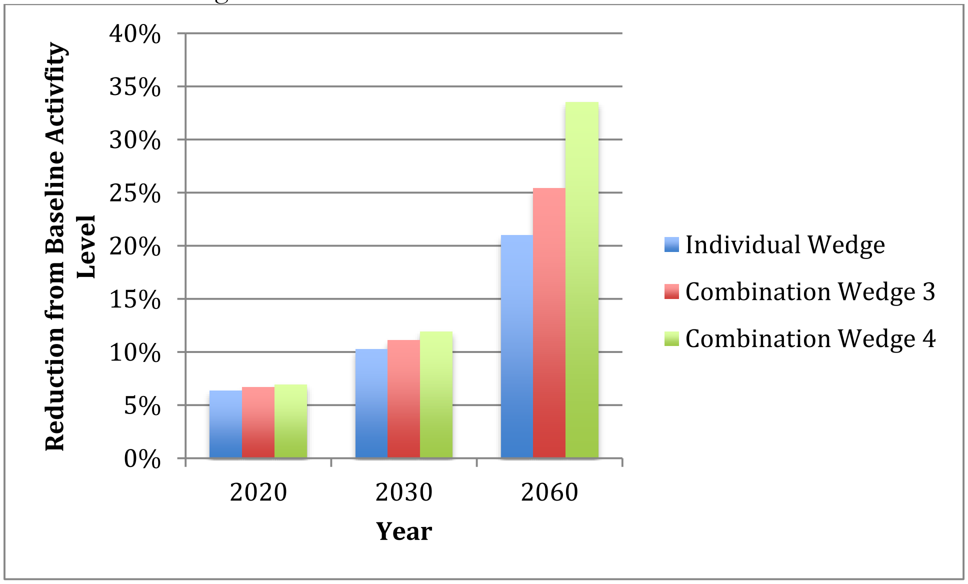
Table C1 describes the combinations of wedge activities used and the estimated potential reductions in activity. The reductions become more pronounced in 2060 as the amount of remaining CO_2 emitted becomes appreciably smaller.

TABLE C1 Potential Reductions for Combined Wedge Activities

Wedge Activities	Number of Total Wedges	Activity	Units	Reduction in Activity 2020	2030	2060
Transportation 1. Combine increased light-duty fuel efficiency and reduction of light-duty vehicle miles traveled	2.0	Vehicle efficiency	Million barrels/day	12%	21%	36%
		Vehicle-miles travelled	Billion miles/year	12%	21%	36%
Buildings 2. Combine increased electric end-use and direct fuel building efficiency	2.0	Electrical efficiency	Terawatt-hours/year	8%	13%	26%
		Direct fuel efficiency	Quads/year	23%	44%	98%
Power Plants 3. Combine increased efficiency of baseload coal plants and two zero-carbon coal substitutions	3.0	Coal plant efficiency	Quads/year	7%	11%	25%
		Coal plant substitutions (per wedge)	Terawatt-hours/year	7%	11%	25%
Buildings and Power Plants 4. Combine efficient buildings wedges and all power plant wedges	5.0	Building electrical efficiency	Terawatt-hours/year	9%	17%	49%
		Building direct fuel efficiency	Quads/year	23%	44%	98%
		Coal plant efficiency	Quads/year	7%	12%	34%
		Coal plant substitutions (per wedge)	Terawatt-hours/year	7%	12%	32%

As an example, Figure C1 shows the change in the required reduction of coal plant energy consumption as the number of combined wedges increases. The reductions are shown for wedge 6 (increased efficiency of baseload coal plants), combination wedge 3 (increased coal plant efficiency combined with two wedges of zero-carbon coal plant substitutions—wedges 8, 9 or 10) and combination wedge 4 (combination wedge 3 with increased building efficiency included—wedges 4 and 5). As one moves from wedge 6 to combination wedge 3 to combination wedge 4, the amount of coal plant efficiency required increases, and the degree of increase becomes stronger toward later years.

FIGURE C1 Comparison of Reduction in Coal Plant Capacities Among Individual and Combination Wedges



7.4 Appendix D: Calculation of Health Co-benefits

7.4.1 Health Impact Function

Health impact functions relate changes in health outcomes to changes in ambient $PM_{2.5}$ concentrations. Health impact functions typically consist of four components: a concentration-response (CR) function derived from epidemiological studies, a baseline incidence rate for the health effect of concern, the affected population, and the projected change in ambient $PM_{2.5}$ concentrations. The majority of the studies we used to estimate CR functions assume that the relationship between adverse health outcomes and $PM_{2.5}$ pollution is best described as log-linear, where the natural logarithm of the health response is a linear function of $PM_{2.5}$ concentrations. The change in number of outcomes (E) of health endpoint J when ambient concentrations (C) of $PM_{2.5}$ change can be given by:

$$\Delta E^J = [\exp(\beta^J \times \Delta C) - 1] \times E_0^J \times Pop^J, \qquad (1)$$

where β^J is the CR coefficient of health endpoint J and E_0^J is the baseline incidence rate of health endpoint J in the affected population, Pop^J. Because β^J is small, Eq.1 can be linearized and expressed as the following:

$$\Delta E^J = \beta^J \times E_0^J \times \Delta C \times Pop^J \qquad (2)$$

The following subsections describe the methods and sources used to define the health impact function elements, along with the uncertainties considered in the analysis.

We use the concept of intake fractions to calculate the exposure concentration of $PM_{2.5}$ associated with a given amount of emissions in the year 2020. An intake fraction is the fraction of $PM_{2.5}$

released from a source (such as motor vehicles or power plants) that is eventually inhaled or ingested by a population. It is dimensionless and can be defined as the ratio of the time-averaged inhalation rate to the time-averaged emission rate (Levy et al. 2002). Mathematically, the intake fraction takes the following form:

$$iF = \frac{\sum_{i=1}^{N} P_i \times C_i \times BR}{Q}, \tag{3}$$

where P_i is the population at location i, C_i is the incremental concentration (μg/m^3) of pollutant at location i, BR is the breathing rate (m^3/day), $Q$is the pollutant emission rate (μg/day), and N is the number of receptor sites.

We can quantify the average population exposure concentration (EC_p) in units of μg/m^3 resulting from $PM_{2.5}$ emissions by multiplying the intake fraction by the expected change in $PM_{2.5}$ emissions in units of μg/day (M) and dividing by the product of the population-averaged breathing rate (assumed to be 20 m^3/day) and the total population used to calculate the intake fraction.

$$EC_p = \frac{IF \times \Delta M}{BR \times P_I}$$

The intake fractions used in our study relied on 1995 U.S. population numbers (P_i) (see Levy et al. 2002), therefore we calculated EC_p using 1995 population estimates.

Performing these operations, we modify Eq.2 to the following:

$$\Delta E^J = \beta^J \times E_0^J \times EC_p \times Pop^J, \tag{4}$$

where EC_p represents population exposure to $PM_{2.5}$ concentrations (μg/m^3) from pollutant source p and Pop^J represents the affected 2020 population. Changes in health outcomes (E) are calculated for each wedge activity as well as the combinations of activities described in Table E1 below.

7.4.2 Affected Populations

We calculated 2020 population estimates from U.S. Census projections for total residents by single-year and sex. The affected population for each health endpoint, Pop^J, was considered to be all members of the age group included in the primary study used to estimate a CR function for that health endpoint (Table D1). As an example, the affected population for cardiovascular hospital admissions includes all those >64 years old. The studies that looked at asthma exacerbation and upper respiratory symptoms based their findings on an asthmatic subpopulation. In these cases, we applied an asthma attack prevalence of 5.51% to the corresponding age groups to calculate the affected population (ALA 2007).

TABLE D1 Health Endpoints, CR Functions and Primary Studies Included in Analysis

Health Endpoint	**Age Group**	**CR Function (SE)**	**Study Description**
Premature Mortality			
All-Cause	<1	3.92E-03 (1.22E-03)	Pope et al. 2002
All-Cause	>29	3.92E-03 (1.71E-03)	Woodruff et al. 1997
Cardiopulmonary	>29	5.83E-03 (1.93E-03)	Pope et al. 2002
Lung Cancer	>29	7.70E-03 (3.53E-03)	Pope et al. 2002
Chronic Illness			
Chronic Bronchitis	>26	1.32E-02 (6.80E-03)	Abbey et al. 1995
Nonfatal Heart Attack	>18	2.41E-02 (9.28E-03)	Peters et al. 2001
Hospital Admissions			
COPD[1]	>64	1.79E-03 (5.04E-04)	Pooled Estimate
			Moolgavkar 2003; Ito 2003
			Moolgavkar 2000
COPD[1]	20-64	2.23E-03 (7.42E-04)	Ito 2003
Pneumonia[2]	>64	3.98E-03 (1.66E-03)	Sheppard 2003
Asthma[3]	<65	3.32E-03 (1.04E-03)	Norris et al. 1999
Asthma-Related ER Visits	0-18	1.47E-02 (3.49E-03)	
			Pooled Estimate
All Cardiovascular[4]	>64	1.64E-03 (3.14E-04)	Moolgavkar 2003; Ito 2003
			Moolgavkar 2000
All Cardiovascular[4]	20-64	1.40E-03 (3.41E-04)	
			Dockery et al. 1996
Other Health Endpoints			Pope et al. 1991
Acute Bronchitis	8-12	2.72E-02 (1.71E-02)	Schwartz and Neas 2000
Upper Respiratory Symptoms	9-11[5]	3.60E-03 (1.50E-03)	Pooled Estimate
Lower Respiratory Symptoms	7-14	1.90E-02 (6.00E-03)	Ostro et al. 2001; Vedal et
Asthma Exacerbations	6-18[5]	4.90E-03 (1.04E-03)	al. 1998
			Ostro 1987
			Ostro and Rothschild 1989
Work Loss Days	18-65	4.60E-03 (3.60E-04)	
Minor Restricted Activity Days	18-65	7.24E-03 (7.00E-04)	

[1]Chronic Obstructive Pulmonary Disease (ICD9: 490-496); [2]ICD9: 480-486; [3]ICD9: 493; [4]Moolgavkar 2000, 2003 (ICD9: 390-429); Ito (ICD9 410-414, 427-428); [5]Study focuses on asthmatic populations

7.4.3 Baseline Health Incidence Rates

Baseline incidence rates for each health endpoint are needed to translate the relative risk of health effect J, derived from the CR function, to the absolute change in health effect, or the number of avoided cases per year. Table D2 provides a summary of baseline incidence rates and their sources.

Whenever possible, average baseline incidence rates for different age groups were determined from national survey data. For those endpoints with survey data, we chose the most recent incidence rate available to include in the analysis. We also generated the last 5 years of survey data to assess trends and ensure comparability of incidence rate estimates between years.

TABLE D2 Sources of Baseline Incidence Rates Included in Analysis

Health Endpoint	Age Group	Incidence Rate	Source
	(Cases/100 persons per yr)		
Premature Mortality			
All-Cause	<1	0.685	CDC 2008
All-Cause	>29	1.344	CDC 2008
Cardiopulmonary	>29	0.615	CDC 2008
Lung Cancer	>29	0.092	CDC 2008
Chronic Illness			
Chronic Bronchitis	>26	0.378	Abbey et al. 1995
Nonfatal Heart Attack	>18	0.286	CDC 2005
Hospital Admissions			
COPD[1]	>64	1.269	CDC 2005
COPD[1]	20-64	0.142	CDC 2005
Pneumonia[2]	>64	2.213	CDC 2005
Asthma[3]	<65	0.146	CDC 2005
Asthma-Related ER Visits	0-18	1.035	CDC 2007
All Cardiovascular[4]	>64	7.811	CDC 2005
All Cardiovascular[4]	20-64	0.989	CDC 2005
Other Health Endpoints			
Acute Bronchitis	8-12	4.300	CDC 1996
Upper Respiratory Symptoms	9-11[5]	12,479	Pope et al. 1991
Lower Respiratory Symptoms	7-14	43.8	Schwartz et al. 1994
Asthma Exacerbations	6-18[5]	2,774	Ostro et al. 2001
Work Loss Days	18-65	412.1	CDC 2006
Minor Restricted Activity Days	18-65	499.0	CDC 1996

[1]Chronic Obstructive Pulmonary Disease (ICD9: 490-496); [2]ICD9: 480-486; [3]ICD9: 493; [4]Moolgavkar 2000, 2003 (ICD9: 390-429), Ito (ICD9 410-414, 427-428); [5]Study focuses on asthmatic populations

Age- and cause-specific mortality data were generated from the Centers for Disease Control and Prevention's (CDC) internet database, CDC Wonder (CDC 2008). CDC derives incidence rates from U.S. death records and Census postcensal population estimates and outputs mortality rates for specified age ranges, locations, and ICD10 codes. Because our study outcomes presented ICD9 codes for mortality-related diseases, we converted ICD9 to ICD10 codes and generated mortality rates for the latest year available in CDC Wonder (2004). It should be noted that CDC Wonder generates age groupings in 10-year intervals. To estimate mortality rates for ages >29, we scaled the 25-34 year age group by half, and by assuming that death rates were uniform across all ages in the

10-year age group, we calculated population-weighted mortality rates for the scaled age groups.

Respiratory- and cardiovascular-related hospital admission incidence rates for 2005 were determined from CDC's National Hospital Discharge Survey (NHDS), which gathers data from nonfederal short-stay hospitals across the U.S. (CDC 2005). Nonfatal heart attack incidence was also ascertained from 2005 NHDS data. Per EPA methodology, we multiplied the incidence data by 0.93 based on a Rosamond (1999) estimate that 7% of hospitalized patients die within 28 days.

Emergency-room visits for asthma were estimated from the CDC National Hospital Ambulatory Care Survey as presented in the CDC report, CDC National Surveillance for Asthma --- United States, 1980—2004 (CDC 2007). CDC presented data for <18, while our population of interest includes 18, so the incidence estimates may be conservative.

Acute bronchitis, work-loss days, and minor-restricted activity day incidence rates were determined from CDC's National Health Interview Survey (NHIS). The last year acute bronchitis and minor restricted activity days were included in the NHIS was 1996 (CDC 1996). For acute bronchitis, incidence rates are presented for the age range 5-17, which most likely represents an overestimate. The incidence rate for work loss days was taken from the 2006 NHIS (CDC 2006).

For other endpoints, the only incidence data for the population of concern comes from the primary study itself. In these cases, the incidence in the study population is assumed to represent the incidence in the national population.

7.4.4 Economic Valuation of Health Endpoints

To value the benefits of reduced premature mortality rates, EPA used the VSL approach. EPA's guidance provided a number of VSL options, ranging from 5.5-6.3 million dollars. We chose a VSL of 6.3 million dollars because it is the primary value used by EPA in its BenMap software (EPA 2008). WTP estimates were used to value reductions in cases of chronic bronchitis, acute bronchitis, upper and lower respiratory symptoms, asthma exacerbations, and minor restricted activity days. WTP estimates are generally not available for hospital admissions, and for these health endpoints, cost-of-illness (COI) valuation estimates are used. COI estimates reflect direct expenditures, medical and opportunity costs, but do not take into account the value associated with reduced pain and suffering, and are thus likely underestimates. Finally, work-loss-days were valued according to the daily median wage in the U.S. Table D3 summarizes the types and sources of economic valuations used in the analysis.

TABLE D3 Economic Valuation Estimates by Health Endpoint

Health Endpoint	Estimate Type	Valuation Estimate
Premature Mortality		
All-Cause	VSL	$6,324,101
All-Cause	VSL	$6,324,101
Cardiopulmonary	VSL	$6,324,101
Lung Cancer	VSL	$6,324,101
Chronic Illness		
Chronic Bronchitis	WTP	$340,000
Nonfatal Heart Attack	COI	$90,727
Hospital Admissions		
COPD[1]	COI	$13,648
COPD[1]	COI	$11,820
Pneumonia[2]	COI	$17,844
Asthma[3]	COI	$7,788
Asthma-Related ER Visits	COI	$261
All Cardiovascular[4]	COI	$21,191
All Cardiovascular[4]	COI	$22,778
Other Health Endpoints		
Acute Bronchitis	WTP	$374
Upper Respiratory Symptoms	WTP[5]	$49
Lower Respiratory Symptoms	WTP	$31
Asthma Exacerbations	WTP	$86
Work Loss Days	Median Daily Wage	$115
Minor Restricted Activity Days	WTP	$51

[1]Chronic Obstructive Pulmonary Disease (ICD9: 490-496); [2]ICD9: 480-486; [3]ICD9: 493; [4]Moolgavkar 2000, 2003 (ICD9: 390-429), Ito (ICD9 410-414, 427-428); [5]Study focuses on asthmatic populations

Source: EPA 2006, 2008

To calculate the monetary benefits associated with reductions in adverse health outcomes, the economic valuation estimate was multiplied by the change in health effect (E^J). Results given are in 2008 US Dollars. Because the economic values obtained from the EPA were in 2000 USD, we updated them to 2008 USD by adjusting by the increase in the US Consumer Price Index for all Urban Consumers (CPI-U) from 2000 to December, 2008 (USDOL, 2008). Economic benefits due to reductions in adverse health outcomes were calculated for each wedge activity as well as different combinations. We note that these economic benefits do not incorporate the costs associated with development and implementation of wedge activities – they reflect gross and not net economic benefits.

7.4.5 Uncertainty Analysis

The change in health and economic outcomes associated with different wedge activities for the year 2020 depends on five main analysis inputs: change in $PM_{2.5}$ emissions, CR functions, baseline health incidence rates, 2020 population projections, and intake fractions (to relate emissions of $PM_{2.5}$ to concentrations). Each is uncertain to a different degree and we characterized the total uncertainty surrounding final health and economic outcomes through Monte Carlo uncertainty propagation of the inputs. In Monte Carlo simulations, inputs generated through random sampling from probability distributions are used to characterize uncertainty in the outputs. Assignment of a distribution to each input was based on the best available information. For example, CR functions were assumed to be normally distributed, with a mean and standard error as reported in the primary study. When no distribution information was available, inputs were assumed to be uniformly distributed with a maximum and minimum of ± 50% the base estimate. Crystal Ball 7.3.1 was used to carry out the health and economic benefits analysis.

Table D4 describes the distributions assigned to each input and their sources. The final outputs were generated along with their standard deviations and 5^{th} and 95^{th} percentiles. In addition to Monte Carlo uncertainty propagation, we conducted sensitivity analyses to test the effect of alternative emissions scenarios on the final estimates. We performed an alternative analysis in which results for 2030 were moved forward to 2020 to reflect that some technologies included in the analysis are cost-beneficial or easily implemented; therefore, it is possible that the initial pace of implementation could be more rapid.

TABLE D4 Distributions for Monte Carlo Inputs

Input Variable	Distribution Shape	Parameter	Source
Baseline Emissions	Normal	SD (assume 10%)	Assumption
Wedge Reductions	Uniform	Min, Max (±50%)	Assumption
Intake Fraction	Normal	SD	Levy et al. 2002
CR Coefficient	Normal	SD	Study-specific
Baseline Incidence Rate	Normal	SD	Calculated; Study-specific
2020 Population Projections	Uniform	Min, Max (±50%)	Assumption
Economic Valuation Estimates	Weibull[a], Uniform[c] Normal[d], Triangular[e] Lognormal[f]	α, β[b] Min, Max SD, Min, Max SD	EPA 2008

[a]Premature mortality (all-cause, cardiopulmonary, lung cancer)

[b]Parameters defined by the Weibull distribution probability density function (EPA 2008):

$$\left(\frac{\beta}{\alpha}\right)\left(\frac{x}{\alpha}\right)^{\beta-1} e^{-(x/\alpha)^{\beta}}$$

[c]Nonfatal heart attack; hospital admissions (COPD, pneumonia, asthma, cardiovascular); upper respiratory symptoms; lower respiratory symptoms; asthma exacerbation; work-loss-days

[d]Asthma-related ER visits

[e]Chronic bronchitis; minor restricted activity days

[f]Acute bronchitis

Results are shown in Table D5 through Table D8.

TABLE D5 Risk Reduction and Economic Benefit Estimates of Implementing Single Wedge Activities (Baseline Scenario)						
Health Endpoints	**Risk Reduction**	**5th**	**95th**	**Economic Benefit**	**5th**	**95th**
	(Cases/year)			**(Millions/U.S.$)**		
1. Increase light-duty vehicle fuel efficiency						
Premature Mortality (All-Cause >29 years)	432	125	836	$2,300	$690	$4,600
Premature Mortality (All-Cause <1 year)	198	87	350	$1,100	$480	$1,900
Asthma-Related ER Visits	1,123	553	1,924	$0.25	$0.12	$0.43
Economic Estimate (Three Endpoints Combined)				$3,500	$1,600	$5,700
Economic Estimate (All Endpoints Combined)				$5,900	$3,700	$8,700
2. Increase heavy-duty vehicle fuel efficiency						
Premature Mortality (All-Cause >29 years)	585	188	1,134	$3,200	$1,030	$6,300
Premature Mortality (All-Cause <1 year)	257	110	454	$1,400	$600	$2,500
Asthma-Related ER Visits	1,404	696	2,413	$0.33	$0.17	$0.56
Economic Estimate (Three Endpoints Combined)				$4,600	$2,300	$7,900
Economic Estimate (All Endpoints Combined)				$7,700	$4,900	$11,000
3. Reduce light-duty vehicle miles traveled						
Premature Mortality (All-Cause >29 years)	447	128	878	$2,400	$700	$4,900
Premature Mortality (All-Cause <1 year)	199	85	350	$1,100	$470	$1,900
Asthma-Related ER Visits	1,142	552	2,008	$0.25	$0.12	$0.43
Economic Estimate (Three Endpoints Combined)				$3,600	$1,700	$6,100
Economic Estimate (All Endpoints Combined)				$6,000	$3,700	$8,700
4. Increase electric end-use building efficiency						
Premature Mortality (All-Cause >29 years)	775	244	1,510	$4,300	$1,340	$8,300
Premature Mortality (All-Cause <1 year)	345	139	598	$1,900	$770	$3,300
Asthma-Related ER Visits	1,913	933	3,177	$0.27	$0.13	$0.46
Economic Estimate (Three Endpoints Combined)				$6,200	$2,900	$10,300
Economic Estimate (All Endpoints Combined)				$10,300	$6,400	$14,800
5. Increase direct fuel end-use building efficiency						
Premature Mortality (All-Cause >29 years)	2,175	645	4,258	$12,000	$3,560	$23,400
Premature Mortality (All-Cause <1 year)	1,026	436	1,836	$5,600	$2,400	$10,100

Asthma-Related ER Visits	5,573	2,677	9,263	$0.32	$0.16	$0.55
Economic Estimate (Three Endpoints Combined)				$17,600	$7,900	$29,600
Economic Estimate (All Endpoints Combined)				$29,700	$18,800	$43,000
6. Increase efficiency of baseload coal plants						
Premature Mortality (All-Cause >29 years)	583	164	1,167	$3,200	$870	$6,400
Premature Mortality (All-Cause <1 year)	253	113	452	$1,400	$630	$2,500
Asthma-Related ER Visits	1,428	689	2,424	$0.32	$0.15	$0.55
Economic Estimate (Three Endpoints Combined)				$4,600	$2,200	$8,000
Economic Estimate (All Endpoints Combined)				$7,700	$4,900	$11,000
7. Substitute natural gas for coal power						
Premature Mortality (All-Cause >29 years)	1,044	319	2,032	$5,700	$1,700	$11,000
Premature Mortality (All-Cause <1 year)	472	188	863	$2,600	$1,000	$4,800
Asthma-Related ER Visits	2,599	1,187	4,374	$0.59	$0.28	$1.00
Economic Estimate (Three Endpoints Combined)				$8,300	$3,800	$14,000
Economic Estimate (All Endpoints Combined)				$14,000	$8,600	$20,000
8. Substitute nuclear power for coal power						
Premature Mortality (All-Cause >29 years)	551	150	1,128	$3,000	$830	$6,200
Premature Mortality (All-Cause <1 year)	261	108	445	$1,400	$590	$2,400
Asthma-Related ER Visits	1,435	682	2,433	$0.32	$0.16	$0.55
Economic Estimate (Three Endpoints Combined)				$4,400	$2,000	$7,700
Economic Estimate (All Endpoints Combined)				$7,600	$4,700	$11,000
9. Substitute wind power for coal power						
Premature Mortality (All-Cause >29 years)	588	178	1,159	$3,200	$960	$6,300
Premature Mortality (All-Cause <1 year)	258	109	462	$1,400	$600	$2,500
Asthma-Related ER Visits	1,440	698	2,454	$0.32	$0.16	$0.55
Economic Estimate (Three Endpoints Combined)				$4,700	$2,200	$8,000
Economic Estimate (All Endpoints Combined)				$7,800	$4,900	$11,000
10. Substitute solar photovoltaic power for coal power						
Premature Mortality (All-Cause >29 years)	586	157	1,164	$3,200	$870	$6,400
Premature Mortality (All-Cause <1 year)	259	110	471	$1,400	$610	$2,600
Asthma-Related ER Visits	1,413	690	2,388	$0.32	$0.15	$0.55
Economic Estimate (Three Endpoints Combined)				$4,600	$2,100	$8,000

Economic Estimate (All Endpoints Combined)				$7,700	$4,700	$11,000

TABLE D6 Risk Reduction and Economic Benefit Estimates of Implementing Single Wedge Activities (Optimistic Scenario)						
Health Endpoints	**Risk Reduction**	**5th**	**95th**	**Economic Benefit**	**5th**	**95th**
	(Cases/year)			**(Millions/U.S.$)**		
1. Increase light-duty vehicle fuel efficiency						
Premature Mortality (All-Cause >29 years)	770	222	1,500	$4,300	$1,200	$8,300
Premature Mortality (All-Cause <1 year)	350	161	646	$1,900	$890	$3,600
Asthma-Related ER Visits	1,983	1,012	3,277	$0.44	$0.22	$0.75
Economic Estimate (Three Endpoints Combined)				$6,200	$2,800	$10,000
Economic Estimate (All Endpoints Combined)				$10,000	$6,500	$15,000
2. Increase heavy-duty vehicle fuel efficiency						
Premature Mortality (All-Cause >29 years)	986	296	1,904	$5,400	$1,700	$10,000
Premature Mortality (All-Cause <1 year)	426	187	742	$2,300	$1,000	$4,100
Asthma-Related ER Visits	2,363	1,140	4,043	$0.55	$0.27	$0.91
Economic Estimate (Three Endpoints Combined)				$7,700	$3,600	$13,000
Economic Estimate (All Endpoints Combined)				$13,000	$8,400	$19,000
3. Reduce light-duty vehicle miles traveled						
Premature Mortality (All-Cause >29 years)	795	227	1,545	$4,300	$1,200	$8,500
Premature Mortality (All-Cause <1 year)	356	145	639	$1,900	$800	$3,500
Asthma-Related ER Visits	1,982	945	3,334	$0.44	$0.22	$0.74
Economic Estimate (Three Endpoints Combined)				$6,300	$3,000	$10,000
Economic Estimate (All Endpoints Combined)				$10,000	$6,600	$16,000
4. Increase electric end-use building efficiency						
Premature Mortality (All-Cause >29 years)	1,302	426	2,498	$7,100	$2,300	$13,900
Premature Mortality (All-Cause <1 year)	582	253	1,023	$3,200	$1,390	$5,700
Asthma-Related ER Visits	3,184	1,543	5,423	$0.49	$0.23	$0.82
Economic Estimate (Three Endpoints Combined)				$10,300	$4,900	$17,000
Economic Estimate (All Endpoints Combined)				$17,000	$10,600	$25,000
5. Increase direct fuel end-use building efficiency						
Premature Mortality (All-Cause >29 years)	4,035	1,109	8,074	$22,200	$6,100	$44,000

Premature Mortality (All-Cause <1 year)	1,909	849	3,418	$10,500	$4,700	$18,800
Asthma-Related ER Visits	10,376	5,023	17,358	$0.55	$0.27	$0.91
Economic Estimate (Three Endpoints Combined)				$32,700	$14,600	$57,000
Economic Estimate (All Endpoints Combined)				$56,000	$34,500	$83,000
6. Increase efficiency of baseload coal plants						
Premature Mortality (All-Cause >29 years)	957	285	1,905	$5,300	$1,600	$10,000
Premature Mortality (All-Cause <1 year)	438	193	772	$2,400	$1,000	$4,300
Asthma-Related ER Visits	2,347	1,129	3,984	$0.54	$0.26	$0.87
Economic Estimate (Three Endpoints Combined)				$7,700	$3,600	$13,000
Economic Estimate (All Endpoints Combined)				$13,000	$8,000	$18,000
7. Substitute natural gas for coal power						
Premature Mortality (All-Cause >29 years)	1,835	570	3,619	$10,400	$3,100	$20,000
Premature Mortality (All-Cause <1 year)	832	339	1,491	$4,600	$1,800	$8,200
Asthma-Related ER Visits	4,576	2,255	7,672	$1.00	$0.47	$1.70
Economic Estimate (Three Endpoints Combined)				$15,000	$6,800	$25,000
Economic Estimate (All Endpoints Combined)				$24,000	$15,000	$36,000
8. Substitute nuclear power for coal power						
Premature Mortality (All-Cause >29 years)	932	259	1,882	$5,100	$1,400	$10,000
Premature Mortality (All-Cause <1 year)	430	181	755	$2,300	$1,000	$4,200
Asthma-Related ER Visits	2,382	1,155	4,065	$0.54	$0.25	$0.87
Economic Estimate (Three Endpoints Combined)				$7,500	$3,400	$13,000
Economic Estimate (All Endpoints Combined)				$13,000	$7,900	$18,000
9. Substitute wind power for coal power						
Premature Mortality (All-Cause >29 years)	956	297	1,837	$5,200	$1,700	$10,000
Premature Mortality (All-Cause <1 year)	433	179	759	$2,300	$960	$4,200
Asthma-Related ER Visits	2,411	1,161	4,026	$0.54	$0.25	$0.87
Economic Estimate (Three Endpoints Combined)				$7,700	$3,700	$13,000
Economic Estimate (All Endpoints Combined)				$13,000	$7,900	$19,000
10. Substitute solar photovoltaic power for coal power						
Premature Mortality (All-Cause >29 years)	959	279	1,900	$5,300	$1,600	$10,000
Premature Mortality (All-Cause <1 year)	427	177	754	$2,300	$960	$4,200
Asthma-Related ER Visits	2,347	1,164	4,025	$0.54	$0.25	$0.87

Economic Estimate (Three Endpoints Combined)				$7,700	$3,600	$13,000
Economic Estimate (All Endpoints Combined)				$13,000	$8,000	$18,000

TABLE D7 Risk Reduction and Economic Benefit Estimates of Implementing Combination Wedge Activities (Baseline Scenario)						
Health Endpoints	**Risk Reduction**	**5th**	**95th**	**Economic Benefit**	**5th**	**95th**
	(Cases/year)			**(Millions/U.S.$)**		
1. Transportation: Combine increased light-duty fuel efficiency and reduction of light-duty vehicle miles traveled						
Premature Mortality (All-Cause >29 years)	931	283	1,783	$5,100	$1,600	$9,800
Premature Mortality (All-Cause <1 year)	423	186	730	$2,300	$1,000	$4,000
Asthma-Related ER Visits	2,392	1,187	4,022	$0.50	$0.30	$0.90
Economic Estimate (Three Endpoints Combined)				$7,400	$3,600	$12,500
Economic Estimate (All Endpoints Combined)				$12,600	$8,000	$18,300
2. Buildings: Combine increased electric end-use and direct fuel building efficiency						
Premature Mortality (All-Cause >29 years)	3,021	867	5,881	$16,600	$4,800	$32,300
Premature Mortality (All-Cause <1 year)	1,367	598	2,422	$7,500	$3,300	$13,300
Asthma-Related ER Visits	7,420	3,631	12,075	$1.70	$0.80	$2.80
Economic Estimate (Three Endpoints Combined)				$24,100	$11,000	$40,400
Economic Estimate (All Endpoints Combined)				$40,600	$24,500	$58,700
3. Power Plants: Combine increased efficiency of baseload coal plants and two zero-carbon coal substitutions						
Premature Mortality (All-Cause >29 years)	1,884	493	3,745	$10,400	$2,700	$20,600
Premature Mortality (All-Cause <1 year)	889	357	1,562	$4,900	$2,000	$8,600
Asthma-Related ER Visits	4,672	2,216	7,903	$1.10	$0.50	$1.80
Economic Estimate (Three Endpoints Combined)				$15,300	$6,600	$25,800
Economic Estimate (All Endpoints Combined)				$25,500	$15,600	$37,000
4. Buildings and Power Plants: Combine efficient buildings wedges and all power plant wedges						
Premature Mortality (All-Cause >29 years)	5,166	1,597	9,981	$28,400	$8,800	$54,900
Premature Mortality (All-Cause <1 year)	2,422	1,041	4,273	$13,300	$5,700	$23,500
Asthma-Related ER Visits	13,295	6,531	22,753	$3.00	$1.50	$5.20
Economic Estimate (Three Endpoints Combined)				$41,700	$19,800	$69,900
Economic Estimate (All Endpoints Combined)				$70,400	$44,400	$102,200

TABLE D8 Risk Reduction and Economic Benefit Estimates of Implementing Combination Wedge Activities (Optimistic Scenario)

Health Endpoints	Risk Reduction	5th	95th	Economic Benefit	5th	95th
	(Cases/year)			(Millions/U.S.$)		
1. Transportation: Combine increased light-duty fuel efficiency and reduction of light-duty vehicle miles traveled						
Premature Mortality (All-Cause >29 years)	1,520	473	2,870	$8,400	$2,600	$15,800
Premature Mortality (All-Cause <1 year)	689	289	1,221	$3,800	$1,600	$6,700
Asthma-Related ER Visits	3,828	1,831	6,431	$0.90	$0.40	$1.50
Economic Estimate (Three Endpoints Combined)				$12,100	$5,800	$20,000
Economic Estimate (All Endpoints Combined)				$20,600	$12,500	$30,000
2. Buildings: Combine increased electric end-use and direct fuel building efficiency						
Premature Mortality (All-Cause >29 years)	5,606	1,724	11,320	$30,800	$9,500	$62,200
Premature Mortality (All-Cause <1 year)	2,484	1,038	4,375	$13,700	$5,700	$24,100
Asthma-Related ER Visits	13,717	6,837	23,094	$3.10	$1.50	$5.20
Economic Estimate (Three Endpoints Combined)				$44,500	$19,900	$75,800
Economic Estimate (All Endpoints Combined)				$74,700	$45,600	$110,800
3. Power Plants: Combine increased efficiency of baseload coal plants and two zero-carbon coal substitutions						
Premature Mortality (All-Cause >29 years)	2,970	804	6,083	$16,300	$4,400	$33,400
Premature Mortality (All-Cause <1 year)	1,362	586	2,384	$7,500	$3,200	$13,100
Asthma-Related ER Visits	7,402	3,386	12,806	$1.70	$0.80	$3.00
Economic Estimate (Three Endpoints Combined)				$23,800	$11,100	$41,400
Economic Estimate (All Endpoints Combined)				$39,900	$24,100	$59,900
4. Buildings and Power Plants: Combine efficient buildings wedges and all power plant wedges						
Premature Mortality (All-Cause >29 years)	9,071	2,513	17,972	$49,900	$13,800	$98,800
Premature Mortality (All-Cause <1 year)	4,277	1,846	7,504	$23,500	$10,100	$41,300
Asthma-Related ER Visits	23,223	10,787	37,812	$5.30	$2.50	$8.50
Economic Estimate (Three Endpoints Combined)				$73,400	$33,300	$125,800
Economic Estimate (All Endpoints Combined)				$124,000	$77,000	$180,000

7.4.6 References

Abbey, D. E., Hwang, B. L., Burchette, R. J., Vancuren, T., and Mills, P. K.: 1995, 'Estimated long-term ambient concentrations of PM(10) and development of respiratory symptoms in a nonsmoking population', *Arch Env Health*. 50(2): 139-152.

ALA (American Lung Association): 2007, *Trends in Asthma Morbidity and Mortality*, Epidemiology & Statistics Unit, Research and Program Services, Washington DC.

CDC (Centers for Disease Control and Prevention): 1996, National Health Interview Survey, 1996. Available online: http://www.cdc.gov/nchs/nhis.htm [Accessed October 27, 2008].

CDC (Centers for Disease Control and Prevention): 2005, National Hospital Discharge Survey. Available online: http://www.cdc.gov/nchs/about/major/hdasd/nhds.htm [Accessed October 27, 2008].

CDC (Centers for Disease Control and Prevention): 2006, National Health Interview Survey, 2006. Available online: http://www.cdc.gov/nchs/nhis.htm [Accessed October 27, 2008].

CDC (Centers for Disease Control and Prevention): 2007, National Surveillance for Asthma --- United States, 1980—2004. MMWR: Surveillance Summaries. 56(SS08); 1-14; 18-54. Available online: http://www.cdc.gov/mmwr/preview/mmwrhtml/ss5608a1.htm [Accessed October 27, 2008].

CDC (Centers for Disease Control and Prevention): 2008, CDC Wonder. Compressed Mortality File: Underlying Cause-of-Death. Available online: http://wonder.cdc.gov/mortSQL.html

[Accessed October 27, 2008].

Chen, C., Wang, B., Fu, Q., Green, C. and Streets, D. G.: 2006, 'Reductions in emissions of local air pollutants and co-benefits of Chinese energy policy: A Shanghai case study', *Energy Policy.* 34, 754-762.

Chen, C., Wang, B., Huang, C., Zhao, J., Dai, Y., and Kan, H.: 2007, 'Low-carbon energy policy and ambient air pollution in Shanghai, China: A health-based economic assessment', *Sci Total Environ.* 373, 13–21

Davis, D. L. and Working Group on Public Health and Fossil Fuel Combustion.: 1997, 'Short-term improvements in public health from global-climate policies on fossil-fuel combustion: an interim report', *Lancet.* 350, 1341-1349.

Davis, D. L., Krupnick, A., and McGlynn, G.: 2000, Ancillary benefits and costs of greenhouse gas mitigation: An overview. Available from: http://www.airimpacts.org/documents/local/M00005776.pdf

Dockery, D. W., Cunningham, J., Damokosh, A. I., Neas, L. M., Spengler, J. D., Koutrakis, P., Ware, J. H, Raizenne, M., and Speizer, F. E.: 1996, 'Health effects of acid aerosols on North American children-respiratory symptoms', *Environ Health Perspect.* 104(5), 500-505.

EPA (U.S. Environmental Protection Agency): 2008, *BenMap: Environmental benefits mapping and analysis program.* User's Manual Appendices. Prepared for Office of Air Quality Planning and Standards. Prepared by Abt Associates.

Ito, K.: 2003. Associations of particulate matter components with daily mortality and morbidity in Detroit, Michigan. In Revised Analyses of Time-Series Studies of Air Pollution and Health. Special Report. Health Effects Institute, Boston, MA.

Moolgavkar, S. H.: 2000, 'Air pollution and hospital admissions for diseases of the circulatory system in three U.S. metropolitan areas', *J Air Waste Manage.* 50, 1199-1206.

Moolgavkar, S. H.: 2003, Air pollution and daily deaths and hospital admissions in Los Angeles and Cook counties. In Revised Analyses of Time-Series Studies of Air Pollution and Health. Special Report. Boston, MA: Health Effects Institute.

Norris, G., Young Pong, S. N., Koenig, J. Q., Larson, T. V., Sheppard, L., and Stout, J. W.: 1999, 'An association between fine particles and asthma emergency department visits for children in Seattle', *Environ Health Perspect.* 107(6), 489-493.

Ostro, B. D.: 1987, 'Air pollution and morbidity revisited: A specification test', *J Environ Econ Managt.* 14, 87-98.

Ostro, B. D. and Rothschild, S.: 1989, 'Air pollution and acute respiratory morbidity: An observational study of multiple pollutants', *Environ Res.* 50, 238-247.

Ostro, B., Lipsett, M., Mann, J., Braxton-Owens, H., and White, M.: 2001, 'Air pollution and exacerbation of asthma in African-American children in Los Angeles', *Epidemiology.* 12(2), 200-208.

Peters, A., Dockery, D. W., Muller, J. E., and Mittleman, M. A.: 2001, 'Increased particulate air pollution and the triggering of myocardial infarction', *Circulation.* 103, 2810-2815.

Pope, C. A., III, Dockery, D. W., Spengler, J. D., and Raizenne, M. E.: 1991, 'Respiratory health and PM_{10} pollution: A daily time series analysis', *Am Rev Resp Dis.* 144, 668-674.

Pope, C. A., III, Burnett, R. T., Thun, M. J., Calle, E. E., Krewski D., Ito, K., and Thurston, G. D.: 2002. 'Lung cancer, cardiopulmonary mortality, and long-term exposure to fine particulate air pollution', *J Am Med Assoc.* 287, 1132-1141.

Rosamond, W., Broda, G., Kawalec, E., Rywik, S., Pajak, A., Cooper, L., and Chambless L.: 1999, 'Comparison of medical care and survival of hospitalized patients with acute myocardial infarction in Poland and the United States', *Am J Cardiol.* Vol. 83(8), 1180-1185.

Schwartz, J. and Neas, L. M.: 2000, 'Fine particles are more strongly associated than coarse particles with acute respiratory health effects in school children', *Epidemiology.* 11, 6-10.

Schwartz, J., Dockery, D. W., Neas, L. M., Wypij, D., Ware, J. H., Spengler, J. D., Koutrakis, P., Speizer, F. E., and Ferris, B. G. Jr.: 1994, 'Acute effects of summer air pollution on respiratory symptom reporting in children', *Am J Respir Crit Care Med.* 150, 1234-1242.

Sheppard, L.: 2003, 'Ambient air pollution and nonelderly asthma hospital admissions in Seattle, Washington, 1987-1994', In Revised Analyses of Time-Series Studies of Air Pollution and Health. Special Report. Boston, MA: Health Effects Institute.

USDOL (United States Department of Labor): 2008, *Consumer Price Index for all Urban Users.* Available online: ftp://ftp.bls.gov/pub/special.requests/cpi/cpiai.txt [Accessed January 16, 2009].

Vedal, S., Petkau, J., White, R., and Blair, J.: 1998, 'Acute effects of ambient inhalable particles in asthmatic and nonasthmatic children', *Am J Resp Crit Care Med.* 157(4), 1034-1043.

West, J, Fiore, A., Horowitz, L., and Mauzerall, D.: 2006, 'Global health benefits of mitigating ozone pollution with methane emission controls', *P Natl Acad Sci USA.* 103, 3988-3993.

Woodruff, T.J., Grillo, J., and Schoendorf, K.C.: 1997, 'The relationship between selected causes of postneonatal infant mortality and particulate air pollution in the United States', *Env Health Perspect.* 105(6), 608-612.

7.5 Appendix E: Additional Discussion

7.5.1 Combination wedge results

Because several wedges may reduce emissions from the same source but through different means, we evaluated specific combinations. The results of these combinations for the baseline and rapid implementation scenarios are in Table E1 (using the estimates for wedge 5 in combination with those of other wedges for illustrative purposes). Benefits in the "optimized" scenario were at least 1.5 times greater than the "baseline" scenario.

TABLE E1 Risk Reduction and Economic Benefit Estimates of Implementing Combination Wedge Activities

	Economic Benefit (All Endpoints Combined) (Millions/U.S.$)	
Health Endpoints	**Baseline Scenario**	**Optimistic Scenario**
1. Transportation Combine increased light-duty fuel efficiency and reduction of light-duty vehicle miles traveled	$12,600	$20,600
2. Buildings Combine increased electric end-use and direct fuel building efficiency	$14,500	$25,500
3. Power Plants Combine increased efficiency of baseload coal plants and two zero-carbon coal substitutions	$25,500	$39,900
4. Buildings and Power Plants Combine efficient buildings wedges and all power plant wedges	$44,300	$74,800

7.5.2 Range of abatement costs for wedge activities

To place our calculated gross economic health benefits in context, estimated implementation costs for wedge activities from the recent literature (Creyts et al., 2007; IEA, 2009; NETL, 2010; Sovacool, 2011; EPA, 2012; Feldman et al., 2012; EIA, 2013) are summarized in Table E2 below.

TABLE E2 Range of CO_2 Abatement Cost Estimates for Wedge Activities

Wedge Activity	Abatement Cost Estimates ($/t$CO_2$)*		References	
	Low	High	Low	High
Transportation				
Efficient Vehicles				
1) Increase light-duty vehicle fuel efficiency	–108	798	Creyts et al. (2007)	IEA (2009)
2) Increase heavy-duty vehicle fuel efficiency	–90	N/A	Creyts et al. (2007)	No data available
Reduce Vehicle Miles Traveled				
3) Reduce light-duty vehicle miles traveled	0	0	No data available; assume zero	No data available; assume zero
Buildings				
Efficient Buildings				
4) Increase electric end-use building efficiency	–90	60	Creyts et al. (2007)	Creyts et al. (2007)
5) Increase direct fuel end-use building efficiency	–90	60	Creyts et al. (2007)	Creyts et al. (2007)
Power Plants				
Efficient Coal Plants				
6) Increase efficiency of base load coal plants	88	292	NETL (2010), EPA (2012), EIA (2013)	NETL (2010)
Substitutions for Coal Base Load Power				
7) Substitute natural gas for coal base load power	–64	–1	NETL (2010), EIA (2013)	NETL (2010)
8) Substitute nuclear power for coal base load power	9	818	NETL (2010), EIA (2013)	Sovacool (2011)
9) Substitute wind power for coal base load power	–15	27	NETL (2010), EIA (2013)	Creyts et al. (2007)
10) Substitute solar photovoltaic power for coal base load power	49	62	NETL (2010), EIA (2013)	NETL (2010), Feldman et al. (2012), EIA (2013)

* All costs in 2008 inflation-adjusted dollars. Negative values indicate a net cost savings over the life of the system (vehicle, building, power plant, etc.).

7.5.3 Critique

In carrying through the analysis to the economic valuation of reduced adverse health outcomes, a number of critical assumptions and methodological choices were made. First, this analysis compares the health co-benefits associated with one wedge of CO_2 reduction, rather than attempting to assess probable or maximum feasible implementation of each specific technological solution. Thus, ratios of health to CO_2 reduction benefits can be compared among options, but the analysis is not intended to predict the likely magnitude of total health benefits associated with climate policies. A second critical assumption was the proportional reduction of conventional air pollutants and CO_2. This assumption is likely to be invalid to varying degrees for the different solutions. For example, vehicle fuel efficiency does not correlate with vehicle pollutant emissions, as catalytic converters and other technologies can control emissions to a specified level of control regardless of fuel efficiency. The same is to some extent true for coal-fired power plant emissions, while solutions involving decreased vehicle miles would be expected to produce more proportional reductions.

Because our analysis assessed relative differences among reductions from specific sources, a method of estimating population-level exposures based on specific source reductions in primary pollutant emissions was necessary. We chose intake fractions as an initial approach in order to provide a computationally simple yet still science-based way of estimating dispersion of emissions. The use of intake fractions involves several major assumptions, including spatially uniform reduction of emissions, continued validity of distribution of sources and dispersion modeling upon which the intake fractions were originally based for 2020, and similar spatial distribution of the U.S. population in 2020.

Lastly, we used health cost data developed by EPA for air pollution regulatory impact assessment. This assumes that these willingness-to-pay and health cost data remain valid in 2020. Should health costs continue to increase at a rate greater than the consumer price index, this would result in an underestimation of the actual costs; conversely, an increase in health costs through 2020 less than the general rate of inflation would result in a relative overestimation of actual costs.

Strengths of this study include the development and analysis of specific technological solutions that are estimated to provide sufficient CO_2 reduction to meet the U.S proportion of the global reduction sufficient to stabilize CO_2 concentrations at approximately 500 ppm. Previous studies either focused on a limited number of solutions or sectors, or else applied a percentage reduction to concentrations without linkage to any specific solutions. While linking pollutant reductions to a broad range of technological solutions introduces substantial complexity to the assessment of health benefits, this study demonstrates the feasibility of a scoping approach and can aid in the design of more sophisticated modeling of these benefits.

A second strength is the use of a relatively conservative baseline for future air pollutant emissions. Previous studies tended to use current emissions as the baseline for assessing interventions well into the future, which fails to take into account likely reductions due to regulatory controls in the absence of climate-specific interventions. EPA's analysis conducted for the CAIR rule provides such a baseline for both power plant and motor vehicle emissions.

This study has clear limitations, some of which are related to simplifying assumptions and methods selected for ease of analysis, some of which are related to significant knowledge gaps. The assumptions involved in the use of intake fractions on a national scale preclude modeling geographic differences in air pollution health co-benefits. One serious consequence is the inability to address issues of equity in the distribution of health co-benefits associated with specific policies. A more complex analysis, which combined modeling of power plant emissions on a facility-by-facility basis combined with air quality dispersion modeling could provide greater insight into regional differences and equity issues.

A second major limitation stems from the assumption that percent reductions in PM and PM precursors equal those of CO_2. While this analysis provides an estimate of potential health benefits if utilities and motor vehicle manufacturers took full advantage of reduced demand and fuel consumption, the decoupling of CO_2 and conventional pollutant emissions through the use of control technology makes reliable prediction of this relationship very difficult.

Assessing all technologies on the basis of one "wedge" of CO_2 reductions limits the types of questions that can be answered by this analysis. Rather than being predictive of likely scenarios, the analysis provides a basis for comparing the ratio of CO_2 reduction to PM pollution reduction of the various technologies, alone and in combination, as well as a rough estimation of the scale of health co-benefits possible. The choice of policy options would be better guided by incorporating overall technical feasibility, ease and speed of implementation, and cost information in analyzing the likely scenarios. This analysis, as a preliminary scoping study, establishes a framework for future work. Subsequent studies that involve collaboration with technological and economic experts are required to inform decision-makers more fully.

In analyzing only health co-benefits related to PM reductions, this study excludes significant other categories of potential health co-benefits arising from GHG reduction polices, including reductions in ozone and other air pollutants, increased physical activity from promotion of active modes of transportation, reduced occupational injuries and illness from reductions in coal and other fossil fuel extraction, and others. These additional health co-benefits are more difficult to assess, but such assessments should be included in ultimate policy decisions.

In addition to exclusion of other health co-benefits, this study did not attempted to assess potential harms to health from the CO_2 reduction activities themselves. The potential for harm to health is likely to vary considerably from one option to another. A comprehensive method, such as that developed for health impact assessments of transportation and other government projects (Bhatia and Wernham, 2008) should be applied to climate change policies as well to fully inform policy makers.

In conclusion, avoided adverse health outcomes related to reduced PM exposures from climate change policies can be anticipated to substantially offset the annual costs of implementing such policies. Our estimates suggest that the economic benefits from reductions in PM would be in a range from $6 to $14 billion. Specific climate interventions will vary in the health co-benefits they provide as well as in potential harms that may result from their implementation. Rigorous assessment of these health impacts is essential for guiding policy decisions as efforts to reduce GHG emissions increase in urgency and intensity.

7.5.4 References

Bhatia, R. and Wernham, A.: 2008, 'Integrating human health into environmental impact assessment: an unrealized opportunity for environmental health and justice', *Environ Health Perspect.* Aug;116(8), 991-1000.

Creyts, J., Derkach, A. et al.: 2007. Reducing U.S. Greenhouse Gas Emissions: How Much at What Cost? McKinsey & Company.

EIA (Energy Information Administration): 2013, Annual Energy Outlook 2013: With Projections to 2040, Early Release. U.S. Department of Energy, DOE/EIA-0383(2013). Available online: http://www.eia.gov/forecasts/aeo/er/index.cfm [Accessed March 2, 2013].

EPA (U.S. Environmental Protection Agency): 2012, *Emissions and Generation Resource Integrated Database (eGRID)*, Version 1. Available online: http://www.epa.gov/cleanenergy/energy-resources/egrid/index.html [Accessed March 13, 2013].

Feldman, D., Barbose, G. et al.: 2012. *Photovoltaic (PV) Pricing Trends: Historical, Recent, and Near-Term Projections*, Lawrence Berkeley National Laboratory and National Renewable Energy Laboratory. DOE/GO-102012-3839.

IEA (International Energy Agency): 2009. *Transport, Energy and CO_2: Moving Toward Sustainability*. Available online: http://www.iea.org/publications/freepublications/publication/transport2009.pdf [Accessed March 13, 2013].

NETL (National Energy Technology Laboratory): 2010. *Cost and Performance Baseline for Fossil Energy Plants, Volume 1: Bituminous Coal and Natural Gas to Electricity,* Revision 2. U.S. Department of Energy. DOE/NETL-2010/1397.

Sovacool, B. K.: 2011. *Contesting the Future of Nuclear Power: A Critical Global Assessment of Atomic Energy*, World Scientific, ISBN: 978-981-4322-75-1, 308 pp.