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International Experiences with Quantifying the Co-Benefits of Energy-Efficiency and Greenhouse-Gas Mitigation Programs and Policies

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Executive Summary

Improving the efficiency of energy production and consumption and switching to lower carbon energy sources can significantly decrease carbon dioxide (CO_2) emissions and reduce climate change impacts. A growing body of research has found that these measures can also directly mitigate many non-climate change related human health hazards and environmental damage. Positive impacts of policies and programs that occur in addition to the intended primary policy goal are called co-benefits. Policy analysis relies on forecasting and comparing the costs of policy and program implementation and the benefits that accrue to society from implementation. GHG reduction and energy efficiency policies and programs face political resistance in part because of the difficulty of quantifying their benefits. On the one hand, climate change mitigation policy benefits are often global, long-term, and subject to large uncertainties, and subsidized energy pricing can reduce the direct monetary benefits of energy efficiency policies to below their cost. On the other hand, the co-benefits that accrue from these efforts' resultant reductions in conventional air pollution (such as improved health, agricultural productivity, reduced damage to infrastructure, and local ecosystem improvements) are generally near term, local, and more certain than climate change mitigation benefits and larger than the monetary value of energy savings. The incorporation of co-benefits into energy efficiency and climate mitigation policy and program analysis therefore might significantly increase the uptake of these policies. Faster policy uptake is especially important in developing countries because ongoing development efforts that do not consider co-benefits may lock in suboptimal technologies and infrastructure and result in high costs in future years.

Over the past two decades, studies have repeatedly documented that non-climate change related benefits of energy efficiency and fuel conversion efforts, as a part of GHG mitigation strategies, can be from between 30% to over 100% of the costs of such policies and programs strategies. Policy makers around the world are increasingly interested in including both GHG and non-GHG impacts in analyses of energy efficiency and fuel switching policies and programs and a set of methodologies has matured from the efforts of early moving jurisdictions such as the European Union, the United States, and Japan.

ES.1. General Steps for Quantifying Co-benefits

There are four general steps for quantifying the co-benefits of energy efficiency and GHG emissions reduction policies discussed in this report:

1. Calculating emissions differences between base case and alternative policy scenarios.
2. Applying air dispersion modeling or simplifications to characterize and compare concentrations of pollutants.
3. Estimating impacts for each scenario and comparing them against each other (using, for example, population-adjusted C-R functions to find health impacts).
4. Monetizing or otherwise quantifying those impacts in relation to the costs of the alternative policy scenario with care to evaluate those costs according to specific pollutants.

ES.2. Co-benefit Models, Guidebooks, and Applied Studies

Generally, co-benefit quantification efforts are classified into three categories: (1) co-benefit models, (2) ex-ante policy assessment methods, and (3) frameworks established by academics looking to improve the field and apply co-benefits to a broader range of geographies, policies, and programs. Table ES-1 shows a summary of some of the major models, guidebooks, and frameworks for co-benefit quantification.

ES.3. Mitigating Uncertainty and Simplification Methods

Co-benefits theory and research is still evolving and even the most advanced studies are still limited in many ways. Substantial uncertainty is introduced in the creation of the models used to forecast energy and emissions growth as energy demand growth and economic change can be affected by a larger number of variables and forecasting both are inexact sciences. Data validity is also a major source of uncertainty, especially in situations when epidemiological data is applied to areas different from the location of data collection. Uncertainty is a familiar obstacle to policymakers, however, and uncertainties within co-benefit studies should not prevent the further development and application of co-benefits analysis. Sensitivity analysis is a key strategy to detail and examine sources of uncertainty and should be incorporated into any co-benefits research.

Furthermore, several methods for simplifying co-benefits analysis have proven useful in the context of developing countries. Qualitative impact evaluations based on predetermined scoring metrics enable initial evaluations of potential co-benefits and allow researchers to determine priority issues to target with quantitative methods. Quantitative efforts can be simplified by replacing atmospheric dispersion models with simplified linear equations and metrics such as intake fractions, although caution is warranted as this can dramatically reduce output accuracy and transparency. Several methods can also be applied to limit the scope of research, such as limiting the geographic area of the analysis to high-priority areas (such as major metropolitan areas), using wider-scale modeling resolution to find average impacts over larger areas, exclusively focusing on high-priority pollutants such as PM_{10} and $PM_{2.5}$, reducing the detail of population characterizations and reducing the number and types of populations examined (for example, by focusing exclusively on adult, rather than child or elderly, populations and treating populations as homogenous), and using rules of thumb for complex sectors such as transportation. The number of impacts examined is also often a source of simplification; rather than attempt to calculate and monetize highly uncertain impacts to eco-system services and less-empirically proven health impacts, co-benefit analyses will often concentrate on only the most well-known impacts to human health that have been thoroughly documented by epidemiological studies. A best practice in this area is the development of databases that contain all relevant epidemiological data relevant to the jurisdiction. Locally-relevant models that focus exclusively on high-priority sectors and technologies and apply rules of thumb, default values, and locally-relevant monetization metrics have been developed in some areas, although more experienced jurisdictions will benefit from current efforts to expand international best-practice modeling suites such as GAINS for application in certain developing countries (for example, China and India). Furthermore, the development of nationally-applicable guidebooks, as undertaken in recent years by the United States and Japan, works to standardize co-benefit research for application to national-level policies and standardize outputs to allow comparisons between studies.

Finally, controversy surrounds the monetization of impacts and many simplification methodologies may result in highly different research outputs depending on their application. The relatively newer methodology of quantifying health impacts in Disability-Adjusted Life Years (DALYs) and Quality-Adjusted Life Years (QALYs) holds promise to dispose of the monetization controversy and replace it with a uniform, globally-comparable impact assessment methodology. Several methods for simplifying co-benefits calculations appear relevant to the Chinese context as well as other developing countries. However, most simplification methods require considerable up-front standardization efforts to ensure that simplification does not result in inaccuracy and conflicts between research outputs.

Table ES-1. Summary of some of the major models, guidebooks, and frameworks for co-benefit quantification

Name of the Model, Guidebook, or Study	Category	Air Pollutants Modeled	Modeling Steps
The Greenhouse Gas-Air Pollution Interactions and Synergies (GAINS) Model	Model	Sulfur dioxide (SO_2), nitrous oxides (NO_x), ammonia (NH_3), volatile organic pollutants (VOCs), total suspended particles (TSPs), particulate matter (PM_{10}, and $PM_{2.5}$), carbon dioxide (CO_2), methane (CH_4), nitrous oxides (N_2O), and the three F-gases (sulfur hexafluoride (SF_6), hydrofloourocarbons (HFCs), and perfluorocarbons (PFCs).	1. Top-down model estimates air pollution emitting activities; 2. User chooses from among pollution control technologies, energy conservation, and fuel switching measures to project emissions levels given user-chosen limiting factors; 3. Atmospheric dispersion model applied to resultant emissions to find new concentrations; 4. Several impacts modeled, including reductions in negative impacts on human health via the exposure of fine particles and ground-level ozone, reductions in damage to vegetation via excess deposition of acidifying and eutrophying compounds, and the reduction in the six GHGs considered in the Kyoto Protocol. Human health damages are calculated in terms of years of life lost, loss in statistical life, and yearly premature mortality.
Simple Interactive Model for Better Air Quality (SIM-Air)	Model	PM_{10}, $PM_{2.5}$, NO_x, SO_2, VOCs, CO_2.	1. User independently projects emission driving activities; 2. User chooses transportation mode switching, efficiency technology measures, fuel switching, and emission source location shifting measures options and applies in a bottom-up manner; 3. User inputs resultant emissions into external pollutant dispersion model to find new concentrations; 4. Human health impacts and/or exceedances of air pollution limit levels are calculated and health impacts are monetized.
The Integrated Global System's Model (IGSM)	Model	CO, VOCs, $NO_{x.}$ SO_2, NH_3, black carbon, and organic carbon, CO_2, CH_4, N_2O, the three F-gases (SF_6, HFCs, PFCs).	1. Top-down model estimates air pollution emitting activities; 2. User chooses fuel switching, energy efficiency technology measures, pollution control technologies, non-energy technologies, household activity and technology changes, carbon sequestration, and IGCC technologies to project emissions levels given user-chosen limiting factors; 3. Atmospheric dispersion and ocean systems models applied to emissions to find new concentrations; 4. Environmental quality improvements and impacts on primary productivity are modeled. Health impacts are not explicitly modeled.
U.S. EPA's Integrated Environmental Strategies (IES) Program	Ex-ante Assessment Guidebook	CO_2, PM_{10}, $PM_{2.5}$, ozone (O_3), SO_2, CO, NO_x, lead.	1. Emissions are modeled from several methodological choices; 2. User chooses technologies and measures to apply, usually air pollution control technologies or activities in the transportation sector; 3. Air dispersion models or simplified methods applied; 4. Human health impact calculation methods are applied, using local data or transferring impact data from other regions. Monetization may also be applied.

Name of the Model, Guidebook, or Study	Category	Air Pollutants Modeled	Modeling Steps
Japan's Manual for Quantitative Evaluation of Co-Benefits Approach to Climate Change Projects	Ex-ante Assessment Guidebook	SO_x, NO_x, soot and dust, CO_2.	1. User given choice of evaluating impacts on qualitative or quantitative basis; 2. For quantitative analysis, user applies formulas following several data input requirements, choosing from several technology and activity change options; 3. Air, water, and waste pollution measures output by model, without further dispersion modeling or quantification of impacts.
Gold Standard Program Model	Ex-ante Assessment Guidebook	NO_x, SO_x, lead, carbon monoxide (CO), O_3, persistent organic pollutants (POPs), mercury (Hg), Chlorofluorocarbons (CFCs), halogens, respirable suspended particulate matter (RSPM), NH_3, $PM_{10,}$ VOCs, TSP, dust, odors.	1. CDM project developers meeting certain technology and activity (renewable energy, energy efficiency, or waste handling) requirements create a project account with the Gold Standard Program Registry; 2. Project developers work with local communities to define community goals according to several possible impact metrics; 3. After approval by the Registry, project developers develop baseline and impact calculations using program guidance; 4. Project developers establish monitoring systems for chosen metrics and after project is approved by local community and third-party auditor, project receives certification by Registry.
Mainstreaming Transport Co-benefits Approach: a Guide to Evaluating Transport Policies	Ex-ante Assessment Guidebook	NO_x, PM, CO, CO_2	1. User is presented with bottom-up model equations regarding several co-benefits of implementing transportation-related technology, fuel switching, and activity (e.g. mode switching measures); 2. Rules-of-thumb or user-generated data is input into equations based on the expected level of implementation of selected measures to find resultant emissions and activity changes; 3. User applies simplified impact quantification formulas to find impacts.
The ClimateCost Project	Ex-ante Assessment Applied Study	SO_2, NO_x, VOCs, NH_3, $PM_{2.5}$	1. Emissions driver activities are forecast using the top-down GAINS model; 2. Technologies and measures such as energy efficiency-oriented technological changes, fuel switching, and conventional pollution control technologies applied in line with existing non-GHG pollution and energy use abatement regulations; 3. Atmospheric dispersion model applied; 4. Impacts on human health, physical infrastructure, and agricultural primary productivity are output and monetized.
Analysis conducted for the European Environmental Agency (EEA) regarding air quality co-benefits of GHGs mitigation policies	Ex-ante Assessment Applied Study	NO_x, SO_2, PM_{10}, $PM_{2.5}$, CO_2, CH_4, N_2O, the three F-gases (SF_6, HFCs, PFCs), NH_3, non-methane VOCs (NMVOC)	1. Drivers of emissions are forecast using a top-down model; 2. A bottom-up methodology is used to project emissions changes given carbon dioxide emissions limits, the implementation of maximum feasible technologies, and the continuation of air pollution control technologies; 3. An air pollution dispersion model is applied to find new concentrations; 4. Impacts of each scenario are given in human health, vegetation damage area, area of forests damaged by acidification, and area of land damaged by eutrophication. Health impacts are monetized.

Name of the Model, Guidebook, or Study	Category	Air Pollutants Modeled	Modeling Steps
ExternE Projects Model	Ex-ante Assessment Applied Study	SO_2, NO_x, PM_{10}, $PM_{2.5}$ NMVOCs, NH_3, certain heavy metals, CO_2, CH_4, N_2O, the three F-gases (SF_6, HFCs, PFCs)	1. Energy demand forecasts are given by IPCC projections; 2. User chooses fuel mix to meet energy demand based primarily on fuel switching measures; 3. Atmospheric, soil, and water pollution dispersion models are applied; 4. Health, agriculture production, silviaculture production, global warming, and other harms are quantified, and health, agriculture, physical infrastructure costs, and some climate change and eco-system damage related impacts are monetized.
Hidden Cost of Energy	Academic Framework	SO_2, NO_x, $PM_{2.5}$, PM_{10}.	1. Current energy production practices in four sectors are modeled based on current energy demands and compared against each other; 2. Plant-level and source emissions are calculated based on fuel mix; 3. Emissions are analyzed using an atmospheric dispersion model; 4. Impacts are assessed for human health, grain crop and timber yields, building materials, recreation, visibility, eco-system services, and climate change impacts.
The Co-benefits of Greenhouse Gas Mitigation Policies in China model	Academic Framework	PM, SO_2, NO_x, CO_2	1. A hybrid modeling approach is used to predict energy demand and changes in energy demand given costs of electricity production practices to meet policy goals; 2. Resultant emissions for scenarios are based on technologies applied given model's explicit price constraints; 3. An atmospheric dispersion model is applied to resultant emissions; 4. Intake fractions are used to find health damages and impacts are monetized.
Resources for the Future's model of U.S. electricity generation sector carbon policy co-benefits	Academic Framework	NO_x, SO_2	1. A top-down model is applied to find electricity demand; 2. Changes in emissions found based on fuel switching and electricity production efficiency technologies implemented based on carbon price expectations and meeting requirements of other pollution regulations; 3. An atmospheric dispersion model is applied to find changes in pollutant concentrations; 4. Human health impacts are modeled and monetized; other impacts include reduced costs of implementing convention pollution control technologies.

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1. Introduction

Energy production and use is necessary for activities that are both ubiquitous and essential to modern economic and social structures. Energy use is also the primary cause of a wide variety of anthropogenic environmental, social, and economic impacts, the most notable of which is climate change. Improving the efficiency of energy production and consumption and switching to lower carbon energy sources can significantly decrease carbon dioxide (CO_2) emissions and reduce climate change impacts (IPCC, 1996).

Positive impacts of policies and programs that occur in addition to the intended primary policy goal are called co-benefits. Co-benefits can positively affect human health as well as ecological, economic, and social systems. The best understood of the energy policy-related co-benefits result from reductions in human exposure to traditional or conventional air pollutants[1] that are emitted in energy production well as the manufacture of industrial products, transportation activities, construction, and other economic activities. Energy use and climate change also have a variety of other impacts not associated with human health harms of air pollution exposure, and these policies generally also reduce these impacts and thereby improve environmental conditions, economic development, and social equity (NRC, 2010).

When policies have adverse consequences on environmental or human health or other economic, political, or social issues, these impacts are generally called trade-offs. This literature review focuses on the positive co-benefits of energy efficiency and climate change policies, rather than undertaking an extensive discussion of negative trade-offs. Trade-offs are generally less well understood than co-benefits, and are usually associated with a large host of externalities[2], including worsening health status, crime, and other externalities (Davis et al., 2000a). As such, they are not commonly included in co-benefits studies.[3]

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[1] Conventional air pollutants typically include regulated pollutants, such as particulate matter ($PM_{2.5}$ and PM_{10}), nitrogen oxides (NO_x), sulfur dioxide (SO_2), ozone (O_3), carbon monoxide (CO) and lead.

[2] For example, a loss of employment or income could be induced by economic structural change or shifts away from heavy industry that occur in response to climate change policies that raise the price of fossil fuel use

[3] When they are discussed, the most commonly identified trade-offs are those related to the increased exposure to air pollutants due to increased physical activity in mobile transport (especially important in transportation studies), changing risks from changes in fuel use due to technology switching (for example, from coal to nuclear or hydro), and impacts associated with increased energy use from the implementation of energy-using pollution abatement technology (for example, SO_2 scrubbers).

Policy analysis relies on forecasting and comparing the costs of policy and program implementation to the benefits that accrue to society from implementation. GHG reduction and energy efficiency policies and programs face political resistance in part because of the difficulty of quantifying their benefits. On one hand, climate change mitigation policy benefits are often global, long-term, and subject to large uncertainties, and subsidized energy pricing can reduce the direct monetary benefits of energy efficiency policies to below their cost. On the other hand, the co-benefits that accrue from these efforts' resultant reductions in conventional air pollution (such as improved health, agricultural productivity, reduced damage to infrastructure, and local ecosystem improvements) are generally near term, local, and more certain than climate change mitigation benefits and larger than the monetary value of energy savings. The incorporation of co-benefits into energy efficiency and climate mitigation policy and program analysis therefore might significantly increase the uptake of these policies. Faster policy uptake is especially important in developing countries because ongoing development efforts that do not consider co-benefits may lock in suboptimal technologies and infrastructure and result in high costs in future years.

Due in large part to the significant co-benefits of energy efficiency and climate policies, policy makers around the world are increasingly interested in including both GHG and non-GHG impacts in analyses of energy efficiency and fuel switching policies and programs (U.S. EPA, 2011; European Environmental Agency, 2004; Davis et al., 2000b). Over the past two decades, studies have repeatedly documented that non-climate change related benefits of energy efficiency and fuel conversion efforts, as a part of GHG mitigation strategies, can be from between 30% to over 100% of the cost of these strategies (Davis et al., 2000b). Although initial efforts began in the 1970s and 1980s (see for example Comar and Sagan, 1976; Mendelsohn, 1980), from the early 1990s, an increasing number of researchers from a multitude of disciplines have dedicated themselves to quantifying co-benefits, and the field has developed a set of methodological steps commonly used in these analyses. As the field has coalesced around key methodological steps several tools, frameworks, and instructional materials have been developed over the past decade to better integrate co-benefits research with policy decision making. However, there have been relatively few efforts to survey and assess the strengths and weaknesses of these efforts and an unintended consequence is that policymakers may find it difficult to navigate the crowded terrain.

Much of the international efforts to quantify the co-benefits of energy-related policies to date have focused on climate change and CO_2 emissions mitigation programs (U.S. EPA, 2011). Energy efficiency and fuel use policies often constitute the majority of measures analyzed in this research. Because these measures have multiple other impacts, research regarding co-benefits of energy efficiency policies does not necessarily require a full discussion of climate change or CO_2 emissions impacts (U.S. EPA 2011). Indeed, co-benefits research in developing countries in Asia often focuses on energy efficiency measures rather than climate policies due to the more immediate and dire local impacts of conventional air pollution in these countries. In this context, climate change mitigation may be considered a co-benefit. The main area of focus now and in the foreseeable future with respect to co-benefits studies in Asia is related to energy, i.e., energy efficiency, security, cost and affordability, supply diversity and reliability (Castillo et al., 2007). U.S. studies and government programs, most commonly frame co-benefits analysis in terms of energy efficiency and fuel conversion efforts, rather than climate change, in part due to energy security issues, cost considerations, and concern about local pollutants. For instance, the U.S. EPA actively pushes states and local governments to consider the multitude of non-climate-related benefits that accrue from "clean energy" policies and programs – including energy efficiency, renewable energy, and combined heat and power systems (U.S. EPA, 2011). European research into co-benefits overwhelmingly focuses on the co-benefits of policies and programs developed specifically to address climate change (European Commission, 2008).

This report provides a summary of co-benefits research, including assessment methodologies to calculate co-benefits. This first section briefly recounts the history of co-benefit analysis and categorizes co-benefit assessments into major analytical and topical categories. As the majority of the literature examining co-benefits concentrates on calculating reductions of the negative health impacts of conventional air pollutants (i.e., particulate matter (PM) and ozone (O_3)) emitted during fossil fuel combustion, this report focuses on methods to quantify these co-benefits. Next, the common steps in undertaking co-benefits analysis are summarized. Examples of methodological and computational efforts are presented and key differences, limitations, and commonalities between these efforts are presented. The conclusion provides a final summary of the literature review's main findings and the application of co-benefits analysis to developing countries.

A few recommendations are worth mentioning here. Although the procedures used to measure co-benefits are increasingly standardized in the developed world, there has been a proliferation of methods developed for application in the developing world. This is due to the common need to overcome severe data limitations in the developing world context while preparing analyses that are sufficiently robust and transparent for policymaking applications. While data limitations may be overcome in the medium term future, there is a need to further develop simple, flexible, and standardized methods of calculating the co-benefits of major energy consuming activities. Furthermore, the field will benefit from testing these simplifications through application to diverse countries and contexts and standardizing how research evaluates and discusses calculation uncertainties. The development of international co-benefit calculation standards will be greatly advanced by consolidating best practices among regions as well as between policymakers and researchers. These cooperative efforts should be targeted in the short term at clarifying the best contexts for the application of each model and framework. Much of the current cooperative efforts are founded on international climate change treaty negotiations and this platform as well as bilateral cooperation between national governments should be optimized by integrating co-benefits research at the highest level of negotiations.

1.1. Definition of co-benefits

Co-benefits are most easily understood as the benefits which accrue from the implementation of a policy that are in addition to the primary objective of the policy. The Intergovernmental Panel on Climate Change (IPCC) defines co-benefits as "the benefits of policies that are implemented for various reasons at the same time – including climate change mitigation – acknowledging that most policies addressing greenhouse gas mitigation have other . . . equally important rationales" (Metz et al., 2001).The Clean Air Initiative for Asian Cities (CAI-Asia) program increases the scope of co-benefits to include a multitude of other policy measures, defining co-benefits as: "those derived from the intentional decision to address air pollution, energy demand, and climate change in an integrated manner, but also considers the other unspecified benefits that may arise such as improved transport and urban planning, reduced health and agricultural impacts, improved economy or reduced overall policy implementation cost" (Castillo et al., 2007).

The primary drivers behind air pollution, energy efficiency, and climate change mitigation policies are often different: air pollution policies often focus on generally short-term, local public health improvements through reducing traditional air pollutant emissions and human exposure. Energy efficiency policies are often targeted at reducing energy costs or increasing energy security as well as spurring national and regional economic development over the medium term, especially through technology development and implementation. Climate change policies are often primarily focused on long-term global environmental protection (European Environmental Agency, 2004).

The approaches taken by policy makers in constructing these policies often differ as well: a technology-based approach with legally-enforceable emissions or air quality limits is often used to combat air pollution; attractive financial incentives and instructional guidance are often used for energy efficiency policies; and economic instruments such as taxes and cap-and-trade schemes are often favored for climate change mitigation. However, through either limitations or incentives, all three policies often focus on reducing the primary means by which air pollutants and other environmental and health hazards are produced – the combustion of fossil fuels. As these reductions are often not the direct purpose of the originating policy or a part of its underlying fundamental policy goal, these improvements are called co-benefits.

Identifying all relevant co-benefits is a high priority for co-benefit studies, as many policies, especially in developed countries, are explicitly driven by a cost-optimization requirement to arrive at the "best" emissions level considering all costs and all benefits. The inclusion of additional monetary and non-monetary co-benefits allows policy makers to increase the stringency and resources of their programs and reap the considerable administrative and public benefits (U.S. EPA, 2011). Faster policy uptake is especially important in developing countries because ongoing development efforts that do not consider co-benefits may lock in suboptimal technologies and infrastructure and result in high costs in future years.

There is no standard co-benefits typology. Many authors however, group co-benefits within four broad categories of impacted systems: health, ecological, economic, and social co-benefits (Davis et al., 2000b). Co-benefits can also be categorized by the particular endpoint impacted, e.g., the IPCC's Fourth Assessment Report separates co-benefits of industrial GHG emissions mitigation strategies as those affecting human health, emissions, waste, production, operations and maintenance, working environment, and "other" (Metz et al., 2007). Example co-benefits that fall into each category are provided in Table 1. **Error! Reference source not found.**

Table 1: Co-benefits of Greenhouse Gas and Energy Efficiency Policies and Programs

Category of co-benefit	Examples
Health	Reduced medical/hospital visits, reduced lost working days, reduced acute and chronic respiratory symptoms, reduced asthma attacks, increased life expectancy.
Emissions	Reduction of dust, carbon monoxide (CO), CO_2, nitrous oxides (NO_x) and sulfur dioxide (SO_2); reduced environmental compliance costs.
Waste	Reduced use of primary materials; reduction of waste water, hazardous waste, waste materials; reduced waste disposal costs; use of waste fuels, heat and gas.
Production	Increased yield; improved product quality or purity; improved equipment performance and capacity utilization; reduced process cycle times; increased production reliability; increased customer satisfaction.
Operation and maintenance	Reduced wear on equipment; increased facility reliability; reduced need for engineering controls; lower cooling requirements; lower labor requirements.
Working environment	Improved lighting, temperature control and air quality; reduced noise levels; reduced need for personal protective equipment; increased worker safety.
Other	Decreased liability; improved public image; delayed or reduced capital expenditures; creation of additional space; improved worker morale.

Source: Metz et al., 2007. See Appendix A for a list of additional co-benefits.

The most frequently studied type of co-benefit of climate change and energy efficiency policies are reduced negative impacts on human health due to air pollution exposure – urban outdoor air pollution is among the top 10 causes of premature death risk factors in both middle and high income countries (WHO, 2009). Urban air pollution-related health impacts are also the majority of co-benefits discussed in the present report. Another key area of co-benefit research focuses on the impacts of pollution and pollutant mitigation on ecosystems. Reduction of acidification and eutrophication are the two most commonly quantified environmental co-benefits of energy efficiency and climate change policies. Such research, for example, could quantify the amount of land area suffering from acidification from sulfur dioxide SO_2, NO_x and ammonia (NH_3) and reductions in the emission of acidifying compounds that can be harmful to soil, water, and forests and may cause corrosion of buildings and monuments. Similarly, eutrophication caused mainly by an excess of nitrogen and phosphorus in the environment that can lead to eco-system chemical changes and physical damage is often also quantified in terms of land or water area affected. Fewer studies attempt to monetize these land-area based assessments; doing so requires calculating the less certain market value of reduced output of specific crops, forestry goods, and ecosystem services. Non-health related ozone impacts such as damage to agriculture and other vegetation is often quantified in terms of land area damaged, but also can be monetized.

In addition to human health, agriculture land area, and ecosystem services impacts, other quantified market and economic impacts that are often considered in co-benefits studies include the: reduced costs of air pollution abatement efforts, employment impacts of policies, and changes in the price of primary production inputs such as fuels. Other less frequently quantified co-benefits include decreased congestion (especially important in transportation studies), reduced damage to the built environment from air pollution, and the economic benefits of technological advancement.

There are a wide variety of social impact co-benefits that are discussed in some co-benefits analyses, but such co-benefits are not typically quantified. These include broader questions of social equity (which might attempt to value the differential impacts of policies on the dispersion of air pollutants towards lower-income areas), energy security, and climate change adaption benefits. An example of the incorporation of less quantifiable co-benefits is given by Japan's Ministry of the Environment manual for the calculation of co-benefits of Clean Development Mechanism (CDM) carbon reduction projects under the Kyoto Protocol (the Japan Manual). The Japan Manual calls for researchers to evaluate CO_2 emissions mitigation policies and activities "in ways that reflect the socio-economic conditions and national policies in each country" (Japan Ministry of the Environment, 2009). To do so, the Japanese envision a future evaluation methodology that considers the locally-relevant scoring of co-benefits policies so as to assign a weighting co-efficient for each co-benefit that is relevant to each country's political, social, environmental, and economic circumstances. The Japan Manual puts significant emphasis on the ease of implementing co-benefits studies and recommends that developing countries start with qualitative evaluations to avoid complications regarding data availability and labor capacity within the local government (Japan Ministry of the Environment, 2009).

This report, however, focuses on the quantitative evaluation of co-benefits and assumes that a qualitative evaluation of co-benefits, while useful, is insufficient to meet the demands of the policy making context. The criteria for the co-benefits studies examined here includes the ability to monetize impacts based on empirically-derived assessment of values, and the relationship between physical human health and environmental impacts and value loss. There is an emphasis in this report on the methodologies used to assess the most commonly quantified co-benefit category: positive impacts to human health associated with air pollution mitigation. Indeed, human health impacts, especially human mortality, associated with poor air quality is considered one of the, if not the, most critical co-benefit. Indeed, reductions in adverse human health effects account for 70%–90% of the total value of quantified co-benefits in energy-related co-benefits analyses (Aunan et al., 2000). Table 2 summarizes the major quantifiable and non-quantifiable human health impacts of air pollution exposure.

Additional health impacts that are quantified in some co-benefits impact studies, especially those studies that assess the impact of transportation policies aimed at changing behavior, include the positive benefits of more exercise on cardiopulmonary health, the reduced incidence of some cancers (for example, breast cancer), and reduced incidence of neurological diseases such as dementia and depression (Woodcock et al., 2009). Energy sector occupational risks are likely significantly contributing to total global occupational-risk related premature mortality (Smith and Haigler, 2008; Ezzati et al. [eds.], 2004) and occupational safety co-benefits such as those related to reduced coal mining, have also been incorporated in some co-benefit studies (Davis et al., 2000b; Markandya et al., 2009; NRC, 2010). However, occupational health risk co-benefits have been found to be substantially smaller than decreased health risks attributable to $PM_{2.5}$ emission decreases from climate policy implementation in the electricity sector (Markandya et al., 2009).

Table 2: Quantifiable and Non-quantifiable Human Health Outcomes used to assess the Impacts of Air Pollution Exposure

Quantifiable health impacts	Non-quantified/suspected health impacts
Mortality	Neonatal and post-neonatal morbidity
Hospital admissions, including: • Respiratory hospital admissions • Cardiovascular hospital admissions • Emergency room visits for asthma	Fetus/child developmental effects
Respiratory illness, including: • Bronchitis- acute and chronic • Asthma attacks • Moderate or worsening asthma status • Lower respiratory illness • Upper respiratory illness • Shortness of breath • Wheezing	Respiratory illness, including: • New asthma cases • Non-bronchitis chronic respiratory illness • Respiratory cell damage • Morphological changes in the lung • Increased airway responsiveness to stimuli
Restricted Activity days including: • Minor restricted activity days • All restricted activity days • Days of work lost	Behavioral effects (e.g. learning disabilities) Neurological disorders Decreased time to onset of angina
Cancer (e.g. lung)	Immunological response, including: • Altered host defense mechanisms (e.g. increased susceptibility to respiratory infection) • Exacerbation of allergies

Source: Davis et al., 2000b, with authors' additions.

1.2. Brief history of co-benefits research and application

Our understanding of the negative human health and environmental impacts associated with fossil fuel combustion predates climate change research (Mendelsohn, 1980; Comar and Sagan, 1976). Cost-benefit analysis (CBA) was the primary methodology used to quantify the externalities associated with fossil-fuel based air pollution control policies. CBA studies require the assessment and weighing of the costs of implementing policies (usually private costs) with the (usually public) benefits of those policies. CBA has become a regular activity in policy analysis in the United States and other Western countries. Specifically, CBA is now regularly used for regulatory impact assessments in the United States, and is mandatory for regulatory acts with expected costs over a certain threshold value of $100 million, and the European Commission also now regularly uses CBA to evaluate directives. The broad methodological outlines of CBA are well established, relying on a long record starting from the mandate for CBA to be applied to all U.S. environmental policies since the *National Environmental Policy Act* of 1969.

However, a major drawback to CBA is that often the costs and benefits weighed against each other are limited to only those actions and events that would directly proceed from the primary goal of the policy being examined. If the policy regards the conservation of energy, for example, the costs to be evaluated are the costs of implementing energy saving technology, to be compared with the direct benefits of conserving energy, such as the fuel cost savings and operations and maintenance cost savings resulting from the technology. However, the direct benefits of air pollution mitigation are more difficult to define as air pollution poses few, if any, direct benefits to the implementers of control measures. Rather, air pollution regulation, in its directly public health-related objective, opened the possibility of certain CBAs including an examination of public externalities. The CBA methodologies developed to examine air pollution (and other pollutant) control policy impacts can be seen as the progenitor of modern co-benefit analysis.

With increasing global attention and interest in mitigating CO_2 emissions that began in the 1990s, several studies indicated that GHG mitigation policy co-benefits could be on the same order of magnitude as the cost of implementing the policies if baseline conditions include relatively high CO_2 levels and inefficient abatement technology, (particularly in the developing world) (Davis et al., 2000b; NRC, 2010). Even in developed countries like the United States, several studies around the turn of the millennium found that co-benefits would significantly reduce the net costs of GHG reduction efforts (Burtraw et al., 2003). Based on these and other studies, as well as in response to the movements towards a global climate treaty in the late 1990s, several international and government bodies initiated considerable efforts to understand co-benefits and integrate co-benefits analysis into climate policy making efforts. Fuel switching and energy efficiency are the two most common policy measures for mitigating climate change and therefore the calculations of the co-benefits of such policies and technologies are almost exclusively discussed as a part of climate-change mitigation-related co-benefit studies.

One of the more prominent national government-level efforts to refine co-benefit research methodologies originated in the United States Environmental Protection Agency (EPA) in the late 1990s (U.S. EPA, 2004). The EPA developed a program called the Integrated Environmental Strategies Program, which undertook partnerships with several countries such as Argentina, Chile, China, and Brazil to test co-benefit research methodologies through targeted applied studies. Another large scale effort was started in the European Union (EU) in the early 1990s and has resulted in an extremely sophisticated suite of models called the Greenhouse Gas – Air pollution Interactions and Synergies (GAINS) to help EU policy makers evaluate GHGs and other air pollution control regimes for optimized results (Amann et al., 2008). Since the early 2000s, Japan also has advocated for the use of co-benefits analysis, especially in regards to Japanese development assistance projects in South East Asia. In addition, International NGOs have developed a co-benefits analysis methodology applicable for certifying the co-benefits resulting from CO_2 emissions credits generation efforts under the Kyoto Protocol Clean Development Mechanism (CDM) markets as well as in volunteer markets (Japan Ministry of the Environment, 2009; The Gold Standard Secretariat, 2012).

Developing countries such as India are also starting the develop co-benefit calculation methodologies to better account for local priorities, capacities, and available data (Environmental Management Center, 2009). Academics and certain NGOs in Western countries are largely the drivers of advancement in the field, with their efforts integrated into national and regional policy efforts as data establishes the fidelity, robustness, and applicability of new models, co-benefits, and methodologies (see Section **Error! Reference source not found.** and Appendix B for an overview of these efforts).

1.3. Categorizing of co-benefits studies

Co-benefit research can be categorized by: 1) the type of policy or program being evaluated, 2) the purpose of performing the co-benefits analysis, and 3) the type of models used in the evaluation.

The first category of co-benefits research focuses on the type of policy or program being evaluated and includes analyses that: primarily focuses on climate change mitigation with recognition that there may be other benefits of such activity; focuses primarily on other issues, recognizing that there may be climate change mitigation benefits; or looks to a combination of policy objectives regarding both climate change and other areas and relates the costs and benefits with an integrated perspective (Davis et al., 2000b).[4] Since 2000, the majority of co-benefits research focuses on evaluating GHG reductions and air pollution health impacts together. Energy efficiency policies are often analyzed as a part of the climate change co-benefits literature, however rarely are energy efficiency policies the sole focus.

A growing body of literature accounts for the various co-benefits which accrue from household and building energy efficiency measures (see for example U.S. EPA, 2011; Wilkinson et al., 2009; Hutton and Rehfuess, 2008; Hutton et al., 2007; von Schirnding et al., 2002). This research has focused on thermal comfort co-benefits due to thermal insulation, indoor air quality benefits from fuel switching and more efficient cook-stoves (especially in developing countries), and improved health impacts from less exposure to extreme temperature and humidity. Energy efficiency measures in industry, power production, and transportation more often focus on outdoor air pollution related human health impacts and environmental impacts. In addition, there are a variety of other policy categories for which co-benefits analyses have been conducted aside from climate change mitigation and energy efficiency, including policies to control non-GHG air pollutants. These studies often model energy savings and CO_2 emission reductions as a function of other air pollution control strategies. For example, Xu and Masui (2009) estimate conventional air pollution concentration co-benefits from SO_2 control policies in China.

A second means of categorizing co-benefits evaluations is the purpose for which they were undertaken. Co-benefits evaluations are undertaken either as part of an *ex-post* evaluation of individual programs aiming to mitigate climate change or other impacts; an *ex-ante* evaluation, often through the application of modeling software, to compare and evaluate different national or regional scale policy initiatives; or the hypothetical application of quantification methodologies by academics, researchers, and others who are not direct stakeholders in the delivery of climate change mitigation or other programs. Most co-benefit studies developed by national and regional governments are *ex-ante* evaluations, and are reviewed in Section 2 of this report. In contrast, the majority of the studies reviewed in Section 3 and Appendix B of this report are based on academic research on the application of quantification methodologies.

A third means of categorizing co-benefits research relies on the type of model used in the analysis. The calculation of co-benefits requires constructing a base-case scenario to which alternative policy

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[4] The term “ancillary benefits” is often used within the first two types of analyses while the term “co-benefits” is often referred to in the third type (Davis et al., 2000b). The present report uses co-benefits to describe all three types.

scenarios may be compared. Both base-case and alternative scenarios are generally based on the same general assumptions to determine economic activity, energy use, population distribution, and other fundamental determinants of air pollution and its impacts, with key policies changes and their effects examined.[5] Base case and alternative scenario energy demand models either rely on *top-down* or *bottom-up* modeling structures, or hybrids of these two methodologies (Cao et al., 2008; U.S. EPA, 2004). This section briefly explains the differences between these three modeling frameworks:

1. *The Top-Down (Aggregated) Approach* requires the initial development of an economy-wide model that forecasts energy use in the future based on interactions between different economic sectors. Computable general equilibrium (CGE) models are commonly used to model economies and incorporate the feedback-like effects of policy-change induced variations in relative prices or income (Cao et al., 2008). Data describing inputs costs and outputs for all modeled sectors is then used to simulate the effect of policy changes on the economy (Jack and Kinney, 2010). Each sector is characterized by energy use technologies, and the cost characteristics and emissions profiles of those technologies are used by the model to determine the economy's energy production and use characteristics.

Top-down models are particularly useful in evaluating the impact of policies on sectors and factor-prices that interact in the larger economy. Macro-economic interactive effects are important to track as climate change policies operate in a system contextualized by environmental, institutional and economic forces, and changes in one sector can feedback as externalities into others (Davis et al., 2000a). The ability of top down models to show the effects of feedbacks and externalities was a significant development over older models that used simple fixed coefficients between GHG emissions and other effects (Davis et al., 2000a). However, top-down models have several limitations. For instance, they use highly aggregated data, like national emission and impact data, to estimate the output and impacts of particular pollutants. This approach fails to include the engineering details of inputs, impacts, and technologies which can play a role in determining the cost-effectiveness of a particular mitigation measure, its impacts on emissions, and its feedbacks on prices and other macroeconomic factors. For example, the cost, emissions, and other profile data of production inputs, including labor, capital, technology, and fuels are often modeled in a smooth aggregate production function. This limits the accuracy of top-down models because smooth production functions (i.e. production functions that are not expressions of actual technologies, but rather theoretical technologies derived from historical experience), may violate fundamental physics and engineering limitations. Also, this approach is not suited to the calculation of marginal costs of abatement and may not accurately depict the pace of technological advancement (Cao et al., 2008). Benefits of this strategy lie in its potentially lower data requirements which may allow for preliminary estimates to be made where detailed information is

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[5] This general rule does not hold true throughout all studies, especially those of the top-down type. As energy production and consumption are integrated with even the most fundamental of economic activity, any manipulation in the price or level of demand for a certain primary fuel or final energy output will likely result in changes to the demand and price for other energy and non-energy goods. In dramatic cases, shifts in the prominence and importance of entire economic sectors may result from broad policies such as a carbon tax or an energy efficiency mandate. The top-down models discussed here are generally premised on the ability to track these macroeconomic effects and thereby the economies that are compared between the base case and alternative scenarios are fundamentally different.

lacking (ETSU and Metroeconomica, 2005). Furthermore, an advantage of top-down models is their potential to model economic feedbacks, such as changing price signals, which are seen by proponents as vital to understanding real potentials for mitigation and co-benefits realization.

2. *The Bottom-Up (Disaggregated) Approach* predicts energy demand or emissions levels using less rigorous means than top-down CGE models.[6] Bottom-up models commonly expect energy demand to grow commensurate to population and/or macro-economic growth or emissions levels. Energy demand growth is then met through continued traditional technology implementation in a base case scenario and more efficient or alternative fuel technologies in alternative scenarios. Another means of projecting future energy demand or emissions levels in bottom-up models is to set them as capped below a given level, usually either current levels or a policy target. Bottom-up models then predict the costs of achieving those emissions based on a detailed catalogue of empirically derived production technologies. Although energy use and technology implementation does not change due to feedbacks between price and quantity as in the top-down model, bottom-up models often evaluate the "best" technologies to use based on technology price, emissions goals, and other factors. The theory behind this methodology is to allow researchers to find an optimum technology mix by specifying technical details and economic, policy, and engineering limitations. Another common means of building bottom-up models is to simply substitute a certain alternative technology for a traditional technology over time without an analysis of whether doing so would be cost-optimal.

Because of the engineering complexities of specific industries as well as other factors, bottom-up disaggregated models are often seen as a superior approach to developing accurate estimates of ancillary impacts of technology interventions (Davis et al., 2000b). Bottom-up models are limited in that they cannot show the effects of macroeconomic market feedbacks within the model and thereby may overestimate the potential penetration of advanced technologies.

3. *Hybrid models* attempt to combine the principles of top-down and bottom-up models to integrate the detailed and discrete technology choices of bottom up models with the general equilibrium principles of top-down models. A fundamental assumption in hybrid models is that the parameters of both models structures will match. In some instances, this is accomplished by inputting the results of the technological and other limitations in the bottom-up model into the CGE model. In other instances, the two components of the model are combined after both models are run iteratively until they reach convergence (Cao et al., 2008; Tu et al., 2007).

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[6] The bottom up methodology is also known as the damage function or impact pathway approach (ETSU and Metroeconomica, 2005).

2. General Steps for Quantifying the Co-benefits of Energy Efficiency and GHG Emissions Reduction Policies

There are four general steps for quantifying the co-benefits of energy efficiency and GHG emissions reduction policies:

1) Calculating emissions differences between base case and alternative policy scenarios.
2) Applying air dispersion modeling or simplifications to characterize and compare concentrations of pollutants.
3) Estimating impacts for each scenario and comparing them against each other (using, for example, population-adjusted C-R functions to find health impacts).
4) Monetizing or otherwise quantifying those impacts in relation to the costs of the alternative policy scenario with care to evaluate those costs according to specific pollutants.

Each of these steps is discussed further below.

2.1. Calculating emissions differences between base case and alternative policy scenarios

2.1.1. Create a baseline energy and emissions forecast

In general, co-benefits studies are based on identifying the impacts of possible future trends in energy use and GHG emissions. Such studies develop a baseline scenario that projects energy demand and associated emissions over time without the policy intervention being examined. Top-down models often determine baseline demand with reference to fuel prices, growth of individual sectors and other factors that both influence and are determined by economic relationships. Although bottom-up models can use the outputs of CGE calculations, more often bottom-up models project baseline future energy demand based on relatively simplified correlations between past economic performance, population growth, and energy demand growth rates and assumptions about the future use of technology by consumers. The most basic bottom-up models simply estimate baseline energy demand growth without factoring in economic considerations. Regardless of how the baseline scenario is formulated, it is the template to which alternative policy scenarios are compared (Capros et al., 2000).

The fuels used to meet energy demand will determine the emission profiles. Energy demand growth forecasted in the baseline and alternative policy scenarios is translated into pollutant emissions. Energy supply forecasts can be defined either at the aggregate level (using average fuel mixes in the economy) or through more detailed evaluations of load order to evaluate the cost-based production choices of specific energy producers (U.S. EPA, 2011). Top-down models estimate fuel use and emissions at the regional or sector scale, and thus generally lack geographic specificity of the point sources of emissions leading to decreased accuracy in emissions impacts on local populations (U.S. EPA, 2011). Bottom-up inventories generally include specific details of energy production at the plant level or even the technology level, and the share of fuels used to power the sector or end-use technology. However, emissions from electricity generation generally rely on economy-wide producer fuel mixes (U.S. EPA, 2011). Fuel use can be limited by characteristics such as fuel and technology availability, and lowest cost optimization will result in the predominance of fossil fuels in the baseline energy mix. For accuracy, the baseline scenario should forecast the future as realistically as possible, including current policy efforts that may have an impact on the emissions being modeled (Davis et al., 2000a).

2.1.2. Model energy and emissions resulting from alternative policy scenarios

Once a baseline is established, alternative policies are then modeled to determine the economic, technological, and subsequent energy and emissions changes that would occur if the policy in question were implemented. Alternative policies are often simple projections of reduced GHG emissions, with reductions in studies of developed countries often driven by the implementation of a price on carbon (often in the form of a tax on CO_2 emissions) and studies in developing countries often driven by technological and physical measures applied to particular sectors (e.g. Markayanda et al., 2009). Other evaluations rely on programs that set emissions caps and technology development expectations that usually assume a constant year-to-year improvement in either energy production or consumption efficiency, or model the implementation of specific technologies into the future which result in production or consumption efficiency (e.g. Jack and Kinney, 2010; Woodcock et al, 2009; Friel et al., 2009). As mentioned above, top down econometric models will determine emissions changes not only due to technology changes but also due to changes in demand based on energy prices and other economic shifts. Bottom-up models are based on technology-driven emission changes often without regard to whether energy prices and other input factor prices have changed (U.S. EPA, 2011). More sophisticated models will sometimes determine which specific fuel is displaced by the alternative scenario at any given time - in most cases this is done by selecting the marginal – or most expensive – energy provider at the time period in question and eliminating that provider from the emissions inventory for that time period (U.S. EPA, 2011). This methodology is most often used for policies which affect the generation and use of electricity. Sometimes a basic assumption that reduced traditional energy demand or improved productive efficiency will decrease all fuels use by the same proportion is used. The changes imposed by the alternative policy scenario are then added over time and the difference in the location and quantity of emissions in the base case and one or more alternative scenarios is then calculated.

2.2. Characterizing pollutant dispersion

Calculating impacts requires carefully tracking of the movement of emissions through their physical environment to the point of impact. In the case of air pollution, efforts must be made to understand pollutant transport and estimate exposure concentrations in specific geographic areas.[7] There are two dominant means of modeling air emissions movements and their impact on ambient air quality and pollutant concentrations: atmospheric dispersion models and photochemical and atmospheric transport models (U.S. EPA, 2011).

There are two types of dispersion models: the Gaussian plume model, a simplified 2-D model that uses basic geometry and physical laws to simplify calculations and find approximate ground level concentrations, and the more advanced 3-D Eularian models that consider the effects of the height of emissions sources as well as the distance and width of the spread of dispersion. Emissions pathways are calculated using exogenously-provided data regarding typical meteorological conditions at the site of interest.

Both types of dispersion models may be refined by considering atmospheric reactions. For pollutants that are considered conserved[8], such as CO, heavier molecular weight polycyclic aromatic hydrocarbon (PAHs), and primary $PM_{2.5}$, simple Gaussian Plume type dispersion models will suffice to estimate ground-level concentrations. But, for non-conserved pollutants, such as PM_{10}, NOx, SO_2, and most VOCs, such models are modified to include deposition (for PM_{10}), and physical and chemical transformation processes that occur in the atmosphere, i.e., gaseous reactions that form secondary PM (either $PM_{2.5}$ or PM_{10}) and ozone, for example (U.S. EPA, 2011). These more sophisticated atmospheric models account for pollutant mixing and the photochemical reactions that occur as the reactive chemicals disperse in the atmosphere.

Atmospheric dispersion models require location-specific inputs for emissions rates, source characteristics (such as stack height), local weather conditions, and regional air patterns (U.S. EPA, 2011). Because of the data inputs and computational resources required, many co-benefit studies opt to use simplified linear equations to scale emission changes to changes in the concentration of pollutants at ground level, rather than employ atmospheric transport and dispersion models (Jack and Kinney, 2010).

Scale is also an important aspect of air pollution models because the level of geographic detail of dispersion model inputs and outputs will limit the resolution of endpoint impact modeling (U.S. EPA, 2011). Figure 1 shows an example of output from air pollution modeling of PM_{10} emissions in Shanghai by Li et al. (2004). There, the air pollution dispersion results are modeled in a grid with cells that are 4km

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[7] This methodology of determining post-emission dispersion of air pollution applies directly to the process of quantifying the human health impacts of air pollution. Pollutant dispersion in other media, such as water pollution and waste, or increased investment levels, are not directly discussed here but regardless of impact category, it will be necessary to similarly quantify the fate and transport of pollutants throughout the eco-system, economy and/or society before impacts may be quantified.

8 By definition, a conserved pollutant does not decay, react, nor deposit rapidly over scales of < 50 km.

by 4km. Consequently, the authors can only characterize impacts at that same scale, with no possibility for finer resolution. As urban environments can significantly impact air dispersion and final pollutant concentrations, due to building and heat island effects, this scale directly limits the reliability of the impact characterization.

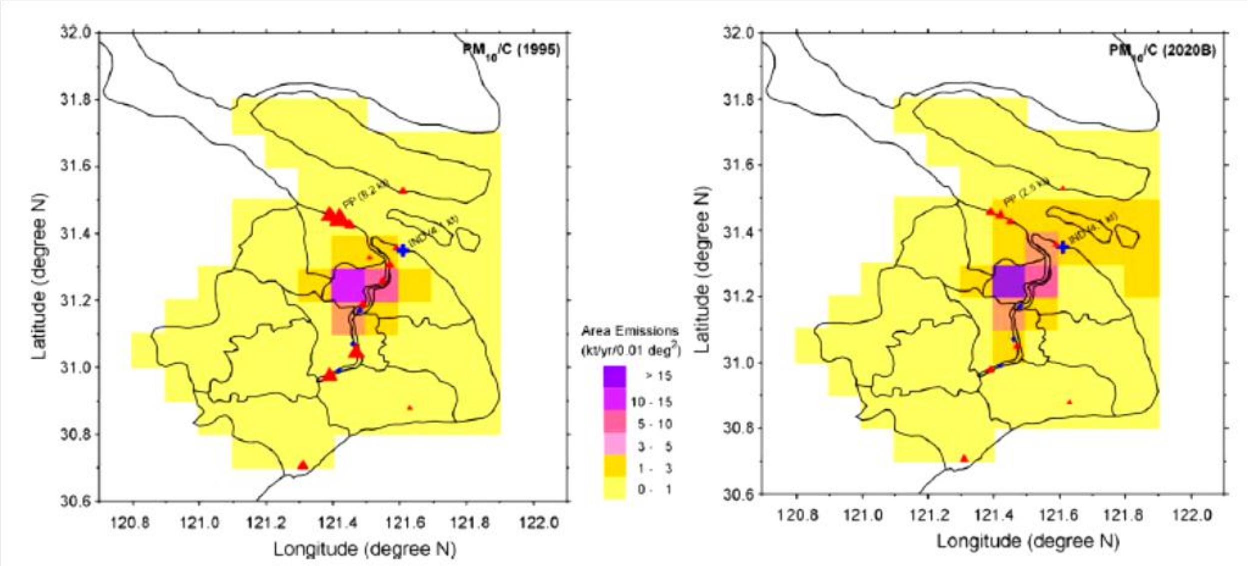

Figure 1: Annual area source emissions of carbonaceous PM$_{10}$ for 1995 and 2020 in Shanghai

Source: Li et al., 2004.

Air pollution dispersion models can be complicated computational tools that require expertise to run and evaluate, and are therefore often outside the scope of environmental agencies and other policy makers in developing countries. An alternative simplified methodology for characterizing health impacts associated with the emissions of conserved pollutants is the intake fraction (iF). The iF approach was formally introduced in 2002 and it characterizes the "the integrated incremental intake of a pollutant, summed over all exposed individuals, and occurring over a given exposure time, released from a specified source or source class, per unit of pollutant emitted" (Bennett et al., 2002). Intake fractions are calculated as a function of the number of people exposed, the volumetric breathing rate of the population, the incremental concentration of the pollution in the breathing zone that is attributable to emissions, and the emissions rate from the source. They are expressed in parts per million to indicate that an exposed population inhales or ingests a certain increment per tonne of total emissions. Intake fractions can be used to replace atmospheric dispersion modeling in co-benefit analyses, allowing researchers to go directly from the quantification of emissions to using concentration-response (C-R) functions[9] to establish health impacts, as long as the intake fractions have been calculated specifically for the source type, geography type and population examined. Intake fractions vary based on the scale

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[9] A detailed description of C-R functions can be found in Section 2.3.

of the areas (i.e., urban, rural, or regional), the size of the exposed population and their proximity to the source, and the lifecycle of pollutants.

The intake fraction methodology is used prominently, in the field of life-cycle impact assessment, and the method is still evolving to more accurately characterize emission sources and geographic scales.. Current models are based on assumptions that may greatly impact accuracy, especially regarding the effects of microclimates in urban spaces. Intake fractions are calculated using average concentration values within the area being studied and therefore cannot indicate the effects of concentration gradients within small areas. The intake fraction metric has been applied to power plant emissions of SO_2, SO_4, NO_3 and particulate matter of various sizes in China and appears especially useful for modeling the health impacts of primary course particles, whereas primary fine particle and secondary particle intakes often occur more than 500km from the source, necessitating the use of atmospheric dispersion models (Zhou et al., 2006). A recent effort has characterized urban intake fractions on a global scale, specifically for distributed ground-level sources such as transportation, diesel generators, and biomass combustion units like cooking stoves) based on the commonly shared characteristics of cities and their populations (Apte et al., 2012). Other means of calculating intake fractions have been developed, such as empirically tracking tracer species of air pollution (Marshall and Behrentz, 2005).

2.3. Calculate of the impacts of emissions and quantify the co-benefits

Once ground-level pollutant concentrations are determined, the question arises of how pollution concentrations impact end points (Table 1). For human health, this step involves characterizing the population and finding the appropriate relationship between the population health and air pollution concentrations.

The impacts of air pollutants are often highly localized: while GHGs can stay in the atmosphere for more than 100 years and are mix thoroughly in the atmosphere, atmospheric lifetimes of conventional air pollutants are generally shorter than GHGs (they can be as short as hours or days) and these pollutants mix less well in the atmosphere, and therefore air pollution impacts are most heavily felt by populations that are proximate to the source (U.S. EPA, 2011). Furthermore, air pollution clusters can form in certain geographies where atmospheric and geographic conditions result in concentration spikes – urban areas often see such concentration spikes. Modeling population characteristics for persons living near sources of pollutants, adds a critical layer of detail to the analysis.[10] Population characteristics to consider when looking at health impacts include enhanced susceptibility to pollutants for certain populations (due to for example, age, genetic predisposition, nutritional status); the geographic distribution of populations (for example, higher density urban populations and population interactions with indoor environments); exposure to risk co-factors (such as exposure to indoor air pollution), and access to health care due to poverty and other characteristics (Davis et al., 2000b).

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[10] It is notable that many co-benefit analyses, especially older studies, do not characterize populations in detail. Population characterization and modeling is a complex and time-consuming process heavily reliant upon high-quality census survey data. In many instances such data is simply not available. In other instances, atmospheric distribution models are scaled so as to make generalizations about population characteristics (such as using national or regional averages) sufficiently valid at that scale.

Critical factors in determining the impact of air pollution include the population density and proximity to emissions sources. Depending on the fate and transport of the pollutant in the atmosphere, the population density at various spatial scales needs to be determined. For example, Figure 2 displays the population density on a 4x4 km grid used to characterize population impacts associated with PM_{10} exposures in Shanghai (Li et al., 2004).

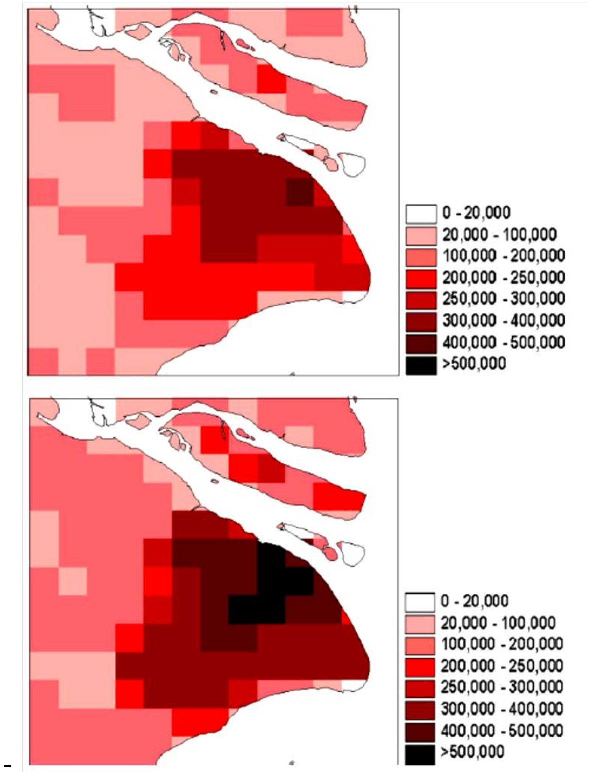

Figure 2: Population distribution in Shanghai in 1995 (upper) and 2020 (lower)

Source: Li et al., 2004.

Population characteristics are needed to determine the number of persons exposed to concentrations and the potential for health impacts based on demographic characteristics within that population. There are several means of simplifying the task of modeling population distributions and sub-population characteristics. Often activity-related impacts such as metabolic rates and population interactions are ignored by averaging impacts across all persons in the city. The scale of air pollution modeling will often require this simplification if the scale is larger than that of a city block, as in Figure 2. Another simplification is to only include certain end-points of interest in the analysis, for example by only examining adult bronchitis as a health end-point and not including childhood bronchitis.

Finding the relationship between air pollution concentrations and health impacts for modeled populations requires analysis of several issues (U.S. EPA, 2011):

1. The pollutants to be analyzed: primary and secondary PM, and SO_2 are most commonly included in co-benefit studies but secondary air pollutants and less health impactful air pollutants such as NO_x, ozone, and CO are also, although more rarely, analyzed.

2. The selection of health impacts of interest: although premature mortality is the most commonly analyzed impact, other impacts of common interest include chronic and acute bronchitis, heart attacks, hospital admissions for respiratory and cardiovascular diseases, emergency room treatment for asthma, asthma attacks, and multi-causal "symptom-days" (including days of work lost).

3. The selection of concentration-response (C-R) functions (as discussed below).

4. The time span of pollution exposure: the health impacts for different pollutants are contingent on exposure times and therefore concentrations are modeled to reflect this critical question of length of exposure. For example, ozone health impacts generally require hourly exposure estimates but may be limited to ozone "seasons" (periods during the year when ozone is dramatically higher due to weather and other conditions), whereas acute (short-term) PM health impacts are often calculated based on hourly or daily averages, and chronic (long-term) are based on yearly average PM levels.

5. Geographic scope: Because the impacts of conventional air pollution are most strongly felt in local areas, the resolution of the modeling is important for determining potential sources of under- or over- estimation in the estimated impacts. Depending on chemical reactivity and deposition rates, dispersion may also be the primary removal mechanism of pollutants. As such, air pollution is trans-boundary in nature, and therefore acknowledgment of the geographic scope of the study is necessary for analytical rigor.

There are several approaches used to determine health impacts of pollution exposure on a population. One method is to simply estimate the "health benefit value per ton of emissions" (also known as the benefit per ton (BPT)), an average monetized benefit of a marginal change in pollutant or pollutant precursor emissions and consequent health impacts (U.S. EPA, 2011). This strategy is most effective (and most justifiable) when applying previous results of an extensive analysis to a smaller project in the same geographic region. This quick and simple methodology is useful for internal policy screening within government agencies already undertaking more comprehensive analysis (U.S. EPA, 2011). However, BPT methods have only a limited ability to account for spatial differences and by their nature must accept and recreate the assumptions of more-extensive analysis conducted previously in the same area. These factors restrict the application of BPT in areas that have not already undertaken extensive air pollution impact modeling efforts.

For co-benefit analysis that applies to a region without existing co-benefits calculation, the BPT methodology will not be sufficient. The health impact analysis then must start with the determination of the local health response to pollutant concentrations. Concentration-response (C-R) functions are mathematically-derived formulas that directly relate health impacts of pollutant exposure to concentrations of pollutants. These functions are based on empirical research that statistically correlates human health outcomes in large groups in geographically-limited areas to the level of air pollutants to which the population has been exposed. A C-R function is sometimes a linear relationship between pollution concentrations and a particular health outcome; in other cases the relationship may be more complex. In most cases C-R functions are given as a range of values around a statistical average (U.S. EPA, 2011). The use of a C-R function requires an examination of how closely the population used in the research from which the function has been derived, approximates the population under study – this often requires an extensive literature review and population level data. Because it is often the case that the two populations do not match, there are a variety of methodologies for adjusting the C-R function to more closely apply to the population under study (ETSU and Metroeconomica, 2005).

Several efforts exist to simplify the need to undertake a thorough review of epidemiological studies to derive appropriate C-R functions – these often are in the form of agglomerated databases of such studies. Several independent efforts have begun to agglomerate the results of such studies into centralized databases and modeling tools. Carnegie Mellon University and the University of Washington have developed a tool, the Fast Environmental Policy Regulatory Evaluation Tool (FERET) to evaluate how policy changes impact air-pollution related health outcomes and economic impacts. The U.S. EPA's Benefits Mapping and Analysis Program (BenMAP) estimates population-level exposures and monetizes health end-points (Bell et al., 2008; see 3.3.4. below for a more extensive description of BenMAP). The ALPHA2 model, developed under the EU ExternE projects, was developed to quantify and value health, agriculture, and materials benefits from activities that affect air quality in Europe, using an EU-specific database (Holland et al., 2008; see section 2.3.1. below for an example of an application of the ALPHA2 model). It also provides a comprehensive framework for cost-benefit analysis with sensitivity and uncertainty considerations and provides qualitative assessments for impacts that are not easily quantified.

Because epidemiological studies are more common in developed countries and are much rarer in developing countries, where data are lacking, C-R functions from developed countries are used in developing countries, but with caution. Determining the appropriate C-R function to apply to the study region is often the most complicated process within co-benefit analysis. For example, non-linear C-R functions could cause endpoint impact estimates to be highly sensitivity to whether emissions reductions from the policy or program in question are the first to be achieved or the last to be achieved amongst other emission abatement policies in the pipeline. C-R functions should be constructed to best fit a large variety of exogenous circumstances, such as income levels, access to health care, nutrition, age, gender and other issues. The ExternE project has established the following set of four criteria for choosing an appropriate C-R function (ETSU and Metroeconomica, 2005):

1. "Credible as a set of functions (including the additivity or not of estimated impacts across different health end-points and individual pollutants) against the background of what is known generally about the impacts of air pollution;

2. Reliable individually, i.e. from well-conducted studies, of appropriate design, using appropriate statistical methods and adjusting for confounding factors such as weather and seasonal or other longer-term trends;
3. Transferable/generalizable, i.e. from studies in situations that are similar enough to the proposed applications;
4. Usable within the project: for example, with a health end-point that can be valued monetarily; with exposure characteristic that is compatible with dispersion modeling of incremental pollution; and with an C-R relationship that can easily be implemented: ideally, linearized, independent of background levels"

As summarized in Table 2, health outcomes can be expressed in several ways, including incidence of premature death, incidence of disease, hospital room visits, and many more. The most common health impacts evaluated are the incidence of premature mortality and certain debilitating illnesses such as chronic and acute bronchitis. Premature deaths are by far the r the greatest human health impact of air pollution (Davis et al., 2000b; Bell et al., 2008).

As discussed below, as part of the final impact monetization step commonly undertaken in co-benefits analysis,, researchers aggregate the monetary value of all the benefits achieved from reductions in health impacts and other co-benefits. However, this summation should be undertaken only for all health impacts associated with a specific pollutant, and preferably adjusted for exposures to other relevant pollutants (e.g., PM health outcomes adjusted for SO_2). Air pollutants can act together, or synergistically either in additive or multiplicative ways, in creating health damages, and the impacts of other air pollutants are not generally disaggregated in C-R functions. Therefore, estimates of co-benefits can be too optimistic if impacts from different pollutants are mixed together. Thus, at the end of this step of quantifying health impacts, it is important to keep all impact calculations separated by the air pollutant reductions from which they arise so they can be individually monetized in the next step.

2.4. Estimate the monetary value of health and other co-benefits

As a last step, many studies aim to compare the cost of the policy in question to the benefits of the positive impacts that may result from decreased pollution and other activities. Monetization of impacts in which dollar values are assigned to quantifiable impacts so as to compare policy and program implementation costs and benefits is the most common form of co-benefit impact analysis, but several others have also been developed and used.

The process of monetization may be simplified into three steps: 1. find the change in air pollution health impacts between the base-case and the alternative scenario(s); 2. assign values to those impacts based on data of the economic or other worth of those impacts; and 3. add appropriately-grouped valuations together and potentially compare them to implementation costs. Ideally, the results will indicate the cost savings associated with the alternative policy in each emission category. The further step of comparing co-benefits to policy implementation costs is commonly undertaken in CBA analyses discussed above. Ideally, co-benefits analyses would quantify all potential benefits from reducing GHG-emission related impacts, such as avoided acidification, eutrophication, other crop damage, visibility losses, pollution clean-up costs, physical deterioration of buildings and other capital assets, etc., as well as the benefits associated with technology development, structural change, and behavior change sometimes implicit to GHG reduction policies. The evaluation of these environmental, policy, and program co-benefits is rarer than the evaluation of health co-benefits, and therefore the focus of this section is the means of monetizing human health impacts. To monetize policy and program benefits, the total avoided health endpoint for each impact category (e.g. deaths avoided from reduced lung cancer) is multiplied by a unit value for that health impact (e.g. value per life saved).

Any attempt to monetize health impacts relies on the assertion that individuals have preferences that extend over environmental quality and its health impacts which may be compared to preferences for other market and non-market goods (Davis et al., 2000a). If this is accepted as true, then it is possible in principle to deduce how individuals trade-off environmental quality or their health for other services and goods that they value. The expression of values in monetary terms is shorthand for what people are willing to give up in alternative real consumption opportunities.

Economic valuation of morbidity and mortality impacts usually consist of three components (U.S. EPA, 2004):

1. The value of lost work or leisure time due to illness or reduced lifespan due to premature mortality;
2. Medical expenditures (e.g. hospitalizations, medicines);
3. The value associated with pain and suffering.

There are several ways to value these components. The two principle means of impact monetization are through finding a “willingness-to-pay” (WTP) value for the entire loss due to health impacts and through summing the opportunity costs of changing behavior due to death or illness. Medical expenditures are less frequently the sole means by which health impacts are valued.

The **Willingness-to-Pay (WTP)** method is based on the maximum sum of money an individual would pay to obtain a statistical improvement (or avoid a decrement) in some good or service. WTP studies use a foundational principle of neoclassical welfare economics – the substitutability of goods – to provide estimates of preferences for improved health (Davis et al., 2000a; Li et al., 2004; Amann et al., 2011; Bell et al., 2008; Jack and Kinney, 2010). Economists generally agree that WTP is the ideal means of monetizing health improvements (U.S. EPA, 2004). WTP values can be estimated through surveys (called stated preference methods) or based on analysis of large-scale economic data about health costs or wages (called revealed preference observations).

Stated preference methods can be undertaken in two ways. **Contingent Valuation** surveys give survey-takers a hypothetical situation about paying to avoid a health end-point for some dollar amount. **Conjoint Analysis**, on the other hand, is a stated-preference technique in which respondents are given alternative hypotheses with different costs and health impact scenarios and then asked to rank them by their preference. By varying the costs and health impacts within the study, the surveyor can analyze the tradeoffs that individuals make in terms of money, illness, time, and other factors (Pearce and Howarth, 2000).

Revealed preference methods look at large-scale market transactions to determine a consumer's willingness to pay. **Averted Behavior Studies** examine the price individuals regularly pay to avert a health end-point, such as investments in preventative care and other health improvement inputs, compared with the quantity of health risk mitigated for such activity. **Hedonic Models** (also called Wage-Risk Studies) estimate the value of job-related risks to estimate WTPs for avoiding the risk of death by the difference in wages between jobs of differing levels of risk (Pearce and Howarth, 2000).

Figure 3 gives a general overview of the relationships between the different WTP monetization methods.

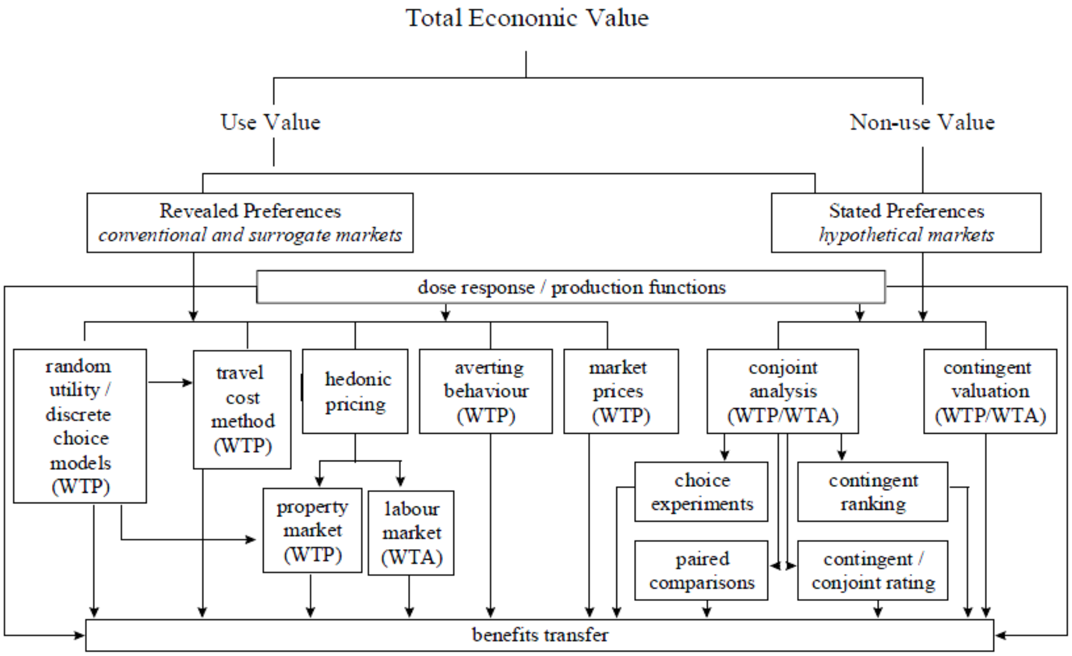

Figure 3: Typology of Monetary Evaluation Methods

Source: Pearce and Howarth, 2000.

Opportunity costs methods are used to value medical expenditures and lost wages when WTP data are not available. These methods do not take into consideration the private cost of pain and suffering and therefore are looked on as comparatively incomplete valuations that may underestimate the actual cost of health damage by air pollutions (NRC, 2010).

The *Cost of Illness* (COI) method is an opportunity cost method most often used for acute and chronic end-points. The COI method incorporates direct (e.g. hospital bills) and indirect (e.g. missed work time) costs of illnesses. COI valuations are generally dependent on four factors: the number of doctor visits, length of hospitalization, length of recovery in bed and at home, and the associated cost of all medical treatment. COI is considered an imperfect means of valuing health benefits as these opportunity costs do not fully capture the social preference for better health (i.e. no valuation of pain and suffering), but rather the direct market losses (contingent on market prices) incurred to the suffering individual. Due to these weaknesses, COI-derived estimates are often thought of as a lower bound on impact valuations (Bell et al., 2008).

The second opportunity cost method, the *Human Capital Approach*, estimates the value of premature death in terms of foregone wages. This method is not based on modern welfare economics as it measures the value of life by merely the individuals productive output to markets. Furthermore, as wages are not fully reflective of value, but rather of other factors like region, market conditions, gender and employer type, these valuations are rarely used in health benefit studies (Bell et al., 2008). However, the total value of future earnings has been used as minimum valuation estimate or "reality check" for benefit transfers between countries, such that value of health quality cannot fall below that of average prevailing wages.

It is important to note that environmental policy changes do not generally cause or avoid specific deaths; rather, they cause small changes in the statistical risk of death for each individual in the affected population. Therefore, often these health valuation numbers are applied not to individuals, but to large groups or sub-populations by assuming that all individuals in the group are represented by the valuation as an "average" preference. The values of future health outcomes and illnesses are generally discounted to their present value by some discount rate assumed in the study. The World Health Organization Guide to Cost-Effectiveness Analysis recommends 3% as the base case in cost-effectiveness analysis for general health interventions, with 6% used for sensitivity analysis (Tan-Torres Edejer et al., 2003).

In the valuation of avoided mortalities, a common way to express WTP or proxy-WTP values (especially data from wage risk-studies) is the **Value of a Statistical Life (VSL)** which is the total amount a society would be willing to pay to avoid the risk associated with causing one "statistical" death in society. For example, if stated preference studies yielded a WTP of $5 to reduce risk of dying by 1/10,000, then the VSL would be $50,000. It is important to note that since VSLs are estimated based on WTP methodologies, they are inherently linked to one's ability to pay, or generally speaking, income levels. VSL is generally only associated with WTP valuation methods. For example, because the Human Capital Approach does not take the value of avoided pain and suffering into consideration, it is not commonly used to determine a VSL.

Despite the theoretical underpinning and analytical rigor found in the WTP-VSL approach, there are limitations to the WTP-VSL approach. . For instance, changes in environmental quality or health status often have impacts on the distribution of real income and utility in society, which might skew WTP survey results. Furthermore, avoided health risks may differ by type of health event and age, which is attributable more so to the public perception of harm rather than actual harm posed. For example, cancer risks are often disproportionately weighted by survey participants when compared with other diseases with comparable risks (Bell et al., 2008).

The Value of a Statistical Life Year (VSLY), also known as the Value of a Life Year (VOLY), is an extension of the VSL methodology that allows the valuation of morbidities. These methods use VSL and average life span expectations to determine the value of a year of an individual life, usually through a linear method of dividing VSL by average life expectancy (Smith and Haigler, 2008). VSLY is less commonly used by public health professionals because the methodology implies that age and WTP are proportionately and inversely related, although this hypothesis is not supported empirically (Bell et al., 2008). In addition, some experts believe that using VSLY incurs the risk of diverting public health protection resources away from older populations; this has resulted in particular political controversy in the United States; however, Canada and the European Union both discount VSL and VSLY estimates based on age (Viscusi, 2011).

A third and increasingly popular methodology to value health impacts requires the calculation of **Quality Adjusted Life Years (QALYs) or Disability Adjusted Life Years (DALYs)**. Both use time, rather than money, to measure the burdens of ill-health and mortality by measuring how a health impact prevents a person from living to the average lifespan in perfect health. QALY calculations are the arithmetic product of life expectancy and a measure of the health-related quality of life that a person is predicted to experience throughout the course of their life (Sassi, 2006). QALYs are calculated by estimating the time period that a person is expected to live in a particular state of health and multiplying that time by a utility score related to that state of health. A DALY can be thought of as one lost year of “healthy life”, measured by the sum of years of life lost (YLL) due to premature mortality and the years lived in disability (YLD). YLL is calculated by the number of deaths at each age multiplied by the standard life expectancy for each age, and YLDs are calculated by the number of disease cases in a period multiplied by the average duration of the disease and weighted by a disease factor. The primary difference between the two calculations is that the QALY represents levels of quality of life enjoyed by individuals in particular health states, whereas DALYs represent a quantification of the reduction in normal functioning caused by disease (Sassi, 2006).

Both the QALY and DALY method derive and apply weights in different ways. QALY weights are assigned to different health impacts based on preference-based surveys from population samples or from groups of patients (Sassi, 2006). DALY weights are assigned to different disabilities based on expert analysis of the impediments to normal life functions cause by a disability. For example, a person with a lost leg might be deemed to have a 30% disability weight. After living for 10 years with this disability, he would be deemed to actually have lost 3 DALYs to his disability. QALYs do not incorporate an age-weighting function and so one static-disease based QALY always have so same value, regardless of the age of the person (Sassi, 2006). However, QALY calculations allow health-related quality of life to vary with disease progression. DALY weights are adjusted based on the age of the person, with DALY weights decreasing as a function of age on the assumption that the lifestyles of older people diverge less from normal when impacted by a disease or disability (Sassi, 2006). The two calculations are therefore not equivalent and can vary dramatically depending on the age of occurrence of the health impact, the duration of the disease, and the age of the person at the time of calculation. However, an analysis of monetized QALYs by EPA found that for situations in which mortality dominates other health outcomes, QALY and WTP methods can provide similar results (Hubbell, 2006).

Mortality or morbidity impacts can be quantified as the change in the number of DALYs or QALYs, which necessarily requires information on life expectancy and age structure of the affected population, as well as a regard to the origin of the QALY and DALY-related data and its applicability in the case being studied. The World Health Organization developed the QALY quantification methodologies and continues to tabulate QALYs from 26 global risk factors throughout the world through the Global Burden of Disease project (World Health Organization, 2012). The QALY therefore has the advantage of centralized oversight and international comparative value, as QALYs are quantified and regulated by the WHO in detailed, coherent global databases with risks differentiated by age, sex, disease type and region (Smith and Haigler, 2008).

One of the often-cited advantages of QALYs and DALYs over both COI and WTP approaches is the independence of the income of the affected population (Krupnick, 2004). As put by Smith and Haigler (2008), the burden from all deaths and diseases is treated equally for everyone "… disregarding social class, income, ethnicity, nation of origin, and all other distinctions" (Smith and Haigler, 2008). However, DALYs and QALYs have limitations. DALY weights are assigned in part from surveys of medical professionals based on their perception of living with a disability. However, evidence indicates that this method can result in weighting disabilities more heavily compared to how disabled persons would view the quality of their own life (Sassi, 2006). Furthermore, DALYs do not vary based on the external circumstances of individuals – a wheel-chair assisted person in the United States may have a significantly higher quality of life in several ways than a wheel-chair assisted person in a less developed-country. DALYs inherently value healthy and younger lives more than the ill and older individuals by assigning lesser weights (and therefore indicate decreased impacts) to older persons who typically comprise the air pollution-susceptible population. Furthermore, as opposed to WTP-based approaches, QALY and DALY approaches may not directly reflect non-disease outcomes, like emergency hospital admissions, lost work days, the effects of medication and others (Smith and Haigler, 2008). Regardless, due to their integrated nature and specificity to health (as opposed to welfare improvement gained through other goods), QALYs and DALYs are now the preferred choice among medical and public health academics and professionals (Institute of Medicine of the National Academies, 2006).

To monetize QALYs for purposes of comparing environmental damages or to do a complete cost-benefit analysis, one must monetize the results using a VSL (or VSLY). This method is not widely practiced among U.S. regulatory agencies and not recommended by experts in the field of health valuation (Krupnick, 2004; Institute of Medicine of the National Academies, 2006). Due to the issues involved in monetizing QALYs and DALYs, these metrics are most commonly used only in cost-effectiveness analyses that compare cost of measures per unit resultant benefit.

As mentioned above, epidemiological studies and valuation surveys have been more commonly conducted in developed countries. Although a growing body of literature is compiling valuations for the developing world and the QALY/DALY work avoids the issue of monetization altogether, a common methodology in co-benefit analyses is to use valuation data from developed countries' WTP studies and adjust it for local economic contexts in the developing world.

The **benefits-transfer method** is commonly used when original valuation studies do not exist in the modeled region and gathering data would be cost prohibitive and time-consuming. Benefits-transfer requires adjusting the original valuation data based on the differences in local economic and health conditions (such as average income per capita or national GDP). Using correlations between the economic characteristics of the origin country and the country to which the benefit is being transferred, unit valuations are depreciated to approximate the value of labor, time, and (most controversially) pain and suffering in the developing world context. There are three basic conditions to undertake a benefits-transfer calculation Viscusi, 2004)(U.S. EPA, 2004):

1. Adequate quality of WTP studies from which the "base VSL" was derived. A handful of high quality studies carried out in the United States are commonly used by many U.S. regulatory agencies, such as the U.S. Environmental Protection Agency. (for example, Mrozek and Taylor, 2002; Viscusi and Aldy, 2003; and Kochi et al., 2006).

2. Similar character of risk change being valued in both studies.

3. Similar population characteristics, in terms of income, demographics, and social characteristics. The income dependency of VSLs can be specifically addressed using appropriate income elasticities to extrapolate appropriate values for the target region, though there is considerable uncertainty about elasticities (Hammitt and Robinson, 2011). Because a choice of elasticity value can dramatically alter the resultant benefit transferred VSL, a range of VSLs are often reported in sensitivity analyses. Researchers also often adjust for differences in life span, health care, and insurance coverage to fit the VSL value to local circumstances.

The choice of discount rate for the purposes of calculating net present value of both benefits and costs is another point of contention as the time value of money differs between countries, with differences between the social discount rate and rate of return on capital investments fluctuating with prevailing economic conditions. A discount rate of 3% is applied as a standard to DALY calculated in WHO databases, with 6% used in sensitivity analyses (Smith and Haigler, 2008). However, a higher discount rate (upwards of 7%) has often been proposed for developing countries where investment risks are higher, though many have argued that health benefits reaped in the future should not be subject to the capital discount rate or even be discounted at all, as the time value of lives saved should not change.

Finally, it should be noted that unit values represent the preferences of the "average individual" and other individuals may have considerably different values and preferences. It is therefore crucial to consider the scale at which these "average" preferences have been determined; as c air pollution often disproportionately affects local populations, and thus the accuracy of impact valuations will be greatly enhanced by more-closely surveying the preferences and characteristics of the directly affected population rather than the national population (U.S. EPA, 2004).

3. Approaches for Co-benefits Identification and Quantification

Since the 1990s, co-benefit theory has been developed through international workshops, nationally and regionally sponsored programs, and the work of academics, think-tanks, and NGOs. This research has resulted in increased international attention for co-benefits: co-benefits research developments are regularly reported on as part of the Intergovernmental Panel on Climate Change reports and new laws in the European Union and California explicitly require the calculation of co-benefits with the evaluation of climate change mitigation strategies. This section will discuss prominent examples of each type of co-benefit analysis, focusing on the methodologies employed.

Generally, co-benefit quantification efforts are classified into three categories: (1) co-benefit models; (2)ex-ante policy assessment methods;, and (3) frameworks established by academics looking to improve the field and apply co-benefits to a broader range of geographies, policies, and programs. A sub-category of ex-ante assessments evaluated here are guidebooks for undertaking such assessments. Co-benefit studies are increasingly created to conduct ex-ante assessments of policy choices before energy efficiency, fuel conversion, and GHG mitigation policies, programs, and projects are put into place. Ex-ante assessments are generally conducted by government organizations, but are also conducted by NGOs. Several countries, most notably the United States and Japan, have developed co-benefit guidebooks to allow development and international aid agencies, developing country governments, and local governments to undertake their own co-benefit assessments (U.S. EPA, 2011; Japan Ministry of the Environment, 2009). However, rather than create guidebooks, many organizations have developed computer modeling suites that are intended to be used to conduct the ex-ante studies discussed above.

A third more diversified class of co-benefits analysis are the frameworks that have been developed by academics and other persons who are interested in testing and further developing co-benefits methodologies, particularly to account for the data limitations in developing countries and sometimes to inform policy makers as well. These are by far the most common type employed in co-benefits research.

The sections below give examples of the aforementioned types of co-benefit quantification efforts using some of the major co-benefit efforts as examples. In this report, quantification efforts are summarized and characterized below by five features:

- the general scope of the model, including the type of energy model used (bottom-up, top-down, or hybrid), region modeled, pollutants, and co-benefits examined by the study;
- the developers of the research and their purposes;
- the methodology by which baselines, changing emissions, atmospheric dispersion, health impacts, and impact valuations are established and calculated;
- model limitations noted by the model developers and by the authors of this report are discussed.

If a model or guidebook is available online, the location and whether it is freely available has been given.

3.1. Co-benefit quantification models

3.1.1. The Greenhouse Gas – Air pollution Interactions and Synergies (GAINS) model

General Scope:

GAINS is a top-down co-benefit modeling suite. Several modules within the suite estimate future emissions of certain pollutants given exogenous market drivers or policies), the impacts of these emissions in terms of human health, damage to vegetation, and GHG emissions, and least-cost technology to achieve emission reductions and the impact of those strategies on other emissions. The model has been used extensively in European environmental policy making and regional models have been developed for South Asia, China, and UNFCCC Annex 1 countries. Versions of the model for Asia and Russia and a global model are in development (Amann et al., 2011). This review focusses on the European GAINS model.

Availability:

The GAINS model online tool is freely accessible at http://gains.iiasa.ac.at/models/index.html.

Developing organization and model history:

GAINS was developed by the International Institute for Applied System Analysis (IIASA). IIASA began work in the late 1980s to develop a cost-optimization model for sources and impacts of acid deposition in Europe and Asia. The resultant tool, the Regional Air Pollution Information and Simulation (RAINS) model, was used to guide negotiations on national emissions ceilings for the 1994 Second Sulfur Protocol and the 1999 Gothenberg multi-pollutant protocol. To develop emissions reduction scenarios for the EU Convention on Long-range Transboundary Air Pollution, the RAINS model was expanded into the GAINS model and used to identify emission control strategies that achieve air quality targets and GHG emissions at least cost. The further development of GAINS is the focus of the work by the Centre for Integrated Assessment Modeling (CAIM), hosted at the IIASA. The model is the main focus of the United Nations' Economic Commission for Europe's Task Force on Integrated Assessment Modeling (Amann et al., 2008).

Methodology:

GAINS uses a top-down economic model to estimate air pollution from anthropogenic driving forces such as future economic, energy, and agricultural development. Source-specific emission factors are used to characterize sources, and country activities levels are individuated to the economic structure of that country (Amann et al., 2008).

<u>Mitigation Measures</u>: GAINS includes and can consider approximately 500 different intervention measures with multi-pollutant impacts. These measures can be categorized into three means of reducing emissions; GAINS explicitly models the first two (Amann et al., 2008):

1. *Structural measures* are measures that result in the supply of the same amount of energy services to consumers but through less polluting activities (e.g. fuel switching and energy conservation). The GHG portion of GAINS includes about 350 types of such measures, however

they are not usually employed in air-pollution focused policy analysis as they require changes in energy policies (Amann et al., 2011).

2. *Technological measures* capture emissions at their source before they enter the atmosphere. GAINS incorporates 3500 pollutant-specific measures for reducing SO_2, NO_x, VOCs, NH_3, PM, CH_4, N_2O and F-gases.

3. *Behavioral change measures* reduce emissions through changing human activities and thereby changing the modeled drivers – these are not modeled explicitly in GAINS. Rather, GAINS users reflect such changes through changing the model's parameters.

Costs of measures: The costs of the above measures 1 and 2 are modeled based on country-specific factors (technology capital costs are the same between countries, but lifetime costs change based on country specific factors). Costs are based on technology, operations and maintenance, and other resource costs of emissions controls to society, rather than a private, profit-oriented technology supplier (Amann et al., 2008).

Pollutant modeling: Based on the top-down economic model and measures, emission of certain pollutants such as SO_2, NO_x, NH_3, volatile organic pollutants (VOCs), TSPs (total suspended particles), O_3, PM_{10}, and $PM_{2.5}$ are quantified, as are the emissions of Kyoto Protocol GHGs: CO_2, methane (CH_4), nitrous oxide (N_2O), and the three F-gases (sulfur hexafluoride (SF_6), hydroflourocarbons (HFCs), and perfluorocarbons (PFCs)). Emissions are projected based on activity data, uncontrolled emission factors, the removal efficiency of emission control measures, and the extent to which such measures are used. Atmospheric interactions, transformations, and dispersion are modeled through empirically-derived simplifications of the over 100 chemical reactions modeled in an external atmospheric dispersion model: the Unified European Monitoring and Evaluation Program (EMEP) Eulerian model.[11]

Simplified functional relationships regarding fuel use and atmospheric dispersion describe changes in annual mean $PM_{2.5}$ concentrations, deposition of nitrogen and sulfur compounds, and long-term ground level ozone. Precursor source-receptor relationships have been developed for emissions of SO_2, NO_x, NH_3, VOCs, and $PM_{2.5}$ on a country-specific level. Modules regarding dispersion as well as atmospheric mixing and transformation are then used to determine the rate by which humans and the environment are exposed to pollutants (Amann et al., 2008).

Impact modeling: The co-benefits modeled in GAINS include: reductions in negative impacts on human health via the exposure of fine particles and ground-level ozone, reductions in damage to vegetation via

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[11] The EMEP/MSC-W model is a chemical transport model developed at the Meteorological Synthesizing Centre - West (MSC-W) at the Norwegian Meteorological Institute (met.no). The EMEP model is a model that covers Europe and some outlying areas designed to calculate air concentration and deposition fields for acidifying and eutrophying compounds (S, N); ground level ozone (O_3); particulate matter ($PM_{2.5}$, PM_{10}), persistent organic pollutants, and heavy metals), as well as their long-range transport and fluxes across national boundaries. A detailed write-up of the model can be found at http://www.emep.int/index_model.html.

excess deposition of acidifying and eutrophying compounds, and the reduction in the six GHGs considered in the Kyoto Protocol (Amann et al., 2008).

- For *human health damage* occurring from air pollution, GAINS does not economically quantify health and environmental impacts.[12] Rather, the impact of $PM_{2.5}$ exposure is quantified as the loss in statistical life as well as the total amount of life years lost (YLL) for the entire population. Likewise, health impacts from ozone are quantified as yearly premature mortality based on daily changes in mortality as a function of daily 8-hour ozone maximum concentrations, but this function is only applies on days with 8 hour maximum ozone concentrations over 35 ppb.
- *Eco-system acidification and eutrophication* impacts are based on databases associated with critical loads (the quantity of deposition over which soil and water quality degrade, which varies based on soil characteristics and other factors), compiled by the United Nations Economic Commission for Europe (UNECE) (Hettelingh et al., 2007; Hettelingh et al., 2008). The computed deposition of pollutants is compared with critical loads to determine the total land area which exceeds these critical load thresholds.
- *Vegetation impacts from ground-level ozone* are modeled based on a critical threshold level over which ozone concentrations have been found to impact vegetative growth.[13]
- *Climate impacts* are modeled based on radiative forcing models with a 100 year outlook and given in increase in Global Warming Potentials within 100 years.
- *Comparing cost-effectiveness*: Cost-effectiveness or the amount of benefit per unit of intervention cost, of certain measures is weighted based on the user specified air quality and GHG target inputs, taking into account regional differences in emissions controls and atmospheric dispersion characteristics. Future costs of technologies are assumed to decrease based on assumed technological progress. Total costs are minimized subject to: (1) energy demand limitations, and other physical constraints, (2) constraints on the application rates of measures or technologies (for example, vehicle emissions controls technologies are generally not applied to existing vehicles), and (3) the user-input constraints, such as emissions caps, on air quality or GHG emissions

Limitations:

- Only anthropogenic primary PM emission and secondary aerosols are modeled, excluding PM from natural sources and primary and secondary organic aerosols.
- The resolution of the model (50km x 50km) “will systematically underestimate” pollution levels in cities so the modelers have developed a methodology to estimate urban air pollutants and their impacts, but this is a separate program that occurs outside the model.
- PM impacts are modeled only for persons 30 years old or more, ignoring health impacts for people younger than 30 years, and infant mortality impacts.

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[12] However, interface programs have been created to link GAINS estimates of physical changes to monetary evaluations. See, Holland et al.,(2008) and Amann et al., (2011).

[13] Excess of critical levels for vegetation is measured with the AOT metric, which quantifies the ‘accumulated ozone exposure over a threshold of 40 ppb’

- Ozone morbidity impacts are not modeled, as ozone-induced *mortality* is the dominant factor in ozone-related economic benefit assessment.
- The ground-level ozone-vegetation relationship is actually more complex than originally modeled and efforts to extract the ozone concentration outputs from GAINS and input them into different vegetative-impacts models are underway.
- Technological progress assumptions may be particularly unreliable past 2030 due to imprecision in estimating the pace of technological development.
- The critical loads used for acidification and eutrophication are set at the level at which no further acidification or eutrophication will occur (i.e. levels at which the pH and nutrients of soils are held at a steady state), however this does not allow areas previously harmed by acidification to recover.
- The model does not yet integrate agricultural policies and the nitrogen cycle (Amann, 2007).
- Economic welfare impacts (employment, competitiveness, income levels, etc.) are not yet modeled (Amann, 2007).

3.1.2. The Simple Interactive Model for Better Air Quality (SIM-Air) model

General Scope:
SIM-Air is a bottom-up simplified air pollutant and GHG reduction co-benefits model. The model (actually a suite of interlinked freeware applications) allows users to model emissions dispersion from transport, industry, power plants, domestic and area sources, and other sources. The tool is capable of modeling PM_{10}, NO_x, SO_2, and CO_2 (Environmental Management Center, 2009)**.**

Availability: SIM-Air is available for free online at http://urbanemissions.info/model-tools.html.

Developing organization and model history:
The SIM Air program was developed by researchers in India and at the World Bank and was initiated in response to the fact that the majority of tools for integrated assessments are complex and data-intensive, leaving underfunded or less sophisticated users with few options in understanding co-benefits of air pollution policies. A set of tools have been developed as part of the SIM-Air program to allow a simplified means of estimating key parameters (for example, emissions from sources), and to simulate the interactions between emissions, pollution dispersion, impacts, and management options. The model has been applied to several cities in Asia, Africa, and Latin America. All tools are free to download and use. The largest project, a study of 6 cities in India, was completed in 2012 with support from the ClimateWorks Foundation and the Shakti Sustainable Energy Foundation (Guttikunda and Jawahar, 2012)**.**

Methodology:
The SIM-Air model allows for a 1-year analysis of a city or region divided into a 5x5 grid. The tool accounts for emissions in five sectors: transport, industry, residential, fugitive dust, and garbage burning and produces a concentration grid for SO_x, CO_2, and PM_{10}). A higher resolution grid can also be attained

within the models (Environmental Management Center, 2009). For example, the Guttikunda and Jawhar (2012) study mentioned above, examined grids large enough to cover the main district area, the nearest satellite cities, and cluster locations with sources that could influence the air quality in the main district areas.

Mitigation Measures: The management options pre-programmed into the SIM-Air suite are: the conversion of buses to compressed natural gas (CNG); low sulfur diesel use; energy efficiency in industry; geographic shifts of sources; coal to liquefied petroleum gas (LPG) shifts in domestic/area sources; scrappage[14] and replacement of inefficient technologies; bypassing of trucks to different city sectors; and a decrease in the percentage of cars on the road (modeled by increasing public transportation). The SIM-Air modeling suite allows users to use either the default emissions factors for many technologies and sectors, or to create their own based on local context, and the interface permits changing both fuel sources and technologies (Environmental Management Center, 2009).

Guttikunda and Jawhar (2012) provide examples of how the SIM-Air modeling suite can be used to create future scenarios. They model a baseline assuming growth in the number of emissions sources (especially from vehicles) and an improvement in vehicle efficiency, and then examine six interventions, such as an increase in non-motorized share of transportation, an increase in public transport, technology improvements in driving industrial categories like brick kilns, and the elimination of heavy duty trucks.

Cost of Measures: The cost of the intervention measures needs to be input by the user. Spreadsheets are integrated into the model to allow for this activity. With the input of cost data, SIM-Air gives an example of how a cost-optimization module would work. However, work is on-going to further develop the cost optimization model (Environmental Management Center, 2009).

Pollutant Modeling: Sources of pollution are enumerated in several categories, including power generation, industrial manufacturing, transportation, distributed diesel backup systems, road dust, and garbage burning. A dispersion model is not included in the modeling suite and therefore external dispersion models must be used to determine air pollution concentration (Environmental Management Center, 2009; Guttikunda & Jawahar, 2012).

Impact Modeling: SIM-Air models co-benefits related to human health impacts or exceedences of air pollution limit levels. Concentration-response functions for health end-points are taken from epidemiological studies from around the world for adult chronic bronchitis, child acute bronchitis, respiratory hospital admission, cardiac hospital admission, emergency room visits, asthma attacks, restricted activity days, and respiratory symptom days. Impacts are monetized into health care costs with exogenous data on the cost of mortality, morbidity, and health services (Environmental Management Center, 2009).

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[14] The model defines scrappage as: "retirement of motorcycles with 2-stroke engines and promotion of using motorcycles with 4-stroke engines."

Limitations:

- The level of detail in the transportation model highly depends on the quality and reliability of information available from the local municipality, which differs between cities.
- The limited scope of the model is clearly defined in the model parameters – only certain technologies in the transportation sector are evaluated and only certain end-points can be modeled.

3.1.3. MIT's Integrated Global Systems Model (IGSM)

General Scope:

The IGSM is designed to analyze global environmental changes that will result from anthropogenic causes and to assess the costs and environmental effectiveness of climate change mitigation policies. The model includes a top-down economic model for the prediction and analysis of GHG and aerosol precursor emissions and mitigation efforts; a coupled atmospheric-ocean-land surface dispersion model with interactive chemistry functions; and includes models of natural ecosystems and human health to forecast impacts of emissions (Socolov et al., 2005).

Availability:

An IGSM run data portal is available for public download for research purposes only at http://svante.mit.edu/research/IGSM/data/IGSM_1/.

Developing organization and model history:

The IGSM was originally developed by researchers at the Massachusetts Institute of Technology (MIT) Joint Program on the Science and Policy of Climate Change in 1999 with the aim of providing a fully-coupled climate model which links the terrestrial-oceanic-atmospheric feedbacks of the climate system with human activities, and provides impacts on human health, eco-systems, and the climate. The model has been used to produce probability distributions for climate sensitivity to GHG emissions and feedbacks, the rate of heat uptake by deep oceans and net forcing due to aerosols, as well as to indicate the overall dimensions of climate change and impacts of a particular GHG emission stabilization policy (Socolov et al., 2005; Socolov et al., 2009).

Methodology:

IGSM Version 2 includes sub-models of the relevant aspects of the natural earth system coupled to a model of human activity as it interacts with climate processes. Baselines are projected based on the MIT Emissions Prediction and Policy Analysis (EPPA)[15] version 4 recursive-dynamic multi-regional CGE model of the world economy. This model projects economic variables (GDP, energy use, sectoral output, consumption, etc.) as well as emissions of the Kyoto GHGs and other pollutants (CO, VOCs, $NO_{x.}$, SO_2, NH_3, black carbon, and organic carbon) associated with the combustion of carbon-based fuels, industrial processes, waste handling, and agricultural activities (Socolov et al., 2005).

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[15] For a description of EPPA and its model structure, please see Paltsev et al. (2005)

Mitigation Measures: The EPPA model includes fuel options, options for several replacement technologies both in generation and energy use, as well as pollution abatement technologies for energy production (electricity, convention crude oil, shale oil, liquid fuel from biomass, refined oil, coal, natural gas, coal gas, hydro, solar, wind, and biomass), non-energy sector technology options in agriculture, energy intensive industry sectors, commercial transportation, other industry, and services; and activity and technology options in the household sector (own-supplied transport, purchased transport, and other goods and services). Other technologies include carbon capture and storage (CCS) and integrated coal gasification combined cycle (IGCC) (Socolov et al., 2005)

Cost of Measures: The EPPA model supports analysis of emissions control policies, providing estimates of projected costs, distribution of costs among nations, and providing methods by which costs can be mediated through international trade. The methodology relies on a constant “best available” technology for pollution controls at current costs, rather than assuming the development of ever-cleaner combustion technology at no cost (Socolov et al., 2005)

Pollutant Modeling: A two dimensional (2-D) atmospheric dynamics, physics, and chemistry model tracks atmospheric chemical and physical processes, as well as urban air chemistry, atmospheric conditions and processes, and land surface changes. A three dimensional (3-D) urban air model takes outputs from the 2-D regional air model and inputs them into the more dynamic topographies of urban spaces. An ocean model includes an oceanic carbon system and sea-ice sub-models. Land and vegetation process are modeled using a dynamically linked set of terrestrial biogeophysical (for water and energy budgets) and biogeochemical (for carbon, methane and nitrogen cycles) sub-models (Socolov et al., 2005).

Impacts Modeling: Co-benefits are assessed in terms of improvements in environmental quality and impacts on primary productivity. Impacts on the eco-system are modeled by a linked set of coupled land models, the Terrestrial Ecosystem Model (TEM) and the Community Land Model, which includes the global, terrestrial water, and energy budgets and important terrestrial eco-system. Urban air quality in “representative cities” in each latitude bandwidth is given and extrapolated to characterize the urban population in the entire region or country. Land and vegetation impacts are represented within a dynamically linked set of terrestrial biogeophysical and biogeochemical sub-models. These models include negative impacts of certain pollutants on primary productivity (for example, from ozone). Health impacts are not explicitly modeled (Socolov et al., 2005).

Limitations:

- The EPPA component of the model needs to be more tightly integrated with the biogeophysical and biogeochemical components.
- The demographic model’s simulation of the spatial distribution of population identifies the changing geographic pattern of emissions and tracks the exposure of the population to pollution. Essentially all population distributions are a function of economic variables produced by the EPPA. This approach was still being integrated into the model as of the last update (2005)

and therefore the model does not currently output direct health impacts. Similar vegetation pollution exposure models are being developed to show the impact of pollution on primary productivity, and the impacts on the agricultural and trade components of the economy.

- Existing policies regarding pollution limits and air quality standards are not included in the analysis and modeled emissions; thus, reducing the accuracy of the model.

3.2. Ex-ante policy assessments – guidebooks

3.2.1. U.S. EPA's Integrated Environmental Strategies (IES) Program

General Scope:

The Integrated Environmental Strategies (IES) Handbook assimilates the methods used to calculate co-benefits in several different projects undertaken by the U.S. EPA and several partner countries to measure the improvements in air pollution and GHG emissions of climate-change related policy interventions. The Handbook reflects the focus on specific air pollutants within the international partnerships: CO_2, and conventional pollutants (PM_{10}, $PM_{2.5}$, O_3, SO_2, NO_x, CO, and lead). Morbidity and premature mortality associated with PM can result from several health end-points (for example, increased incidence and prevalence of respiratory symptoms and illnesses, increased asthma attacks, chronic and acute bronchitis, hospital admissions, days of work loss, and infant and elderly mortality) are estimated based on an atmospheric dispersion model and concentration-response functions. These impacts are then monetized through a "benefits-transfer" technique (U.S. EPA, 2004).

Availability:

The Handbook is available for free download at http://unfccc.int/resource/cd_roms/na1/mitigation/Resource_materials/Integrated_Environmental_Strategies_Handbook_US_EPA/ies_comp_screen.pdf

Developing organization and model history:

The goal of the IES handbook is to promote integrated planning to address local environmental concerns and also reduce associated GHG and PM emissions by providing tools and approaches to analyze and quantify environmental, public health and economic co-benefits in major developing countries; improving analytical methods for co-benefits analysis; and building expertise in integrated energy and environmental analysis. The IES handbook has been in development since 1998, growing out of a U.S. domestic effort to analyze the costs and benefits of air quality measures under the Clean Air Act (CAA). Methodologies were developed and tested in partner countries with the support of the U.S. Agency for International Development and the U.S. DOE's National Renewable Energy Laboratory. The methods of the 2004 IES Handbook have been applied in case studies in Argentina, Brazil, Chile, China, India, Mexico, the Philippines, and South Korea (U.S. EPA, 2004).

Methodology:

The IES Handbook takes readers through a process of energy and emissions modeling to build a baseline emissions inventory to project annual emissions of GHGs and co-pollutant emissions (conventional air pollutants); air quality modeling to project emission concentrations; health impacts modeling to project public health impacts; and economic valuation modeling to project economic benefits. The preferred method is to analyze fuel use and characteristics and use local emissions factors to model emissions of pollutants of interest. However, the Handbook also suggests that teams collect data regarding stack heights, combustion technology, emissions control technology, production data, and geographic location of emissions sources. The Handbook encourages analysts to gather emissions from as many sources as possible, including power plants, refineries, incinerators and open burning, manufacturing plants, domestic households, automobiles and other on and off-road vehicles, animal farming operations, fossil fuel extraction and mining, office and municipal buildings, fuel distributions pipelines, agricultural land use, and landfills. Methods to estimate emissions from stationary point sources, mobile sources, and dispersed sources are also discussed (U.S. EPA, 2004).

Mitigation Measures: Energy use is the target mitigation measure of this analytical framework, including the power generation, transportation, residential, commercial, and industrial sectors. However, the sector focus may change with location: for example, in implementing the framework in Hyderabad, India, implementers focused on the transportation and industrial energy sectors. Three scenarios are commonly discussed across application studies: business as usual (BAU), air pollution control, and no-further control. Model selection criteria are evaluated and several energy and emission models are discussed, including the U.S. EPA's Industrial Source Complex Model (ISC3), the U.S. EPA's Urban Airshed Model (UAM), and the Comprehensive Air Quality Model (CAMx) (U.S. EPA, 2004).

Cost of Measures: The Handbook states that methods to integrate locally relevant costs of abatement measures to find "net co-benefits" are essential and provides several means by which these costs of implementation can be compared to the quantified benefits found. However, the Handbook does not explicitly detail how measure costs are to be calculated (U.S. EPA, 2004).

Pollutant Modeling: The pollutants included in the IES program include CO_2, PM, O_3, SO_2, CO, NO_x, and lead. Emissions forecasting is discussed, as well as options for using pre-collected data, rather than computational models. Air dispersion computational model selection is discussed with reference to several options, with the 2-D Gaussian dispersion-based models cited as being the most commonly used. Photochemical 3-D Eulerian models and their qualities are discussed. The various models used by the IES projects in their host countries were enumerated and discussed. Ambient concentration and meteorological data is discussed in terms of its importance to scenario accuracy, especially in calibrating air quality models (U.S. EPA, 2004).

Impact Modeling: The Handbook focuses on co-benefits arising from changes in air pollution-induced human health impacts. Several important issues are discussed in the modeling of health impacts, including the time horizon of impacts (most programs model impacts using 10 and 20 year time horizons), geographic area, targeted emissions, and health end-points (the health end-points listed by the EPA includes most of the compiled list of health end-points in Table 2)Table 2: Quantifiable and Non-quantifiable Human Health Outcomes used to assess the Impacts of Air Pollution Exposure The avoided health impacts are a function of changes in air quality for each analysis scenario, the number of people exposed to these changes, C-R functions, and the baseline incidence of adverse health impacts. The difficulties of finding the relevant C-R functions are discussed, including the issues of the use of C-R functions from other regions, using C-R functions from time-series versus long-term cohort studies, characterizing local populations, and issues regarding double counting. Sources of uncertainty are also discussed, including extrapolation to foreign studies, statistical uncertainty for C-R functions, statistical uncertainty of the baselines incidence of the health impacts, and others. The Handbook then discusses several potential means of quantifying and comparing health impacts, and offers support for the WTP-based monetization of health impacts as the most common and best supported means of calculating co-benefits (U.S. EPA, 2004).

Limitations:

- Several different methodologies for assessing the different stages of co-benefits calculation are discussed, but the Handbook does not recommend any specific one as the best option.
- Some methodological points do not receive sufficient emphasis in the Handbook, such as methods to calculate abatement technology costs.

3.2.2. Japan’s Manual for Quantitative Evaluation of Co-Benefits Approach to Climate Change Projects

General Scope:

The purpose of this manual is to establish a means for evaluators of GHG emissions reduction projects undertaken under the Kyoto Protocol’s Clean Development Mechanism (CDM) to calculate several enumerated co-benefits based on quantitative methodologies. The model therefore targets the other goal of the CDM program – to promote sustainable development in host countries. The Manual was constructed largely in response to plans by the Japan International Cooperation Agency to integrate co-benefits analysis into its carbon mitigation and other climate change related efforts (Japan Ministry of the Environment, 2009).

Availability:

The manual is available for free download at http://gec.jp/gec/en/Activities/cdm/cdmjimanual2009e.pdf.

Developing organization and model history:

Japan’s Ministry of the Environment is partially responsible for the oversight of Japan’s commitments for carbon reduction under the Kyoto Protocol, and thereby partially responsible for the oversight of projects initiated by Japan under the Clean Development Mechanism to meet those targets (Japan Ministry of the Environment, 2009). The Japan International Cooperation Agency (JICA) proposed the incorporation of a framework to account for co-benefits in Japan’s international GHG emission reduction projects and the Ministry of Environment developed the Manual to establish a framework for co-benefits calculation.

Methodology:
The Manual is a guidebook on how to use either qualitative or quantitative data to form increasingly specific evaluations of co-benefits. For quantitative evaluations, the manual specifies formulas to use in calculating co-benefits of several types of projects. Methodologies are given for establishing baseline pollution values in each highly specified measure, and the manual concentrates on the means of producing the data needed to calculate the data inputs rather than a final calculation of total impacts. The manual gives methods of calculating both the GHG impacts and other pollution impacts (mostly in water and air pollution emission rates) from the measures specified (Japan Ministry of the Environment, 2009).

Mitigation Measures: Three categories of environmental pollution countermeasures are focused on in the Manual: water quality improvements, air quality improvements, and waste management. Several technological measures for accomplishing the calculated reduction in impacts are described (Japan Ministry of the Environment, 2009).

Cost of Measures: Although measures are described in summary, the Manual contains no information about costs of the measures. Costs do not seem to be a priority of the Manual (Japan Ministry of the Environment, 2009).

Pollutant Modeling: Methods, including specific formulas, are provided for calculation of pollutant changes (Japan Ministry of the Environment, 2009). Air pollutants included in the guidebook are SO_x, NO_x, soot and dust, and CO_2. Water quality-related pollutants included in the guidebook are chemical oxygen demand (COD), odors, CH_4, and CO_2, nitrogen (N), phosphorus (P), and hazardous substances.

Impacts Modeling: The co-benefits modeled by the Manual are limited to reductions in emissions of air and water pollutants, without consideration of ambient air quality or air dispersion model use. The Manual does not monetize these impacts, but rather only permits quantification of the amount of pollution reduced (Japan Ministry of the Environment, 2009).

Limitations:

- This methodology, in avoiding calculation of health impacts or monetized values, represents only a partial use of the full co-benefits valuation methodology described in Section 2 of this paper.

3.2.3. The Gold Standard Program model

General Scope:

The Gold Standard Program is a bottom-up method of certifying Kyoto Protocol CDM projects as well as other voluntary programs that also result in verifiable co-benefits. After renewable energy, energy efficiency, and waste handling carbon offset projects developers record co-benefits and an appointed third party verifies that co-benefits have been accounted for and result from the project, the Gold Standard board certifies that the carbon certificates resulting from project have also attained these co-benefits. These certified carbon credits command a premium on the international carbon market by buyers who are looking for high quality credits (The Gold Standard Secretariat, 2012b).

Availability: The Gold Standard Framework is available for download at http://www.cdmgoldstandard.org/project-certification/rules-and-toolkit.

Developing organization and model history:

The World Wildlife Foundation (WWF) established the Gold Standard certification mechanism in 2003, and it is now endorsed by more than 90 NGOs worldwide, as well as several governments and multi-national corporations. United Nations agencies also use the Gold Standard in the development of their own carbon mitigation and sustainable development projects. More than 500 Gold Standard projects have been listed in the last decade, predominantly in China, India, Turkey, and Africa (The Gold Standard Secretariat, 2012b).

Methodology:

To be eligible for Gold Standard certification, projects must employ renewable energy and/or energy efficiency technologies; be certified as adhering to the Kyoto Protocol CDM requirements regarding additionally, and positively impact the economy, health, welfare, and environment of the local community hosting the project. The first step for applicant projects is to create an account in the Gold Standard Registry – a web-based tracking tool which serves to track projects as they move through the co-benefits identification, recording, and verification process (The Gold Standard Secretariat, 2012b).

Project developers start the process of identifying and recording co-benefits by filling out a series of templates supplied by the Registry. An important part of this process is local stakeholder consultation to allow the local community to understand the proposed project and provide feedback. A follow-up meeting is scheduled to review the templates as they have changed in response to stakeholder comments in the first round. Once this initial project design document has been approved by the Registry, a deeper effort to calculate baselines and emission reductions, co-benefits, and ongoing monitoring efforts is established in the Project Design Document (PDD). More feedback is given through stakeholder consultations and the PDD is made publicly available. During this step, a UN-accredited auditor is brought in to review and validate the project activity and they and the Gold Standard Secretariat reviews all submitted documents before the project becomes registered to verify emission reductions and sustainable development monitoring activities. After full verification and approval by the

Secretariat, the Gold Standard Technical Advisory Committee, and the independent auditor, the project is then issued Gold Standard-certified carbon credits (The Gold Standard Secretariat, 2012b).

Mitigation Measures: The Gold Standard is limited to projects entailing renewable energy, energy efficiency, or waste handing measures that are evaluated to be additional under the Kyoto Protocol CDM (The Gold Standard Secretariat, 2012b).

Cost of Measures: The cost of measures is not incorporated into the co-benefits evaluation process (The Gold Standard Secretariat, 2012b).

Pollutant Modeling: Project developers are responsible for defining the co-benefits to be monitored throughout the project with the input of the affected community (for a list of potential co-benefits supplied by the Registry; see Appendix C of the present report). The community is asked to define the most important indicators of social, economic and environmental success along with project developers in a series of consultation meetings. To aid this process the Gold Standard Foundation requires the submission of a list of indicators of sustainable development in several different categories, including local air pollutants, water pollution and use, and many other categories. The selection of which indicators are used within each impact category is the choice of the project developer, as informed by the community stakeholder feedback process. There is a large amount of leeway incorporated into these documents and the primary criteria by which these indicators and the associated projected co-benefits are evaluated by The Gold Standard Secretariat and independent auditors is whether or not they are well-documented, traceable, informed by community stakeholder input, and that sincere and best efforts were made to apply the Gold Standard's tools while remaining transparent and pragmatic. Both the independent auditor and Secretariat reviews are there to "make sure the fundamental principles of The Gold Standard are followed and documented to the best extent possible, using existing sources wherever possible to limit the need for additional efforts unless quality of information is insufficient" (The Gold Standard Secretariat, 2012b).

In addition, all projects must fulfill host country requirements on environmental and social impacts assessments at the local, regional, and national levels. The appropriateness of the sustainable development indicators chosen is a balance between pragmatism (for example, based on whether reliable information exists and whether monitoring efforts be combined) and the importance of the issue given the sustainability of the region and potential impacts of the project (The Gold Standard Secretariat, 2012b).

Impacts Modeling: Any project that seeks to obtain The Gold Standard must demonstrate clear benefits in terms of sustainable development[16] – the Gold Standard criteria does not require a focus on any one co-benefit, but rather allows for a multitude of potential co-benefits to be calculated, including those

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[16] The Gold Standard uses the World Commission on Environment and Development's definition of sustainable development: "development that meets the needs of the present without compromising the ability of future generations to meet their own needs."

arising from improvements in environmental quality, health impacts, physical infrastructure impacts, the availability and price of transportation, energy, and other infrastructure and services that impact equity, and others. Using the collectively-chosen indicators of sustainable development and their parameters, project developers are required to develop a baseline situation for each and the eventual improvements to be achieved by the project. Project developers are then required to give their project a score (negative, positive, or neutral) in comparison to the baseline situation. There is an opportunity to mitigate negative indicators with further mitigation measures. This process of prioritizing co-benefits and their calculation is repeated during the stakeholder consultations. To be eligible for Gold Standard certification, the project must contribute positively to at least two of the three general categories of indicators (environment, social development, and economic and technological development) and be at least neutral to the third. The Gold Standard also requires project developers to conduct a "Do No Harm Assessment" using a series of pre-defined safeguard principles to determine the risk that the proposed project might result in negative environmental, social, and/or economic impacts (The Gold Standard Secretariat, 2012b). As an optional practice, The Gold Standard Project encourages developers to also look at localized Millennium Development Goals set in the region of the project, and assesses the impact of the project on these goals.

Limitations:

- There is no absolute guidance on which co-benefits are appropriate for each project. Rather, The Gold Standard allows project developers and local communities to co-develop co-benefit analysis.
- There is no guidance on how baselines and co-benefits are to be modeled.

3.2.4. Mainstreaming Transport Co-benefits Approach: a Guide to Evaluating Transport Policies

General Scope:

The Transport Co-benefits Guidebook (TCG) gives the means to develop several different bottom-up co-benefits estimates for transportation sector policies aimed at reducing transport-sector GHG emissions. The manual gives advice on how to measure co-benefits related to local air pollutant emissions, time savings, vehicle operating costs, and accidents (IGES, n.d.).

Availability: The TCG is available for free download at http://www.iges.or.jp/en/cp/pdf/co-benefits/Transport%20Co-benefits%20Guidelines.pdf.

Developing organization and model history:

The TCG was co-developed with researchers at Nihon University in Japan and associated organizations in Thailand and the Philippines, benefiting from recommendations of international panel of transport experts and policy makers at an international forum (International Forum on a Sustainable Asia and the Pacific) as well as feedback from the Asian Transport Research Society (ATRANS), the Ministry of

Transport, Operations and Transport Planning (OTP) Office, the Clean Air Initiative for Asian Cities (CAI-Asia), and other organizations in Thailand and the Philippines who participated in field testing workshops. The project was supported by the Ministry of Environment, Japan (MoEJ).The methods in this guidebook are based on Japan Research Institute's (JRI's) *Guidelines for the Evaluation of Road Investment Projects* (IGES, n.d.).

Methodology:

The TCG presents equations for calculating the enumerated co-benefits. These are not integrated into a comprehensive model but rather may be used individually to estimate various benefits of transportation GHG policies. Rules-of-thumb are given for data inputs needed for each equation, such as emissions factors for different vehicle types at a range of speeds (IGES, n.d.).

Mitigation Measures: The variables in each equation give a sense of the values which might change with the implementation of transportation policies; the TCG method however does not account for uncertainty inherent to the transportation data inputs, aside from advising on how to find average values for each input. Several tables in the TCG give rule-of-thumb values for input variables, often based on national averages. Equations are generally categorized by dominant energy use changing characteristics (fuel economy policies, mode shifts, etc.). Specific mitigation measures therefore are not preprogrammed into the equations but rather are reflected by changing variables (IGES, n.d.).

Cost of Measures: Costs of measures are not included in the TCG (IGES, n.d.).

Pollutant Modeling: Pollutant releases for NO_x, PM, CO, and CO_2 are modeled based on emission factors for different vehicle type (IGES, n.d.).

Impacts Modeling: The guide gives means of calculating several impacts and co-benefits of changes in transportation patterns and mode shifts, including time-saved because of reduced travel times, reductions in vehicle operating costs from shifting modes, traffic safety benefits, and environmental benefits such as those from NO_x, PM, and CO emission reductions. Pollution impacts are given in damage cost estimates as rules of thumb in units of thousand US$/tonne of emissions, based on studies conducted in Japan, the EU, and the United States (IGES, n.d.).

Limitations:

- This tool is simplified and gives a very rough approximation of the impacts, based on economic costs, of air pollution on human health based on damage functions.
- Most rules-of-thumb are developed for Japan or Thailand, and therefore may not be applicable to other regions.

3.3. Ex-ante policy assessments – applied studies

3.3.1. ClimateCost Project

General Scope:

This hybrid modeling effort uses the GAINS model to calculate energy and emissions changes, with technology-specific detail added through a bottom-up approach, and the Atmospheric Long-range Pollution Health/environmental Assessment Model (ALPHA2) to predict the direct climate change-related and indirect physical and economic impacts of the climate policies of Europe, China, and India (Holland, et al., 2011; European Commission, n.d.).

Availability:

The Climate Cost Project modeling suite is only available to Climate Cost Project Partners.

Developing organization and model history:

ClimateCost (the Full Costs of Climate Change) is a major research project on the economics of climate change, funded by the European Community's 7th Framework Programme for Research and Technological Development.[17] The project team includes partners from 10 European countries, India, and China, mostly affiliated with universities (European Commission, n.d.)

Methodology

A baseline scenario describes the "no action" or BAU policy situation. Assumptions about economic development and population growth are used in GAINS to model emissions scenarios for all major pollutants in both the baseline scenario and for climate policies of two different stringency levels consistent with medium and long term GHG reduction and stabilization goals modeled to 2050. The scope includes climate change impacts on coastlines, human and ecosystem health, energy and water availability, and infrastructure; including impacts induced by major catastrophic events as well as socially contingent events.

<u>Mitigation Measures</u>: Measures examined in the alternative policy scenario include energy efficiency, fuel switching, non-CO_2 GHGs prevention measures and sink creation, and recent convention pollution control technologies already being deployed. Measures include those induced by other policies, such as the National Emission Ceilings Directive (European Parliament, 2001), UNECE Gothenberg Protocol under the Long Range Air Pollution Convention (UNECE, 1999), directives on air quality including the Clean Air for Europe (CAFÉ) Directive (European Parliament, 2008), directives on fuel quality, and directives on emissions limits for industry (Holland et al., 2011).

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[17] The European Commission's 7th Framework Program for Research and Technological Development is an effort to bundle all research-related EU initiatives together under a common roof to combine knowledge and decision-making in research and development efforts. The Programme offers direct grant funding to applicable projects that have a "European added value" and attempts to strengthen both research applicable to the European Community as a whole, as well as to individual Member States. For more information on the 7th Framework Program, see http://ec.europa.eu/research/fp7/pdf/fp7-inbrief_en.pdf.

Cost of Measures: Measure costs as well as avoided abatement costs (calculated by the reduction in the need to install air-pollution control equipment) are modeled using the GAINS database (Holland et al., 2011).

Pollutant Modeling: Pollutants modeled include SO_2, NO_x, VOCs, NH_3, $PM_{2.5}$ (excluding N_2O and PMs originating from the atmospheric transformation of VOCs). PM and ozone exposures resulting in adverse human health effects and acidification and eutrophication are the major impacts studied in this model (Holland et al., 2011).

Impacts Modeling: The co-benefits examined in the ClimateCost project include pollution reduction-related improvements in human health, the lifespan of physical infrastructure, and agricultural primary productivity. Concentrations of pollutants are calculated and compared to critical loads and levels, relative risk factors, population-specific C-R responses, and ecosystem characteristics. The economic impacts of mortality and morbidity impacts in humans, as well as impacts on building materials and crops are monetized at the regional level and in certain instances by country. (Holland et al., 2011).

Limitations:

- The project and models do not include how climate change might affect air quality concentration more generally – such as increasing concentrations of some pollutants during summer, the frequency and intensity of episodes, and the formation and disposition of particulate species due to particular climate-change induced direct impacts.
- Ecosystem impacts are not fully monetized (aside from forestry and agricultural worth losses) due to lack of data.
- Excludes impacts of long-term exposure to ozone on mortality.

3.3.2. Analysis conducted for the European Environmental Agency (EEA) regarding air quality co-benefits of GHGs mitigation policies

General Scope:

In response to the European Commission's Thematic Strategy on Air Pollution goals for 2020, Eerens et al. (2005, 2006) created a bottom-up model to forecast the benefit of climate change policies on air pollution and costs of air pollution abatement to 2030. The model looks at the impacts of NO_x, SO_2, PM, and ozone, emitted mostly from the energy and transport sectors. Damage is assessed in terms of life years lost due to $PM_{2.5}$ exposure, premature deaths due to $PM_{2.5}$ and ozone exposure, and monetized health costs from both (calculated both in VSL and VSLY), as well as the area of forests suffering from acidification and the areas of ecosystems suffering from eutrophication. The geographic scope of the study is the EU-25 (Eerens et al., 2006**;** Eerens et al., 2005).[18]

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[18] The EU-25 is the original 12 Member States of the EU (Belgium, Greece, Luxembourg, Denmark, Spain, Netherlands, Germany, France, Portugal, Ireland, Italy, and the United Kingdom) that existed from the formation of the European Union on 1 November 1993; plus Austria, Finland and Sweden (together, the EU-15, existing from 1 January 1995), plus Poland, Czech

Availability:
Eeren's et al.'s (2005, 2006) rely primarily on the PRIMES model to forecast results. PRIMES does not appear to be available publicly, but more information about the PRIMES model is available at http://www.e3mlab.ntua.gr/e3mlab/index.php?option=com_content&view=category&id=35&Itemid=80&lang=en.

Developing organization and model history:
This modeling effort is based on the projections of carbon emissions abatement by the European Union under various mild-to-aggressive carbon emission abatement scenarios, originally developed under the EU's CAFÉ Programme and the Thematic Strategy on Air Pollution. The model and scenario was developed through a joint effort of numerous government and academic institutions working together in the European Topic Centre on Air and Climate Change (ETC/ACC), including the. Netherlands Environment Assessment Agency at the National Institute for Public Health and the Environment (MNP/RIVM, the Netherlands), the Norwegian air pollution institute (NILU, Norway), the Norwegian meteorological institute (DNMI, Norway), The Aristotle University of Thessaloniki (AUTH, Greece), the National Technical University of Athens (NTUA, Greece), AEA Technology (UK), the International Institute for Applied Systems Analysis (IIASA, Austria). Other institutes that contributed in this report and are not partners in the ETC/ACC consortium, are the Joint Research Centre (JRC)-Institute for Prospective Technological Studies (IPTS, Spain) and JRC-Institute for Environment and Sustainability (IES, Italy) (Eerens et al., 2006**;** Eerens et al., 2005).

Methodology:
Four emissions scenarios to 2030 are analyzed: a baseline without new climate policies; a Climate Action scenario which models actions taken to limit global temperature change to 2°C above pre-industrial levels; a Climate Action Maximum Feasible Reductions scenario that includes a higher level of technology (all possible technical abatement measures irrespective of their cost) than the Climate Action Scenario; and an Air Strategy which is identical to the thematic strategy and assumes some continuance of the Kyoto commitments and a carbon market. The PRIMES model[19] is used to create a long-range energy model scenario with socio-economic and energy projections to 2030 (Eerens et al., 2006**;** Eerens et al., 2005).

Mitigation Measures: Measures analyzed are given in a previous report, also undertaken for the EEA, which focused on possible European responses to climate change (Eerens, et al., 2005). The EEA baseline

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Republic, Cyprus, Latvia, Slovenia, Estonia, Slovakia, Hungary, and Malta (added to the European Union 1 May 2004). The EU-25 formed the entirety of the EU community until 31 December 2006, when the Union was expanded to its current form, the EU-27, with the addition of Bulgaria and Romania.

[19] The PRIMES model is a detailed agent-based and price driven top-down CGE model of the energy system covering 35 European countries. PRIMES is a modular system with individual sub-models for several demand sectors and energy supply system, including detailed electricity, CHP, gas, renewable energy systems, and biomass models. The integrating module of PRIMES simulates simultaneous market equilibrium. The model projects dynamically to the future energy balances, investment costs, prices, and emissions per country. It also projects the flows of electricity and gas among all countries. For more details on the PRIMES model, see:
http://www.e3mlab.ntua.gr/e3mlab/index.php?option=com_content&view=category&id=35&Itemid=80&lang=en

scenario is based on previous energy scenario work for the European Commission undertaken for the CAFÉ program. Population and GDP growth are the drivers of the baseline scenario, and the baseline excludes explicit climate policies. The Climate Action policy uses cost optimization to find technologies that would be implemented in response to set levels of carbon taxes. The Climate Action Maximum Feasible Reductions scenario includes all feasible measures regardless of cost to limit both traditional air pollutants and GHGs. The air strategy baseline scenario includes technologies necessary to meet the EU's policy goals in the Thematic Strategy on Air Pollution as well as modest climate policies in line with the Kyoto Protocol, despite this being inconsistent with the EU's long term goal of limiting global temperature change to 2°C above pre-industrial levels (Eerens et al., 2006**;** Eerens et al., 2005).

Cost of Measures: The cost of control measures regarding SO_2, stationary sources of NO_x, stationary sources of Non-methane VOCs (NMVOCs), NH_3 emissions, and mobile sources in the road and non-road sectors have been incorporated into the model. Controls on mobile sources have been treated separately because they simultaneously affect the emissions of more than one pollutant and therefore it is not possible to attribute costs separately to each mobile source pollutant. Costs are based on the previous modeling efforts as described above. Percentage reductions in emissions levels due to implementation of climate policies are scaled to these costs and are used to arrive at a cost savings measurement. A carbon price of EUR 20/t CO_2 in 2020 and EUR 65/t CO_2 in 2030 is assumed, but the authors do not factor the cost of implementing the GHG mitigation measures into the air pollution abatement costs. Rather, the cost of implementing climate action policies is estimated by previous studies to be 100 billion Euros a year in 2030 and this number is compared to the reduction in air pollution abatement costs and positive health impacts found in this study (Eerens et al., 2006**;** Eerens et al., 2005).

Pollutant Modeling: Emissions are decreased in the climate action scenarios in response to the implementation of GHG emission reduction technologies, as previously studied (Eerens et al., 2005). Three air quality issues are modeled: changes to regional air quality and resultant impacts on health and eco-systems; the increase in ground-level tropospheric ozone from global (non-EU) sources, and urban air quality. Regional air quality and resultant changes to health and eco-systems are modeled by the European Monitoring and Evaluation Programme (EMEP) model.[20] Ground level tropospheric ozone levels are deduced by the authors through assuming an increase in the background ozone levels modeled by EMEP due to non-European emissions of O_3 precursors (particularly from Asia). For urban air quality at the street level, model simulations were performed using the multi-scale cascade modeled by the use of the EMEP, Ozone Fine Structure Model (OFIS),[21] and the Operational Street Pollution

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[20] See footnote 9 (in the discussion of the GAINS modeling suite in Section 3.1.1) above for a description of the EMEP model.

[21] OFIS is a two-layer two-dimensional Eulerian photochemical dispersion model and is capable of simulating ozone concentrations arising from transport and photochemical transformation within an urban plume as well as the exceedances of ozone threshold values based on wind statistics during the period considered. The model was developed by the Laboratory of Heat Transfer and Environmental Engineering (LHTEE), Aristotle University of Thessaloniki (AUT). for a detailed description and download of the model see http://pandora.meng.auth.gr/mds/showlong.php?id=70

Model (OSPM)[22] specifically for the street-scale in 20 European cities (Eerens et al., 2006**;** Eerens et al., 2005).

Impacts Modeling: The co-benefits modeled in the EEA study include air pollution related health impacts (such as changes in statistical life expectancy attributable to anthropogenic $PM_{2.5}$ and premature deaths attributable to ground-level O_3), vegetation damage from ground level O_3, acid deposition to forests, and eutrophication of land. Changes in vegetation damage, forest acidification and eco-systems suffering from eutrophication are given in percentage of area reductions. However, it is unclear how the health benefits are monetized, but it appears that the WTP-based VSL and VSLY calculations are added to avoided costs to assess the need to implement air pollution control measures (Eerens et al., 2006**;** Eerens et al., 2005).

Limitations:

- The model does not address larger-scale hemispheric background air pollution levels and thereby doesn't take into consideration intercontinental transport of ozone and heavy metals and persistent organic pollutants, all of which will increase background air quality levels and increase the need for abatement.
- Emissions from aviation and marine shipping are not included in any scenarios.
- Negative trade-offs between climate and air pollution policies also have not been taken into consideration, such as increased energy use in desulphurization equipment.

3.3.3. ExternE projects model: EcoSense

General Scope:

The ExternE model quantifies, in terms of economic cost, the impacts, costs, and benefits of different fuel use patterns in Europe. The purpose of the ExternE project is to give European and national policymakers an advice for environmental, energy, and transportation policies, particularly regarding the impact of energy sector development and fuel use. A bottom-up model, EcoSense, estimates environmental benefits and costs by following the pathway from source emissions through an atmospheric dispersion model and increased concentrations of certain pollutants, to changes in air, soil, and water quality and other physical impacts based on C-R functions, which then are expressed in monetary units. The model applies to Europe, but northern hemispheric modeling is used to calculate impacts downwind of emissions sources. Two versions of the Ecosense model are available: (1) EcoSenseLE is a web-based simplified model that allows the user to calculate a single stationary source's marginal external costs due to air pollutant emissions; and (2) EcoSenseLW allows for estimating external costs due to emissions from a typical source or all sources within a sector in an EU country or

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[22] OSPM calculates concentrations of exhaust gases using a combination of a plume model for the direct contribution and a box model for the recirculating part of the pollutants in the street. The model was developed by the Department of Environmental Science at Aarhus University, Denmark. A detailed description of the model is available at
http://www.dmu.dk/en/air/models/ospm/

group of EU countries. The EcoSense model now covers the emission of SO_2, NO_x, primary particulates, NMVOCs, NH_3, and certain heavy metals, as well as GHGs (ETSU and Metroeconomica, 2005).

Availability:
Ecosense models are available for a fee-based download at http://ecosenseweb.ier.uni-stuttgart.de/how_to_get.html.

Developing organization and model history:
ExternE is a series of projects initiated in 1991 by the European Commission in collaboration with the U.S. Department of Energy. The developed model has been applied to support several policy decisions in Europe EcoSense has also been adapted to other regions, specifically China, Russia, Brazil and Mexico. Furthermore, the model's transport subparts have been adapted and used by several other Euro-centric transportation policy analyses. In its current form, ExternE and EcoSense are the result of more than 20 research projects (ETSU and Metroeconomica, 2005).

Methodology:
The ExternE project relies on the EcoSense model to calculate environmental external costs of energy use using a bottom-up methodology. As a first step, a base case scenario is developed based on the "'92a' energy forecast scenario" developed by the IPCC and economic, population and sectoral breakdowns to 2100 provided by various IPCC and other sources. To create policy scenarios, users must exogenously choose fuel types to meet the 92a forecast's projected energy demand (ETSU and Metroeconomica, 2005).

Mitigation Measures: The ExternE project addresses complete cradle-to-grave analysis for site and technology specific fuel cycles. Measures include fuel switching among carbon-based fuels (coal and oil technologies with varying degrees of flue gas cleaning, natural gas, centralized systems and CHP, and emulsion); nuclear (including pressurized water reactors, and open and closed systems for fuel provision); and renewables (onshore and offshore wind, hydro, and a wide range of biomass fuels and technology). Fuel switching and increased use of alternative transportation modes can be modeled for the transportation sector (ETSU and Metroeconomica, 2005).

Cost of Measures: The costs of measures are not directly calculated by the ExternE project – the model does not optimize for lowest control costs or lowest energy production costs. Rather, the focus of the model is changes in impacts due to the technologically feasible fuel switching necessary to meet lower carbon dioxide emissions goals (ETSU and Metroeconomica, 2005).

Pollutant Modeling: Atmospheric, soil and water pollution dispersion models (The Industrial Source Complex Model[23], the Windrose Trajectory Model,[24] and the EMEP/MSC-W Eularian model used in

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[23] The Industrial Source Complex Model is a steady-state Gaussian plume model that tracks emissions from point sources) to end-points of interest at the local level. See http://www.epa.gov/scram001/dispersion_alt.htm#isc3 for a model description and user's guides.

GAINS) are used to follow atmospheric pollution as well as water and soil pollution (ExternE Project, 2012).

<u>Impacts Modeling:</u> The ExternE project forecasts co-benefits arising from:

1. Health, agricultural, silviculture, material, oceanic and freshwater and forestry impacts caused by changes in air, soil, water and soundscape quality as well as through radiological impacts;

2. Global warming impacts (for those impacts that can be quantified) added together with an avoidance cost approach for risks with large uncertainties; and

3. Other impacts such as accidents from operation of new technologies, visual impacts, employment benefits, energy security and ecosystem impacts (e.g., avian risks). Monetized co-benefits include several human health end-points (both fatal and non-fatal impacts – see Table 3), impacts on crops, and degradation of buildings (see Table 4). Global warming damage on a global scale have also been assessed using ExternE, however results include high uncertainty ranges. Costs for ecosystems and global warming, where direct damage costs are often obscured by large uncertainty ranges, are calculated using marginal and total avoidance costs (ETSU and Metroeconomica, 2005).

Table 3: Human Mortality and Morbidity Impacts Modeled in the ExternE Project using the EcoSense Model

	Cause (Pollutant or burden)	Human Health Impacts
Mortality	PM_{10}, $PM_{2.5}$, SO_2, O_3	Reduction in life expectancy due to short and long time exposure
	Heavy Metal (HM), Benzene, Benzo-[a]-pyrene, 1,3-butadiene, Diesel particles, radionuclides	Reduction in life expectancy due to short and long time exposure
	Accident risk	Fatality risk from traffic and workplace accidents
	Noise	Reduction in life expectancy due to long time exposure
Morbidity	PM_{10}, $PM_{2.5}$, O_3, SO_2	Respiratory hospital admissions
	PM_{10}, $PM_{2.5}$, O_3	Restricted activity days
	PM_{10}, $PM_{2.5}$, CO	Congestive heart failure
	Benzene, Benzo-[a]-pyrene, 1,3-butadiene, Diesel particles, radionuclides, Heavy Metal (HM)	Cancer risk (non-fatal) Osteroporosia, ataxia, renal dysfunction
	PM_{10}, $PM_{2.5}$	Cerebrovascular hospital admissions, Cases of chronic bronchitis, Cases of chronic cough in children, Cough in asthmatics, Lower respiratory symptoms
	Mercury	Developmental delay in children (e.g., Loss of IQ)
	O_3	Asthma attacks Symptom days
	Noise	Myocardial infarction, Angina pectoris, Hypertension, Sleep disturbance
	Accident risk	Risk of injuries from traffic and workplace accidents

Source: ExterneE Project, 2012.

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[24] The Windrose Trajectory Model is the atmospheric dispersion sub-model used by Ecosense and models primary pollutants and acid species at the regional level. The specific model version used by the Ecosense model does not exist independent of the model suite.

Table 4: Non-human Health Impacts Quantified by the ExternE Program and EcoSense Model

Damage Category	Pollutant/Burden	Impacts
Building Material	SO_2, Acid deposition	Ageing of galvanized steel, limestone, mortar, sand-stone, paint, rendering, and zinc for utilitarian buildings
	Combustion particles	Soiling of buildings
Crops	NO_x, SO_2	Yield change for wheat, barley, rye, oats, potato, sugar beet
	O_3	Yield change for wheat, barley, rye, oats, potato, rice, tobacco, sunflower seed
	Acid deposition	Increased need for liming
	N and S deposition	Fertilizing effects
Global Warming	CO_2, CH_4, N_2O	World-wide impacts on mortality, morbidity, coastal impacts, agriculture, energy demand, and economic impacts due to temperature change and sea level rise
Amenity losses	Noise	Amenity losses due to noise exposure
Ecosystems	SO_2, NO_x, NH_3	Acidity and eutrophication, "PDF"* of species
Land use change	-	"PDF"* of species

*: *The costs for ecosystems are based on the concept of the Potentially Disappeared Fraction (PDF). The PDF can be interpreted as the fraction of species that has a high probability of non-occurrence in a region due to unfavorable conditions caused by acidification and eutrophication.*
Source: ExternE Project, 2012.

C-R functions have been established both for health impacts as well as non-health related categories provided in Tables 3 and 4, respectively. Monetization of damages to crops and materials is based on market price of those assets; non-marketed or semi-market based goods like human health are based on a WTP approach (ETSU and Metroeconomica, 2005).

Limitations:

The project developers state several sources of uncertainties:

- Data uncertainty: for example, regarding the cost of a day of restricted activity, and deposition velocity of the pollutant.
- Model uncertainty: for example, assumptions about the causal links between a pollutant and a health impact, assumptions about the form of a dose-response function (e.g. with or without a threshold), and choice of model for atmospheric dispersion and chemistry.
- Uncertainty about policy and ethical choices: for example, the discount rate for intergenerational costs, and the value of statistical life.
- Uncertainty about the future: for example, the potential for reducing crop losses by the development of more resistant species.
- Idiosyncrasies of the analyst: for example, the interpretation of ambiguous or incomplete information.

3.4. Academic studies

During the course of this research, over 100 separate academic efforts were identified that have been used to model co-benefits of GHG policies. Additional information (a shortened synopsis) about some the more prominent efforts can be found in Appendix B. For the sake of brevity, this section focuses on selected models and analytical frameworks that are good examples of academic co-benefit assessments.

3.4.1. United State National Academies' Hidden Costs of Energy study

General Scope:

This bottom-up modeling effort assesses all lifecycle impacts of current energy use technologies compared with the impacts of other energy use technologies in the United States. Three major energy use technologies, including electricity, transportation and heating are included. . The co-benefits of reductions in energy use associated with the major fuel constituents of each energy technology are assessed. For electricity, fuels such as coal, natural gas, nuclear power, wind, solar power and biomass, as well as issues related to transmission are included. For transportation, all petroleum based fuels, biofuels, electric vehicles, and hydrogen fuel cells are assessed. The co-benefits associated with a reduction in fuel use to generate heat is broken down according to sector. In addition, the NRC report quantifies the damages associated with direct climate change, fuel infrastructure, and fuel security related costs.

Developing organization and model history:

In the Energy Policy Act of 2005, Congress directed the National Academy of Sciences to undertake research to "define and evaluate the health, environmental, security, and infrastructure external costs and benefits associated with the production and consumption of energy that may or may not be fully incorporated into the market price of such energy. The National Academies formed the Committee on Health, Environmental, and Other External Costs and Benefits of Energy Production and Consumption and produced the final report five years later (NRC, 2010).

Methodology:

The report measures externalized costs of energy production and consumption technologies individually so as to allow comparisons against each other (NRC, 2010). This method calculates 2005 and 2030 projected impacts.

<u>Mitigation Measures:</u> No measures are applied in scenarios because the study only includes an evaluation of current practice. Each energy-generating plant was modeled by the emissions sub-model, which was based on fuel conversion rates given detailed assessments of technologies at each individual pant in the United States (NRC, 2010).

<u>Cost of Measures:</u> No measures are applied, so no measure costs were given (NRC, 2010).

Pollutant Modeling: For production technologies, each production plant in the United States was individually modeled using an emissions and atmospheric dispersion model, the Community Multi-scale Air Quality (CMAQ)[25] model (NRC, 2010). The impacts of four pollutants were monetized: SO_2, NO_x, $PM_{2.5}$, PM_{10}.

Impacts Modeling: A large variety of impacts are examined, with a particular focus on air pollution damages related to emissions of PM, SO_2, and NO_x in terms of human health damages, grain crops and timber yields, building materials, recreation, and visibility of outdoor vistas. Due to uncertainties and the evolving nature of the science, eco-system services and climate change impacts are not quantified in the same way and discussed separately from short-term pollution related damages (NRC, 2010). A damages assessment model, the Air Pollution Emission Experiments and Policy analysis (APEEP)[26] model, is used to calculate each plant's monetary impact on air quality for the year 2005 – these were found on a per ton of fuel used for four pollutants (SO_2, NO_x, $PM_{2.5}$, PM_{10}) at each power plant. Health impacts per ton are multiplied by the tons of each of the four pollutants emitted, then multiplied by the total plant emissions to get total damages. Health and other impacts were monetized by WTP-based evaluations undertaken previously by the EPA. VSLY was expressly rejected as a valuation strategy because of the assumption that VSL changes proportional to remaining life years (NRC, 2010).

Limitations:

- This model does not include alternative policy scenarios and therefore it does not include any indication of how to mitigate or change the modeled emissions and impacts.

3.4.2. Co-benefits of Greenhouse Gas Mitigation Policies in China: An integrated top-down and bottom-up modeling analysis

General Scope:

This hybrid modeling effort optimizes the co-benefits of several different potential GHG mitigation policies using a detailed bottom-up electricity sector technology catalog fitted into a top-down recursive dynamic CGE model of the Chinese economy to model the impact of three taxes aimed at reducing carbon emissions from power generation in China. As fundamental market forces change in reaction to policy instruments, direct impacts and co-benefits also change, and these changes are then equilibrated in the bottom-up model before final policy evaluation. Monetized co-benefits include health related

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[25] The CMAQ modeling system contains three types of modeling components: a meteorological modeling system for the description of atmospheric states and motions, emission models for man-made and natural emissions that are injected into the atmosphere, and a chemistry-transport modeling system for simulation of the chemical transformation and fate. The modeling suite was developed by the Community Modeling and Analysis System (CMAS) Center at the University of North Carolina at Chapel Hill. Modeling details and downloads can be found at http://www.cmaq-model.org/.

[26] APEEP is an integrated assessment model that links air pollutant emissions to population exposures, physical impacts, and monetary damages in the contiguous United States. It was developed by scientists at the Yale School of Forestry and Environmental Studies. A more detailed description of the model can be found at https://sites.google.com/site/nickmullershomepage/home/ap2-apeep-model-2.

outcomes resulting from reductions of primary pollutants (such as TSP and SO_2) and secondary particles (such as formed from sulfate and nitrate emissions) (Cao et al., 2008).

Developing organization and model history:
This model is a part of a longer-term research effort supported by the China Project at the Harvard University Center for the Environment and the Luce Foundation. The model was developed based on past research efforts of the model developer's and its use has been limited ((Cao et al., 2008).

Methodology:
Top-down CGE model: The economy is modeled dynamically based on consumption decisions by households, capital and investment, taxation policies, and international trade (Garbaccio et al., 2000). Market prices are set endogenously and the model is calibrated to actual economic data for the year 2000. The objective function of the top-down model is based on private enterprises to maximize a profit function which is calculated as the total revenue minus total costs of various inputs (capita, labor, energy aggregate, non-energy aggregate, and land), and various taxes (Cao et al., 2008).

Bottom-up electricity sector model: The authors use an electricity sector model based on the Harvard Power Sector Electricity Generation Technology Choice Model.[27] The model distinguishes 15 different technologies for electricity generation and characterizes future electricity-capacity expansion pathways by determining the optimal technology mixes using a present-cost of generation minimization strategy that accounts for plant lifetime, annual generation hours, efficiency of fuel use, fuel energy conversion factors, fuel costs, coal cleaning costs, cost of fuel transport, variable plant operating costs, fixed plant operating costs, and new investment costs. The bottom-up model is also constrained by three factors: fuel supply constraints; technology conversion efficiency, capacity factor, and fuel heat content constraints; and sector specific environmental constraints. The objective function of the bottom-up model is to minimize the total cost of meeting electricity demand (Cao et al., 2008).

Integration principles: Electricity demand, price variables, and all exogenous parameters are consistent in the integrated model. In order to accomplish this, three principles were used to build linkages between the top-down and bottom- up models (Cao et al., 2008):

1. Electricity demand: Future electricity demand is computed by the CGE model's simulated output for the electricity sector and input into the bottom up model.
2. Price variables: The changes induced in prices, for example due to the introduction of taxes, that are output as a part of the CGE model are iteratively integrated in the bottom up model.
3. All exogenous parameters: This task was particularly difficult given the large number of parameters in the bottom-up model and therefore the authors only used primary key parameters. The authors found a means of making the economic cost structures of the energy production technology measures consistent. For example, the authors equate variable operating

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[27] The Harvard Power Sector Electricity Generation Technology Choice Model was developed by a group of scientists at the School of Engineering and Applied Sciences at Harvard University. A full model description can be found in Murray (1996).

costs in the bottom-up model to labor inputs in the top down model. After costs were equated, the exogenous parameters of the CGE model were adjusted and the model was run until it achieved optimization solutions consistent with the bottom up model. In the integrated model, an optimal technology mix was determined by minimizing the net present-cost function of total electricity power generation. These costs were made consistent in the top-down model.

Mitigation Measures: Three environmental tax policies are applied in each scenario analyzed: an output-based tax, a fuel tax, and a carbon tax, as well as national mixed policies (a national tax policy with emission caps in the electricity sector). Technology choice measures range from fossil fuel plants with and without emissions control technologies (such as ESP and scrubbers) to renewable energy plants. Results of the different scenarios were compared to a steady state scenario (a base case, or BAU in which no policy was implemented (Cao et al., 2008).

Cost of Measures: In this model, the capital costs, construction periods, lifetimes, annual generating hours, discount rate, thermal efficiency, fuel intensity, fuel prices, fuel costs, variable costs, and fixed costs are all endogenously assumed. However, the cost of emissions is simulated in three forms of tax and in another scenario by an absolute cap on emissions (Cao et al., 2008).

Pollutant Modeling: The top-down model provides estimates of emissions associated with each combination of fuel type and use. It appears that some atmospheric modeling was also employed to model the dispersion of pollutants after emission, but this effort is not described well (Cao et al., 2008). The model accounts for PM, SO_2, NO_x, and CO_2 emissions.

Impacts Modeling: Only health-related co-benefits from reductions of primary pollutants of PM, SO_2, and secondary particles like sulfates and nitrates (NO_x) are modeled. Sectoral intake-fraction estimates given in previous papers by the same authors appear to be estimated from the results of an atmospheric pollution dispersion model (although the details of this model are not explicitly given) and China-specific epidemiological studies. Benefits-transfer methodologies are used to compute marginal WTP values from Chinese and international contingent valuation studies (Cao et al., 2008).

Limitations:

- The government tax rate is held constant – new fuel and environmental taxes are modeled as reducing the taxes on other sectors, rather than adding to them.
- The atmospheric dispersion model lacks documentation and therefore cannot be directly assessed.
- It appears that technology characteristics do not change in the models, implying unrealistically flat learning curves.

3.4.3. Co-benefits of carbon policies applied to the U.S. electricity generation sector

General Scope:

This top-down study quantifies the human health benefits that would result from decreased NO_x and SO_2 emissions resulting from two levels of carbon taxes imposed on the electricity sector in the United States. A CGE model of the U.S. electricity sector is used to calculate market equilibrium by season and time of day for three customer classes at the regional level, with power trading occurring between regions (Burtraw et al., 2003).

Developing organization and model history:

This study is one of many undertaken by a team of researchers at Resources for the Future (RFF), in collaboration with researchers at the U.S. DOE's Argonne National Laboratory. The report was funded by the Integrated Assessment program, Biological and Environmental Research at the U.S. Department of Energy and by the U.S. Environmental Protection Agency (Burtraw et al., 2003).

Methodology:

Several energy sector development baselines are established in the absence of GHG policies. One case specifies the implementation of Title IV of the Clean Air Act (CAA) in the electricity sector in addition to Phase II of NO_x reductions in the northeastern 11 state Ozone Transport Commission region (these policies are modeled as a NO_x cap-and-trade system). Another case looks at further reductions in the baseline emission of NO_x due to the implementation of standards that were expected to take effect in 2004 (requirements for states to change CAA implementation plans) – this is in effect an expansion of the Case 1 cap-and-trade system to a larger geographical region. These baseline emissions scenarios are characterized by exogenously provided emissions estimates, based on previous government studies (Burtraw et al., 2003).

Mitigation Measures: The Haiku model[28] simulates the impacts of two levels of carbon taxes on investment, retirement, and system dispatch for the year 2010. Investments in new generation capacity and retirement of existing facilities are endogenously determined based on capacity-related "going forward costs." Generator dispatch is based on generator's minimization of short-run variable costs of generation (Burtraw et al., 2003).

Cost of Measures: Costs of technology implementation, costs of fuels, and other implementation costs are explicitly modeled based on exogenously provided market costs that change over time based on demand and learning curves. However, modeling results indicate that there is a net savings in the costs of NO_x and SO_2 abatements and thereby implementation costs are equal to the cost of the carbon taxes themselves (Burtraw et al., 2003).

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[28] Haiku is a model developed by RFF that simulates regional electricity markets and interregional electricity trade in the United States, accounting for capacity planning, investment, and retirement over a multi-year horizon and for system operation over seasons of the year and times of day. For full documentation of the most recent version of the Haiku model, see http://www.rff.org/rff/documents/rff-rpt-haiku.v2.0.pdf.

Pollutant Modeling: The Haiku model calculates changes in emissions of key pollutants resulting from changes in electricity generation in response to the carbon taxes. Changes in the emission of NO_x pollutants -- both direct emissions of NO_x and through secondary particulate matter formation are modeled based on changes in power sector activity (generation, development of new capacity, and shutting down). Pollutant emissions decrease in response to reductions in fossil fuel use (especially coal), the use of which is replaced with lower emitting fuels in response to carbon taxes. SO_2 reductions are not affected in the moderate carbon tax scenario due to the imposition of a cap on SO_2 emissions within the CAA that is integrated into the base-case models. An atmospheric dispersion model (the Tracking and Analysis Framework) is used to calculate the change in pollutant concentrations (Burtraw et al., 2003).[29]

Impacts Modeling: The co-benefits modeled include both mortality and morbidity impacts from reduced NO_x and SO_2 exposure, accounting for expected changes in population characteristics (size and age), and changes in income affecting estimates of WTP estimates for health benefits. Additional benefits accrue to firms in the form of reduced investment in NO_x and SO_2 CAA compliance-related abatement activities (Burtraw et al., 2003).

Limitations:

The general limitations which apply to all studies also apply here, including uncertainties regarding population characteristics and C-R functions. However, this model is one of the more detailed models found.

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[29] The Tracking and Analysis Framework (TAF) is an integrated modeling framework developed to assess, inform, and guide U.S. regulatory policies on emissions of precursors to acid rain, developed specifically to assess te effects of the 1990 Clean Air Act Amendment's Title IV SO_2 trading scheme. The TAF model was created with Analytica.. A download of the model is available at http://www.rst2.edu/ties/acidrain/PDF/5geninfo/gi9.pdf.

4. Limitations of Co-benefit Theory and Recommendations for Improvement and Application to Developing Countries

Co-benefits theory and research is still evolving and even the most advanced studies are still limited in many ways. Two primary sources of uncertainty are discussed in this section, as well as means of dealing with these sources of uncertainty associated with each step of a generalized co-benefit methodology.

4.1. Uncertainties

As Davis et al. (2000b) state, "there is general agreement that the uncertainty surrounding the estimates of ancillary impacts is at least as great relative to the value of those estimates as that associated with other mitigation costs." Given the inherent simplification process in energy and economic modeling, the incomplete state of impact data, and the controversies which surround the monetization of non-market goods, even studies of the highest quality are by no means immune to uncertainty-based errors, as indicated by the wide variances in studies' valuation results (Bell et al., 2008; Jack and Kinney, 2010).

4.1.1. Forecast uncertainty

A substantial amount of uncertainty is introduced in the creation of the models used to forecast energy and emissions growth. Many models, especially top down models, project future energy demand based on population growth and economic growth. Whereas population growth is determined by a relatively shorter list of factors and is a well-researched area of demography, energy demand growth can be affected by a larger number of variables. The track record of the most advanced energy forecast modeling efforts (for example, those produced by the International Energy Agency (IEA)) shows that even multi-year, extremely sophisticated energy demand forecasting is an inexact science. Many researchers prefer to avoid constructing their own energy forecasts and rely on those constructed by either the IEA or through other centralized modeling efforts as inputs to their analysis.

Economic growth is a major determinant of most energy growth forecasts, and these underlying economic growth assumptions can skew results in other ways. For example, income elasticities are important to determining WTP factors, and these can and do change with economic development. Although economic growth-induced income changes are considered in benefit transfer calculations, future impact projections often do not increase health impact valuations with ongoing economic growth. Discount rates are also crucial to measuring future economic impacts and costs, and there are no universally agreed upon best discount rate. Whether discounting should even be applied to future climate change and other impacts are debatable. However, it should be noted that most co-benefit studies mitigate uncertainty about future projections by limiting their projections to between 10 and 20 years into the future. The limitation of co-benefits models to near-term time horizons reduces the impact of energy demand forecast uncertainties (Bell et al., 2008).

4.1.2. Data validity

Data validity is also a major source of uncertainty. Faced with the limited empirical research on the impacts of pollution exposure as well as economic valuations of those impacts, researchers will often focus their studies on a limited number of pollutants and a limited number of impacts. The majority of studies focus on the impacts of PM and ozone, and mortality impacts are the most commonly analyzed type of health end-points. These choices are driven by the fact that the impacts of conventional pollutants on mortality have been studied the longest and in the most depth in the epidemiological literature. Data validity issues are also important when considering the characteristics of the population in question, especially when applying epidemiological data developed from studies in counties with very different population characteristics.

In particular, considerable uncertainties regarding concentration-response (C-R) functions exist. Drivers of uncertainties in C-R functions include: 1. the question of causality between air pollutants and health impacts; 2. the impacts of co-pollutants and pollutant mixtures; 3. toxicity related to the specific composition of PM; 4. the reliance on electronic ambient air monitors and their poor approximations for ground level exposure; 5. the shape of many C-R functions and the existence of threshold values for effects; 6. chronic and acute impacts of exposures; 7. unknown health end-points; and 8. whether all mortality (for all age groups, e.g., neonatal or infants) is being taken into consideration (Bell et al., 2008).

An additional, and perhaps the most important, uncertainty is whether or not the C-R function is applicable to the population in question with regard to both temporal and spatial characteristics. A wide variety of factors can influence a population’s response to pollution (Ostro, 2004).Although epidemiological findings are increasingly being compiled for developing countries, the health impact of greatest concern – premature adult mortality due to long-term exposure to PM is largely unavailable outside of Europe and the United States. The China Air Pollution and Health Effect Study (CAPES) (Chen et al., 2012) is a recent study which focuses on the association between PM10 exposure and mortality in Asia. Typically though the WHO’s comparative risk analysis of the global environmental burden of diseases is often used for a relevant C-R function for PM_{10} and $PM_{2.5}$, which may skew results in developing countries. Furthermore, existing studies do not characterize the C-R functions specific to the elderly (above 60 years of age), and for children who often represent a greater proportion of the total population in developing countries.

4.2. Mitigating uncertainties

Uncertainty is a familiar obstacle to policymakers. Co-benefit analyses provide an important means for reducing uncertainty because policy makers often lack access to detailed descriptions that tie energy use to human health and environmental quality. Monetization of co-benefits is particularly important in the policy-making context given the importance of monetarily evaluating the indirect costs and benefits of energy efficiency and climate change mitigation policies. Although full information about a study’s limitations should be given and sensitivity analyses should be conducted and presented in order to indicate the importance of certain variables in output accuracy, uncertainties within co-benefit studies should not prevent the further development and application of co-benefits analysis.

Indeed, the highest quality studies usually undertake a rigorous evaluation of the bounds of certainty through the use of sensitivity analysis to model the effect of the key assumptions that drive energy demand and health impact models. Considering the wide variety of factors taken into account in co-benefits analyses and the limitations of current data regarding those factors, sensitivity analyses should be undertaken as part of any co-benefits analysis to determine the key assumptions that have the largest contribution to variance in the model outputs. The use of sensitivity analyses is even more important in the application of co-benefit techniques in regions where data is limited.

4.2.1. Modeling simplification

The simplification of modeling efforts within the individual steps is a considerable limitation on the accuracy of estimates. Examples of simplified assumptions used in predicting air pollution dispersion and assumptions related to population characteristics in determining C-R functions are provided below.

4.2.1.1. Modeling simplifications in air pollution dispersion models

The assumptions which most greatly affect co-benefit calculation accuracy include: 1. the choice of the "baseline" scenario and its ambient concentrations; 2. the translation of a policy into emissions changes in various sectors; 3. whether or not physical or chemical transformation of pollutants is modeled; and 4. the scale at which concentrations are modeled (Bell et al., 2008).

According to a literature review conducted in 2010, although the scientific understanding of ambient air pollution has progressed in recent years, few co-benefits analyses have included state-of-the-art modeling frameworks, like the Goddard Earth Observing System-Chem (GEOS-Chem)[30] and the Congestion Mitigation and Air Quality Improvement (CMAQ) programs' models (Jack and Kinney, 2010). Rather, many studies, "particularly those based on the CGE models, use highly simplified linear equations to scale emissions changes to ambient concentration changes," thereby ignoring atmospheric transport and the chemical transformation processes that occur in the atmosphere (Jack and Kinney, 2010). The use of atmospheric dispersion models can improve the accuracy of model outputs, but depending on geographic scale and location of the analysis, the use of intake fractions appears to be a desirable option for some cases.

A second category of simplifying assumptions used in air quality models are those that pertain to the geographic scale at which air pollutant concentrations are modeled – because dramatic differences in the concentration of some air pollutants can be witnessed over areas as small as city blocks, higher resolution air pollutant dispersion modeling more accurately depicts real world patterns. Regional air

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[30] The GEOS-Chem model is a global 3-D model of atmospheric composition driven by assimilated meteorological observations from the Goddard Earth Observing System (GEOS) of the NASA Global Modeling Assimilation Office (GMA). Details of the model can be found at http://acmg.seas.harvard.edu/geos/.

quality models are better than their larger-scale peers at determining changes in concentrations at a scale more relevant to assessing impacts on local populations (Bell et al., 2008). Some studies which have integrated active transport as a mitigation option have included more sophisticated and complex local-level air quality models that rely on the fluid dynamics of air in urban spaces within city block sized spaces (Woodcock et al., 2009). These smaller scale models are better able to capture the impacts of pollution gradients near roadways and other emissions sources (Bell et al., 2008). Furthermore, models generally assume that emissions sources are constant over time, whereas it is likely that emissions sources and resultant concentrations will change over time as economic and social changes induce factories to update control technologies, switch fuels and/or energy technologies, move, shut down, and start up. Indeed, climate change induced temperature changes may themselves have significant impacts on air pollution concentrations due to changes in biogenic emissions. These warming-induced air pollution impacts are not often modeled, although some studies have been undertaken to begin integrating this factor into co-benefit assessments (Lamy and Bouchet, 2008).

4.2.1.2. Modeling simplifications in the characteristics of local populations

Due to the shorter atmospheric life of many conventional air pollutants and therefore the relatively limited scope of their atmospheric dispersion, the proximity and density of the local population is a critical factor in determining exposure rates. Comparisons of co-benefit analyses from the United States and the EU have found that population density differences between the two regions accounts for two to three times larger benefits estimates in Europe due to an increase in the number of people exposed (Davis et al., 2000b). Furthermore, the health and mortality risks associated with air pollution disproportionately affect the elderly and the very young. Therefore, ignoring key demographic characteristics may result in an incomplete assessment of co-benefits. Socio-economic status is another key factor due to its effects on the valuation of health impacts. Davis et al. (2000b) note that populations with higher unemployment or lower income levels will have significantly different WTP valuations than higher income populations. In simpler models, these factors are generally ignored and populations are treated as homogenous. More advanced models, such as the GAINS modeling suite, explicitly model local population characteristics in great detail.

4.2.1.3. Modeling simplification in the boundaries and scope of analysis

The scope of pollutants and health impacts is an important consideration – data limitations often prevent researchers from examining the full scope of impacts related to the emission of GHGs or that are otherwise impacted by GHG reduction policies. As discussed above, co-benefits studies overwhelmingly concentrate on the impacts of air pollution on human health despite the multitude of other impacts identified (see Appendix A for a list of identified co-benefits). A complete co-benefits assessment would also incorporate tradeoffs of policies, evaluating whether gains made in reducing some health or other risks are offset by negative impacts of the new technology or strategy. For example, policies which affect energy production might result in reduced employment in some areas. Reduced employment and income levels have been empirically found to be the drivers of several negative health impacts, such as increased suicides, domestic violence, depression, and mental illness

(Bell et al., 2008). One example of a co-benefits study which included a partial examination of negative impacts, in addition to a wide variety of positive impacts, is the transportation technologies study undertaken by Woodcock et al. (2009). There, the authors modeled the negative health implications of more active transportation methods, such as walking and biking that forced individuals to come into significantly greater contact with roadside air pollutants (Woodcock et al., 2009).

Physical boundaries and the geographic scope of studies is also an important issue. Despite shorter atmospheric lifetimes of conventional air pollutants, air pollution and other externalities of energy use are often trans-boundary in nature. Most co-benefits studies, especially those undertaken on a sub-global scale; create artificial boundaries at political borders thereby reducing the anticipated co-benefits of pollution mitigation (Davis et al., 2000b). Furthermore, the impacts of conventional air pollutants are largely a localized phenomenon, whereas GHGs and their impacts are global in nature. The geographic location of emissions sources, such as power plants, will greatly impact the extent of co-benefits found and their relationship to GHG mitigation costs. Indeed, it may be that a GHG emissions policy which is found to have greater benefits than costs in urban areas due to reductions in PM emissions may not be justifiable in rural areas. Even using sophisticated co-benefit analytical techniques, political problems may arise in determining the best course of action when the costs of policies are not borne by the populations which are to benefit most directly from air pollution reduction impacts.

4.3. The controversy of impact valuation and its effects

The largest controversy surrounding co-benefits study is inherited from the CBA framework from which co-benefits studies originated. In CBA, the goal is to weigh the actual real costs of policy implementation and its externalities to the benefits of those externalities. For readily-marketized goods, such as technology inputs and fuel, these costs are easily obtainable and relatively uncontroversial. However, for calculating the value of the majority of the benefits that accrue from environmental policies no single methodology is without its faults and no consensus has been reached on best practices. The statistical value of a human life often underpins the valuation of health impacts and little progress has been made in overcoming the ethical and quantitative complications inherent in placing a monetary value on human health. The valuation of eco-system services is similarly difficult, as are valuations of social goods such as equity, fairness, and participatory decision-making.

One means by which studies have avoided the monetization issue is by bounding the research scope to exclude monetary valuations. Rather than produce equally comparable monetary values of impacts, such studies report on health outcomes and other benefits directly, using less controversial metrics such as improvements in QALYs and DALYs, reductions in premature deaths or morbidities, or even simply the changes in pollution concentration and emissions quantities. However, as noted by Davis et al., (2000b), “these types of estimates are not easily compared without a framework for assessing the economic impacts and the efficiency with which various GHG reductions can be achieved”. As such, cost-effectiveness quantification, which indicates how much directly market-related costs are required to reduce a health impact risk or a unit of pollution, are becoming increasingly popular means of comparing policies.

4.4. Simplification methodologies for co-benefits analysis in developing countries

Co-benefits studies are becoming more common in Asia, and China and its cities have been a key area of new co-benefit research. However, data limitations and a lack of experience with large-scale CEG and bottom-up models may present significant barriers. Several means of simplifying co-benefits calculations in data and resource-limited circumstances are discussed below.

4.4.1. Qualitative evaluation strategies

The Japan Manual recommends that developing countries start with qualitative evaluations to avoid complications regarding data availability and labor capacity within the local government (Japan Ministry of the Environment, 2009). The Japan Ministry of the Environment envisions the creation of an integrated evaluation methodology that scores co-benefits (including qualitative evaluations) by creating a weighting system for each co-benefit-generating activity according to the needs and characteristics of the host country. This would require the establishment of predetermined criteria to guide the qualitative evaluation so that evaluations are transparent, fair, and reproducible (Japan Ministry of the Environment, 2009). As an example of such a criteria-based qualitative evaluation system, the Japan Manual looks to subjective indexes that have been established as earthquake magnitude scales (Japan Ministry of the Environment, 2009). The Gold Standard, in its use of loosely-defined, cooperatively-developed co-benefit indicators appears to allow for the use of qualitative indicators that simply measure progress towards achieving project goals (The Gold Standard Secretariat, 2012).

4.4.2. Limiting the scope of co-benefit analyses

Under the U.S. EPA's efforts in the Integrated Environmental Strategies (IES) program, several methods were used to simplify co-benefit calculations to accommodate resource and data limitations found in partner countries (Argentina, Brazil, Chile, China, India, Mexico, the Philippines, and South Korea). Due to data limitations, many of the IES program studies greatly limited the scope of analysis by limiting the number of pollutants and health end-points, concentrating on particular sectors, and geographically focusing on urban areas. Most studies only analyzed a very limited number of pollutants and health end-points – most often concentrating on adult mortality impacts of PM_{10} exposure. Furthermore, analysis was often restricted to certain sectors, most commonly transportation. Also, geographic scope was often limited to concentrate on capital cities or large metropolises. These strategies reduced the resources needed to undertake the analysis and are justifiable considering the importance of certain pollutants and impacts on total health costs (especially adult PM_{10}-exposure related mortality) and the importance of capital cities as centers of population and economic activity.

4.4.3. Simplifying impact calculation methods

Several sector-specific methodologies have been developed using rules-of-thumb to calculate the impacts of policy activities. For example, IGES developed a simplified methodology for calculating transportation sector co-benefits using several rules-of-thumb (IGES, n.d.). IGES's Transportation Co-benefits Guidebook (TCG) presents the means to calculate CO_2 and conventional air pollutant reductions, as well as time savings, vehicle operating cost reductions, and decreases in accidents occurring from the implementation of transportation projects. The TCG details how to use its simplified formulas as well as the data needed for the completion of each estimate. However, the TCG also notes the need for locally-relevant data to complete each calculation, requiring data gathering work on the part of researchers (IGES, n.d.).

The use of economic damage functions, which directly relate emissions to total health costs that have been found in other studies, have been common practice in the past to avoid atmospheric dispersion modeling and epidemiological study review (e.g. Caton and Constable, 2000). However, the use of simplified damage functions is not a preferred methodology as damage functions generally give only total economic costs and therefore lack transparency, and costs are highly dependent on their region of origin. Intake fractions are a more transparent means of simplifying co-benefit calculations and they allow researchers to avoid the use of complicated atmospheric dispersion models (Bennett et al., 2002; Apte et al., 2012; Zhou et al. 2006). This methodology allows researchers to go directly from the quantification of emissions to using C-R functions to establish health impacts, as long as the intake fractions have been calculated for the source type, geography type, and population examined. This area or research is still maturing, but globally relevant intake fractions have been developed for a variety of city sizes, population densities, and meteorological characteristics for ground level emissions sources, and intake fraction theory has been applied in China in regards to power plant emissions (Apte et al., 2012; Wang et al. 2006; Zhou, et al. 2006).

4.4.4. Locally-relevant standardized impact data from local and developed country data

Epidemiological studies are more common in developed countries and are much rarer in developing countries. Where data are lacking, C-R functions from developed countries are used in developing countries, but with caution. Determining the appropriate C-R function to apply to the study requires finding epidemiological data from populations with similar economic and demographic characteristics as the study location. This can result in substantial variance in findings for studies within the same region, depending on the researcher's choice of methods by which health impacts are translated from origin countries. Impact valuation data is also commonly transferred from developed countries to developing countries by adjusting the data for local economic contexts in the developing world. Generally using simple correlations between the economic characteristics of the origin country and the country to which the benefit is being transferred (often based on purchasing power parity-based gross national income per capita quotients), unit valuations are adjusted to approximate the value of labor, time, and (most controversially) pain and suffering in the developing world context.

A best practice means of reducing the burden of epidemiological and impact monetization study review and translation is to develop a locally-relevant database that standardizes impact and monetization calculations. A sophisticated example of a locally-relevant impact database framework is the U.S. EPA's Environmental Benefits Mapping and Analysis Program (BenMAP) (U.S. EPA, 2012). BenMAP is a computer program that uses an impact database and geographic information system (GIS)-based local population data to estimate the health impacts and economic benefits that would occur when a population experiences a change in ambient air quality. The BenMAP database includes health impact functions for several health end-points and their monetary values, gathered from epidemiological and WTP studies with an emphasis on studies from the United States and Europe. $PM_{2.5}$ and ozone are the only pollutants modeled by the program. BenMAP relieves the burden and biases of undertaking new epidemiological study reviews by allowing users easy access to a uniform and verified database on C-R functions and monetized values of impacts. However, BenMAP also requires users to input data regarding changes in air pollution concentrations and therefore requires both emissions forecasting and atmospheric dispersion modeling. BenMAP has also been applied internationally and the program has developed a database on health impact functions specifically for use in China (Abt Associates, 2010).

4.4.5. Simplified locally-relevant model frameworks

The SIM-Air modeling suite developed for India is a simplified Excel-based modeling framework that could be used as a model for the development of similar locally-relevant frameworks in other countries (Environmental Management Center, 2009). The model allows the computation of an emissions inventory for key pollutants, monetarily evaluates health impacts, and finds the optimal combination of policies and programs to meet objectives, such as cost minimization subject to constraints like ambient air quality standards. Simplifications included in the SIM-Air model are default emissions factors (these can be changed based on local circumstances), default emissions elasticities for policy choices, a select number of key technologies and management options, and default exposure-damage relationships. Importantly, it should be noted that the SIM-Air model requires several data inputs from users and does not include an atmospheric dispersion model and therefore requires the external calculation of pollutant dispersion. Although the SIM-Air model only simplifies a few steps of the co-benefits calculation process, the development of a similar tool using locally-relevant emissions factors, technologies and management options, exposure-damage relationships, and other factors may allow easier co-benefits calculations for China and other developing countries.

4.4.6. Internationally-developed modeling suites

The use of the GAINS-Asia suite holds potential to easily develop co-benefits analysis for energy efficiency efforts in several sectors in China on a wide geographic scale. A version of the GAINS modeling suite specific to China has been developed in partnership with the Energy and Resources Institute (ERI) of the National Development and Reform Commission (NDRC) and is available through a free, web-based interface (IIASA, 2012). The GAINS China model allows users to access IIASA-developed data regarding emissions generating activities in the past and the future, outputs emissions for user-input scenarios, includes costs on emissions control strategies, and computes impacts for several air quality indicators as well as health impacts attributable to $PM_{2.5}$ and ozone exposure and environmental impacts regarding critical loads for acidification and eutrophication for a variety of terrain types. However, the application of GAINS China to local-level co-benefits analysis will be limited by the spatial resolution of the model, which appears to be limited to a 50km-by-50km scale (Toth, 2008).

4.4.7. A nationally-applicable guidebook to standardize co-benefits calculations by local governments

The United States and Japan have developed co-benefit guidebooks to allow local governments to conduct their own co-benefit assessments (U.S. EPA, 2011; Japan Ministry of the Environment, 2009). For example, the U.S. EPA's state government-oriented guidebook gives local governments a variety of tools and tips to evaluate co-benefits of clean energy programs using either simplified or complex methods (U.S. EPA, 2011). An alternative is given by the European case, where EU-level regional co-benefit calculation programs are been undertaken by the community as a whole and can now inform local-level policy decisions. The development of similar guidebooks for China will standardize calculation methodologies and allow easy comparison of research outputs.

5. Summary and Conclusions

The early efforts of academics and NGOs to evaluate the co-benefits of climate change mitigation and energy policies in the 1990s has evolved into an international and national government effort to apply these lessons to national energy and climate change mitigation plans. Although cost-benefit analysis has long been a requirement of the U.S. federal-level regulatory development process, the effort to detail co-benefits particular to energy and climate policy and to provide a unified framework for co-benefits assessment has advanced most in Europe. The European Commission's strong and continuous support for the development of EU-specific models and the application of these models to evaluate and decide between European policy options represent a level of sophistication beyond the efforts of the United States and Japanese governments to integrate co-benefits analysis into select policy evaluations. However, with the development of co-benefit calculation guidebooks, Japan and the United States may increase the attention paid to co-benefits in the future. Furthermore, it is expected that energy efficiency will receive greater attention in co-benefit studies as developing countries focus on calculating the most cost-effective means of reducing local, rather than global, air pollution.

Co-benefit calculation methodologies have coalesced around a four-step process, including:

1) Calculating emissions differences between base case and alternative policy scenarios.

2) Applying air dispersion modeling or simplifications to characterize and compare concentrations of pollutants.

3) Estimating impacts for each scenario and comparing them against each other (using, for example, population-adjusted C-R functions to find health impacts).

4) Monetizing or otherwise quantifying those impacts in relation to the costs of the alternative policy scenario with care to evaluate those costs according to specific pollutants.

This general framework, as detailed in Section 2 of this report, is likely to continue to be the predominant means by which co-benefits analysis is undertaken in the future in the developed world. However, while the procedures used to measure co-benefits are increasingly standardized in the developed world, there has been a proliferation of methods developed for application in the developing world. This is due to the common need to overcome severe data limitations while preparing analyses that are sufficiently robust and transparent for policymaking applications. Several methods for simplifying co-benefits calculations appear relevant to the Chinese context as well as other developing countries. However, most simplification methods require considerable up-front standardization efforts to ensure that simplification does not result in inaccuracy and conflicts between research outputs.

Several broad recommendations may be derived from this review. While data limitations may be overcome in the medium term future, there is a need to further develop simple, flexible, and standardized methods of calculating the co-benefits of major energy consuming activities. Furthermore, the field will benefit from testing these simplifications through application to diverse countries and contexts and standardizing how research evaluates and discusses calculation uncertainties.

The development of international co-benefit calculation standards will be greatly advanced by consolidating best practices among regions as well as between policymakers and researchers. As global platforms such as GAINS continue to expand and create locally-relevant models for all areas of the world, the wider application of complex modeling suites may allow the development of more directly comparable co-benefits research and a general consensus as to the most appropriate means of calculating co-benefits at either the project scale or at the macro-economy scale. Continuing down this trajectory will, however, require significant buy-in from countries of varying political and scientific maturity and cooperative efforts will be the general rule rather than the exception. Regardless of the specific platform, cooperative efforts should be targeted in the short term at clarifying the best contexts for the application of each model and framework. Much of the current cooperative efforts are founded on international climate change treaty negotiations and this platform as well as bilateral cooperation between national governments should be optimized by integrating co-benefits research at the highest level of negotiations.

Several significant questions remain in the further development of co-benefits research. Perhaps most important is the appropriate methodology to calculate and monetize health impacts. Although near universal consensus calls for the use and expansion of WTP methodologies, this will require the long-term development of survey and epidemiological data. As developing countries expand initial efforts into co-benefit analysis, especially regarding energy efficiency measures, future research will test the utility and political appropriateness of monetizing benefits, especially in regions with less mature markets for health and environmental externalities. The relatively newer methodology of quantifying health impacts in DALYs and QALYs holds promise to dispose of the monetization controversy and replace it with a uniform, globally-comparable impact assessment methodology. Furthermore, as empirical evidence grows regarding the connection between short-lived climate pollutants such as black carbon and tropospheric ozone, traditional pollutants, and human health co-benefits, the developed countries should work to integrate these pollutants into co-benefits research.

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Appendix A. Non-CO_2 related impact of energy efficiency and climate-related projects

Table A: Non-CO2 related impact of energy efficiency and climate-related projects (co-benefits and trade-offs)

No.	Co-benefits	Projects/Programs*
1	Reduction in particle pollution when fossil fuel use is reduced	Any project that saves fossil fuels especially coal (or electricity that is generated from fossil fuels)
2	Increased availability of recreational sites when reforestation programs are introduced	Reforestation projects
3	Increase in technological efficiency when new technologies are adopted and unit costs fall	Technologies transfer and demonstration
4	Increase in welfare when GHG reduction project reduces unemployment	Awareness raising, training programs, policy supports, etc.
5	Reductions in road-use related mortality when a shift from private to public transport takes place	Promotion of public transport systems
6	Reductions in congestion when a shift from private to public transport takes place	Promotion of public transport systems
7	Increases in employment resulting from GHG mitigation projects where there is excess supply of labor	Any project that requires the employment of new staff like the new biomass power plant, new RE hybrid system in rural area, etc.
	Decrease in employment resulting from GHG mitigation projects where it cause the job cuts	For instance, unemployment resulted from shutting down the old inefficient Vertical Shaft Kiln cement plants in China.
8	Savings in household time in poor rural households when fuel wood use is replaced by renewable energy	Replacing fuel wood by renewable energy
9	Occupational health and safety	Any project on changes in the use of fuels (from coal to NG or RE) will have implications for the number and severity of workplace injuries
10	Energy security	Guaranteeing a reliable source of energy for the country by implementing Renewable Energy and Energy Efficiency projects.
11	Induced technological change	Technologies transfer, RD&D projects
12	Reduction in Mortality	Any GHG mitigation activity that could result eventually to reduction in GHGs as well as air pollution.
13	Reduction in Chronic morbidity	Any GHG mitigation project that could result eventually to reduction in GHGs as well as air pollution.
	Increase in Mortality or Chronic morbidity	For instance, an increase in indoor air pollution associated with a switch from electricity to dirtier household energy sources such as wood or lignite.
14	Benefits to ecological resources	Various types of GHG mitigation project would benefit ecological resources eventually. For instance, the RE and EE project has an indirect impact on this and reforestation project has a direct impact on ecological resources.
15	Damage to ecological resources	For instance a switch to hydroelectric power could create many negative externalities to river ecosystems
16	Reduction in Materials damage (buildings, fabrics, monuments, etc.)	The RE projects that will reduce coal use, thus reduces acid rain that harms the monuments, building and other materials.
17	Better Visibility	Any GHG mitigation project that could result eventually to reduction of air particle pollution. Promotion of public transport systems in cities, promotion of electric or hybrid cars, reduction of coal use in industry and power sector.
18	Benefits to Crops and tree farming	Projects that eventually reduce ambient ozone concentrations (such as reforestation or RE projects) will have indirect impact on a sizable increase in crops yields and, as a result, social

No.	Co-benefits	Projects/Programs*
		welfare.
19	Flooding of landscape for hydropower production	Hydropower projects
20	Conversion of landscape for carbon sequestration	Carbon sequestration projects
21	Reduced soil erosion from land management changes	Land management and reforestation projects
22	Changes in catastrophic fire/pest/disease in a well-managed ecosystem/forests	Forest preservation
23	Improvement in water quality from the reduced soil erosion	Land management and reforestation projects
24	Reduction in flood damage from reduced soil erosion	Land management and reforestation projects
25	Reduced accumulation of toxics in freshwater fisheries	Any project that saves fossil fuels especially coal (or electricity that is generated from fossil fuels)
26	Reduction in damage from oil spills	Any project that eventually saves crude oil
27	Reduction in damages from underground mining of coal	Any project that saves fossil fuels especially coal (or electricity that is generated from fossil fuels)

** The Projects/Programs given for each impact is just an example and does not tend to be an exhaustive list of projects/programs that have that type of impact.*

Source: authors' compilation.

Appendix B: Short form synopsis of several applied co-benefits frameworks

Table B: Authors' compilation of the primary categories of analysis and methodologies employed by various co-benefits applied studies

Source	BU, TD, H[31]	Region and Timeframe	Pollutants	Interventions/Policies	Methods and Models	End points
(Zvingilaite, 2011)		Denmark; 2005-2030.	SO_2, NO_x, $PM_{2.5}$	Three scenarios are modeled against BAU: 1. A no externalities scenario in which only the global cost of CO_2 is included in plant operations costs; 2. A single average externality cost scenario in which system-wide air pollutant externalities are incorporated into operations costs; 3. A different area cost scenario which includes localized externalities into operations cost.	1. Balmorel[32] model used to model technology choices to meet exogenously set energy demand based on upfront and operation costs. 2. Generalized area-wide emission rates are converted to exposure rates by intake-fraction-like emissions factors produced by Danish government for current and new technologies. 3. Health damage costs are given by THOR, an air pollution dispersion and health impacts assessment model.[33]	Health impacts– otherwise undefined.
(Gilmore et al. 2010)		New York, 2009	NO_x, $PM_{2.5}$, O_3, VOC, CO_2	BAU (including technology improvements expected by state regulators) is compared to the installation of a 500 MW NaS battery onto New York grid. Several scenarios are created depending on the type of plant the battery replaces and the type of plant used to charge the battery.	1. Electricity demand is provided exogenously by government predictions. Fuel use is modeled using a cost-minimization based grid dispatch model. 2. emission factors for each generator result in emissions, based on dispatch and control technologies 3. PMCAMx[34] model used to simulation emissions, atmospheric chemistry and dispersion and deposition. 4. BenMAP[35] is used to find and monetize health impacts.	WTP-based VSL $PM_{2.5}$ and O_3 mortality and CO_2 emissions (modeled as value of $20/ton)

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[31] BU: bottom-up; TD: top-down; H: Hybrid.

[32] Balmorel is a linear optimization model of the Danish heat and power system which minimizes operational costs by determining optimal operation of generation units and future investments into energy production plants and supply infrastructure. Model documentation and downloads can be found at http://www.balmorel.com/.

[33] The THOR air pollution modeling suite includes several meteorological and air pollution models capable of operating for different applications and different scales. The system is capable of accurate and high resolution three-days forecasting of weather and air pollution from regional scale over urban background scale and down to individual street canyons in cities - on both sides of the streets. Coupling models over different scales makes it possible to account for contributions from local, near-local as well as remote emission sources in order to describe the air quality at a specific location – for example, in a street canyon or in a park. The system is used in connection with the urban and background monitoring programs in Denmark. The model is detailed more in depth at http://www2.dmu.dk/1_viden/2_miljoe-tilstand/3_luft/4_spredningsmodeller/5_thor/default_en.asp.

[34] The Particulate Matter Comprehensive Air Quality Model with extensions (PMCAMx) is a 3D Eularian grid model which simulates ambient air quality concentrations based upon emissions, atmospheric distribution and several atmospheric chemistry factors. More details can be found at http://people.web.psi.ch/keller_j/WWW_tools_PMCAMx/PMCAMx.html

Source	BU, TD, H[31]	Region and Timeframe	Pollutants	Interventions/Policies	Methods and Models	End points
(Rive, 2010)		Worldwide but EU-17-centric; to 2020	CO_2, $PM_{2.5}$, SO_2, NO_x	Baseline of existing air pollution control technologies with no climate policy compared with several climate and air quality policies (using carbon cap-and-trade scheme and carbon tax; with an air pollutant tax in the air pollutant scenarios) which induces either decrease in output or technology change towards efficiency	1. In part using the MIT EPPA model, energy production baseline based on GRACE[36] CGE model which includes production in 87 regions and 57 economic sectors and is based on economic growth and population growth. 2. RAINS-based emissions (for combustion and processes) are integrated into the model only once from exogenous data, thereafter falling or rising endogenously. 3. Abatement technology (stationary sources only) is also from RAINS and is applied at a marginal abatement cost schedule once it is economical for it to be applied. 4. The costs of CO_2 abatement are compared with the cost of controlling the other three pollutants.	Cost of abatement per unit pollutant
(Chae, 2010)		Seoul, Korea; 2003-2014	NO_x, PM_{10}, CO_2	Three scenarios compared to BAU: 1. GHG scenario for 10% reduction of expected 2014 BAU; 2. Seoul Air Quality Management Plan scenario to reduce conventional air pollutant emissions to 2014 targets; 3. Integrated scenario aiming for both goals. Each scenario used same set of technology costs with goal of minimizing abatement costs.	1. Emissions from various source categories were estimated based on fossil fuel use to meet energy demand using methods and emissions factors given by the Korean government. Changing emissions factors integrated from IPCC and other sources.	Emissions of air pollutants and CO_2.

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[35] The Environmental Benefits Mapping and Analysis Program (BenMAP) estimates the health benefits from improvements in air quality by running health impact functions, which relate a change in the concentration of a pollutant with a change in the incidence of a health endpoint. The model was developed by the Community Modeling & Analysis System. More details can be found at http://www.benmap-model.org/overview.cfm

[36] The model for Global Responses to Anthropogenic Change in the Environment (GRACE) is a multi-sector, multi-regional, recursively dynamic global computable general equilibrium model (CGE) written in GAMS. It was developed for long-term economic analysis of climate change impacts and greenhouse gas abatement policy. The model allows for additional modules for analysis, including emissions permit trading and climate impacts on the forestry sector. Coupled with an atmospheric model, the model can also be used for integrated assessment modeling of the climate and economy. More details can be found at (Aaheim and Rive, 2005).

Source	BU, TD, H[31]	Region and Timeframe	Pollutants	Interventions/Policies	Methods and Models	End points
(Xu and Masui, 2009)		China; 1997-2020	CO_2, SO_2, and NO_x	BAU and four policy scenarios are modeled: 1.Energy efficiency improvements (an average efficiency increase applied generally across all sectors). 2. SO_2 tax (exogenously set). 3. SO_2 cap and penalty (price set endogenously). 4. A mix of cap (price set endogenously) and energy efficiency improvements.	1. Given exogenously input energy demand forecasts the top-down AIM[37] model is used to develop emissions forecasts, as are modeled based on coefficients given in the IPCC Reference Manual (IPCC, 1996) and (Hu, Jiang, and Yang, 2002) based on fuel use characteristics from China Statistical Yearbook and China Environmental Report. 2. SO_2 emissions are forecast by the AIM model.	SO_2, NO_x and CO_2 emissions and sectoral output GDP.
(Woodcock et al., 2009)		London, UK, and Delhi, India; 2030	$PM_{2.5}$	Business as usual compared with four scenarios: 1. Reduced emissions factors from technology improvement. 2. Increased active transport. 3. Combined 1 and 2. 4. Combined 1 and 2 with shorter-distance active travel.	1. Estimate combined pollutants emitted from transport sector fuel use, with emissions estimated on average for vehicles by type. 2. Estimate dispersion of pollution based on exogenous air-dispersal model (ERG's Air Pollution Toolkit[38], which includes ADMS 4[39] street canyon model, reactive gas transport and uptake models, and road pollution dispersion models). 3. Estimates of the dispersion of physical activity and resultant exposure to air pollution based on metabolic equivalent hours (METs) (by age group and sex, based in part on concentrations of air pollutants and in part on increased outdoor exposure due to more active transport). 4. Change in disease burden due to change in exposure (with specification by age group if available) and modified approach for traffic accident-related deaths. 5. This change in disease burden due to pollution exposure was offset by decreases in DALYs from increased physical activity (in minutes of increased activity) due to more active transport.	Impacts of exposure of $PM_{2.5}$ on cardiorespiratory disease and lung cancer in adults, and from acute respiratory infections in children and all injuries due to traffic deaths; offset by improvements in health in several disease outcomes (diabetes, cardiovascular disease, breast cancer, colo-rectal cancer, dementia, and depression) due to increased physical activity from more active transport. These were combined to estimate changes in years of life lost (YLL) and years of healthy life lost as a result of disability (YLD) (summed to Disability Adjusted Life Years (DALYs)).

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[37] The Asian-Pacific Integrated Model (AIM) suite "comprises three main models—the greenhouse gas (GHG) emission model (AIM/emission), the global climate change model (AIM/climate) and the climate change impact model (AIM/impact). The AIM/emission model consists of country level bottom-up energy models and top-down type energy and land-use models of global level. For model details, see (Matsuoka, Morita, and Kainuma, 2001).

[38] ERG's Air Pollution Toolkit is a bottom up road transport emission modeling suite to measure and predict the impacts of NO_x, O_3, PM, and other transport related road emissions through a GIS software interface. For model details see http://www.erg.kcl.ac.uk/Modelling.aspx?DeptID=Modelling&CategoryID=ModellingDevelopment.

[39] ADMS 4 a dispersion model used to model the air quality impact of existing and proposed industrial installations. The model was developed by Cambridge Environmental Research Consultants. Details can be found at http://www.cerc.co.uk/environmental-software/ADMS-model.html.

Source	BU, TD, H[31]	Region and Timeframe	Pollutants	Interventions/Policies	Methods and Models	End points
(Markandya et al., 2009)		EU, India and China; 2010-2030	$PM_{2.5}$	BAU with no GHG mitigation measures other than policies already in place compared with technology costs and emissions impacts of two alternative scenarios. 1. Limited trade scenario in which developed countries are responsible for most of 2050 climate stabilization target burdens and are allowed to trade emission rights; 2. A full trade scenario in which 2050 target is applied generally with full trading	1. POLES[40] model used to find energy demand growth under carbon emissions constraints (carbon pricing) and technology implementation costs to find energy use and emissions from all sectors. Electricity use emissions changes are the only ones used in scenarios, with other sector's emissions unchanged from BAU in alternative scenarios. 2. GAINS used to model dispersion and population exposures. 3. Comparative Risk Assessment framework used to estimate premature mortality and Life Years Lost.	VSLY (From EU) regarding $PM_{2.5}$ impacts on deaths from cardiorespiratory disease and lung cancer in adults, and acute respiratory infections in children
(Bollen et al., 2009)		World (but with heavy reliance on EU data, e.g. emission coefficients); 2000-2050	$PM_{2.5}$ (but as proxy of PM_{10} concentrations)	3 policy measures compared against BAU: 1. internalization of GCC damages in production costs, 2. internalization of PM damages in production costs, and internalization of both. Separate technologies are defined for each main electric and non-electric energy option, which can address CO_2 abatement or PM or both. Technology choice is driven by cost optimization model and abatement costs changing over time with technological development and increased price of inputs.	1. Model for Evaluating Regional and Global Effects of greenhouse gas reduction policies (MERGE)[41] used to find emissions of primary PM and CO_2 from energy use 2. A local air pollution model built to find expected exposure to increased PM concentrations. 3. Found premature deaths from chronic PM exposure using epidemiological study based C-R functions 4. monetized impacts using WTP.	Monetized PM chronic exposure premature deaths as measured by per capita GDP-dependent VSL.

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[40] POLES: Prospective Outlook on Long-term Energy Systems, developed by the University of Grenoble as a part of European Community climate modeling effort. See http://www.eie.gov.tr/turkce/en_tasarrufu/uetm/twinning/sunular/hafta_02/5_poles_description.pdf..

[41] MERGE is a top down general equilibrium energy and GHG emissions forecasting model developed by a group of scientists at Stanford University, Palo Alto, California. More details about the model as well as model download is available at http://www.stanford.edu/group/MERGE/

Source	BU, TD, H[31]	Region and Timeframe	Pollutants	Interventions/Policies	Methods and Models	End points
(Groosman et al., 2009)		2006-2030	SO_2, $PM_{2.5}$, PM_{10}, NO_x, NH_3, and VOC	Two policy scenarios modeled: 1. BAU with current environmental policies, transportation fuel prices and electricity prices. 2. Impact of Warner-Leiberman bill on fossil fuel use in electricity and transportation.	1.EDF Regional Electricity Model[42] optimizes fuel use based on costs and exogenous elasticities, and predicts emissions 2. MOBILE6[43] model used to predict emissions from transport. 3. Air Pollution Emission Experiments and Policy Model (APEEP) used to predict dispersion, atmospheric chemistry, concentrations, human exposure, physical and monetary damages (using both revealed preference and stated preference hybrid)	$PM_{2.5}$ related adult mortality rates and infant mortality rates, as well as O_3 impactss on all age mortality rates, as monetized by VSL (increased over time by income growth)
(Tollefsen et al., 2009)		EU	SO_2, NH_3,VOC, CO, NO_x, black carbon, organic carbon, $PM_{2.5}$, and CH_4	Damage costs associated with human health impacts and agricultural output loss are combined with CO_2 credit prices are compared to modeled abatement costs to optimize fuel choices. Two scenarios are developed: one with a high carbon price and one with a low carbon price, as well as for 20 year valuations and 100 year valuations.	1. Baseline energy and emissions taken from other sources assuming implementation of current EU policies. 2. RAINS technology-based abatement costs used to find optimized change in emissions. 3. The Clean Air for Europe (and other) study's combined health and crop damage estimates for emissions of each pollutant per unit are used to estimate damage costs to compare to abatement costs.	VOLY-based mortality due to exposure
Invalid source specified.		India; 2001-2021	CO_2, CO, CH_4, NMVOC, N_2O, NO_x, TSP and SO_2	Four scenarios compared to BAU: 1. Fuel substitution, 2. Energy conservation 3. Integrated energy conservation/fuel substitution.	1. LEAP used to model energy consumption and emissions from housing sector energy, with energy demand based on appliance use population, number of households, income, and urbanization. 2. Emissions factors used to predict pollution emissions	Emission reductions

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[42] EDF Regional Electricity Model is a top down energy supply and emissions forecast model based upon a detailed inventory of the US electricity sector by breaking the United States into 8 electrical service regions.

[43] MOBILE 6 is an emission factor model for predicting gram per mile emissions of Hydrocarbons (HC), Carbon Monoxide (CO), Nitrogen Oxides (NOx), Carbon Dioxide (CO2), Particulate Matter (PM), and toxics from cars, trucks, and motorcycles under various conditions. The model was developed by the U.S. EPA. Model details and downloads can be found at http://www.epa.gov/oms/m6.htm

Source	BU, TD, H[31]	Region and Timeframe	Pollutants	Interventions/Policies	Methods and Models	End points
(Guttikunda, 2008)		Hyderabad, India, 2006-2020	PM_{10}, SO_2, NO_x, CO_2	BAU compared with 1 alternative scenario several different control strategies applied to transportation and roads, industry fuel change, waste collection and disposal improvements, and reduced coal in residential units.	1. Emissions inventory from all sources within gridded city for all pollutants modeled based on detailed empirical assessment of sources in city, including transportation, using domestic emissions factors embedded in the SIM-air model. 2. ATMOS model used for dispersion and population 3. Dose response functions, mostly from China studies, applied to populations in grids, as evaluated for emissions concentrations in excess of WHO standards 4. WTP values applied to health endpoints.	WTP for PM_{10} related mortality, adult chronic bronchitis, respiratory hospital admission, cardiac hospital admission, emergency room visit, asthma attacks, restricted activity days, respiratory symptom days
(Mazzi and Dowlatabadi, 2007)		UK, 2001-2020	$PM_{2.5}$,NO_x, CO, HC, benzene, 1,3 butadiene, CO_2	BAU (no growth in diesel powered car market share) compared to alternative scenario in which increasing number of consumer switch from petrol to diesel-fueled passenger cars in the UK	1. Emissions in both cases estimated based on government projections of transport sector demand, and UK specific emissions factors. 2. Intake fractions from previous UK transportation studies used 3. C-R functions for $PM_{2.5}$ mortality from U.S. epidemiological study and $PM_{2.5}$ related respiratory and cardiovascular hospitalizations	$PM_{2.5}$ related mortality and respiratory and cardiovascular health related hospitalizations for morbidity
(Chen et al., 2007)		Shanghai, China,2000-2020	PM_{10} and SO_2	BAU of economic growth compared with three alternative scenarios: energy efficiency improvements (average 2% annual improvement across all energy end use sectors), switching coal and oil for gas use for final sectors and wind electricity generation.	1. LEAP model used to model energy demand growth in four sectors (residential, commercial, primary industry and other industry) and resulting emissions. 2. ATMOS used to model dispersion and concentration. 3. Population mapped onto grids to find exposure rates. 4. C-R functions of epidemiological studies used to find PM_{10} based mortality. 5. Health impacts monetized using 8 endpoints with two calculation methods.	PM_{10} and $PM_{2.5}$ related premature death (WTP based VSL), chronic bronchitis (adjusted WTP), respiratory hospital admission (COI), outpatient visits (internal medicine) (COI), outpatient visits (pediatrics)(COI) , acute bronchitis (WTP), and asthma attack (WTP).
(Chen et al., 2006)		Shanghai; 1995-2035	SO_2, PM_{10}, and NO_x, CO_2	Two policy scenarios are compared to BAU: both involve capping coal consumption. Coal is replaced mostly by natural gas and 173 energy technologies in 22 energy using sectors	1. Energy use modeled based on economic development and population growth using MARKAL model which integrates energy efficiency improvements and structural change 2. Emission coefficients used to find conventional emissions	Reduction in emissions of SO_2, PM_{10}, NO_x and CO_2

Source	BU, TD, H[31]	Region and Timeframe	Pollutants	Interventions/Policies	Methods and Models	End points
(McKinley et al., 2005)		Mexico City, 2003-2020	PM_{10}, SO_2, CO, NO_x,HC, CO_2, CH_4, and N_2O	BAU compared with five alternative scenarios in which five control measures (taxi fleet renovation, public transportation expansion, hybrid buses, LPG buses, and cogeneration for heat and electricity) applied in alternative scenario against baseline.	1. Based on previous emissions quantification work, emissions factors and activity levels for all relevant activity modeled. 2. Study authors developed a reduced-form air quality model based on source apportionment studies developed by previous research (Chow, Watson, Edgerton, and Vega, 2002) (Salcido et al., 2001) and derived reduction fractions from primary pollutants. Population-weighted pollutant concentrations from previous study (Molina and Molina, 2002) are extrapolated linearly and multiplied by reduction fractions to find populated weighted concentrations. 3. C-R functions estimated based on Mexico City studies where possible, and international studies where not. 4. Valuation based direct health costs (COI) and productivity losses for hospitalizations and emergency room visits; and WTP-based VSL for mortality, chronic bronchitis and minor restricted activity days.	PM_{10} and O_3 based mortality, chronic bronchitis, hospitalizations, emergency room visits for cardiovascular and respiratory disease, and minor restricted activity days.
(Wang and Mauzerall, 2006)		Zaozhuang City, Shandong Province, China; 2000-2020	CO_2, NH_3, NO_x, NMVOC, SO_2, $PM_{2.5}$and PM10.	BAU (continued use of convention coal combustion technologies and limited environmental controls) compared with 2 alternative policy scenarios: 1. Implementation of best available control technologies to combustion emission control technologies; 2. Substation of advanced coal gasification and syngas use technologies with 24% penetration.	1. Energy demand forecast to increase by 150% in all scenarios. 2. Technology emissions factors are applied to find emissions. 3. Atmospheric dispersion modeled used SMOKE.[44] 4. Concentrations modeled with CMAQ 5. Population modeled based on 200 provincial population census data with exogenous growth. 6. Epidemiological data from China applied to find total health damage 7. VSL applied to damages.	VSL-based WTP valuations used to monetize all impacts. Mortality due to $PM_{2.5}$ exposure for adults >30 years, mortality due to PM_{10} exposure to infants, both in years of life lost. Morbidity from PM_{10} related chronic bronchitis, PM_{10} related acute bronchitis, PM_{10} related cardiovascular hospital admissions, PM_{10} related respiratory hospital emissions, PM_{10} related restricted activity days, and PM_{10} related asthma attacks for adults and children. Impacts from SO_2, NO_x and NMVOCs are estimated based on generalized damage functions (US$/year impacts/ton emissions)

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[44] Sparse Matrix Operator Kernel Emissions Modeling System Version 1.3 is primarily an emissions processing system designed to create gridded, speciated, hourly emissions for input into a variety of air quality models such as CMAQ, REMSAD, CAMX and UAM. SMOKE supports area, biogenic, mobile (both onroad and nonroad), and point source emissions processing for criteria, particulate, and toxic pollutants. For model details please see http://www.smoke-model.org/overview.cfm.

Source	BU, TD, H[31]	Region and Timeframe	Pollutants	Interventions/Policies	Methods and Models	End points
(Aunan et al., 2004)		Shanxi, China; no specific time horizon as impacts are reported in changes in annual number of cases (or person-days) per million people per 1 mg/m3 change in concentration	SO_2, PM_{10}, CO_2	Considered six options for reduction of emissions from combustion of coal: 1. Co-generation, 2. Modified boiler design, 3. Boiler replacement, 4. Improved boiler management, 5. Coal washing, 6. Briquetting	1. Emissions reductions are estimated for each abatement option assuming a reasonable percentage of usage change 2. Chinese exposure response (E-R) functions and supplements results with European and U.S. E-R functions only for PM_{10} 3. Disaggregated cohort-year approach to determine long term mortality 4. The number of life years gained was calculated for each 5 year cohort for 90 years using estimates for the increase in life expectancy at birth from a 10 µg/m3 reduction in PM_{10} 5. Valuation of health benefits are performed using Value of a Life Year (VOLY) or Value of a statistical life year (VSLY) estimated for Europe and transfer this benefit to China. The same is done for cases of chronic bronchitis and acute respiratory illness (using fractions of VSLs) and adding to it cost of illness	PM_{10} mortality calculated Value of a Life Year (VOLY) or Value of a statistical life year (VSLY) estimated for Europe and transfer this benefit to China. The same is done for cases of chronic bronchitis and acute respiratory illness (using fractions of VSLs) and adding to it cost of illness
(Li et al., 2004)		Shanghai, 1995-2020	PM_{10}, SO_2, NO_x, $PM_{2.5}$, and TSP	Two baseline scenarios compared with two policy options: 1. use of state-of-the-art integrated gasification combined cycle (IGCC) technology for coal combustion and expected gas and oil power generation expansion; 2. Elimination of coal use in industry in 2020 with shut downs and relocation of coal-using industrial plants away from population centers.	1. Energy use modeled based on RAINS-Asia (as a function of economic growth, sectoral shifts and population growth), using actual or standard emissions rates by fuel and combustion technology, in addition to emissions from non-energy activities estimates from yearbooks and other sources. Emissions from outside sources are modeled with ATMOS. 2. Ground level concentrations modeled using the UrBAT.[45] 3 Based on predicted population distribution, dose response functions from epidemiological studies in China and other countries used to determine health impacts. 4. WTP and cost-of-illness methods used to calculate economic costs of health impacts. **6. Costs of implementing new technologies: 1. compared with baseline (SO_2 scrubber integrated conventional pulverized coal-based plants) expansion costs; 2. Cost of new capacity builds due to industrial relocation.**	Acute mortality (WTP based VSL), chronic bronchitis (Cost-of-illness), hospital visits (WTP based VSL), hospital admissions (Cost-of-illness) and emergency room visits (Cost-of-illness).

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[45] Urban Branching Atmospheric Trajectory Model: a three-layer Lagranfian puff-transport forward trajectory model which includes detailed meteorological input data. http://www.cgrer.uiowa.edu/ATMOS/atmos-urbat-linux

Source	BU, TD, H[31]	Region and Timeframe	Pollutants	Interventions/Policies	Methods and Models	End points
(Wang and Smith, 1999)		China; 1995–2035	SO_2, PM_{10}, NO_x, CO_2, CH_4,N_2O	BAU case compared with 1. least- cost energy efficiency, 2. least-cost per unit global-warming- reduction fuel substitution, and 3. least-cost per unit exposure- reduction fuel substitution in two sectors, household and power	1. Emissions are calculated from operational stages of each policy. 2. Inhaled dose is determined by using exposure concentration, breathing rate, size of affected population, and duration of exposure to determine intake fraction. 3. A Gaussian plume model is applied to estimate changes in PM concentrations from coal plant emissions. Both outdoor and indoor exposures are included 4. Available data on indoor air pollution were used to approximate emissions and determine the particulate dose effectiveness. 5. the change in health risk is calculated using exposure-response curves using both Chinese and U.S. studies 6. Chose U.S. VSL of $3 million and transferred this benefit using average Chinese income.	

Appendix C: Gold Standard Registry Sustainable Development Indicators and Corresponding Possible Parameters

Table C: Gold Standard Registry sustainable development indicators and corresponding possible parameters

Indicator	Description	Possible Parameter
Environment		
Air quality	Air quality refers to changes compared to the baseline in: • Pollution of indoor and outdoor air which may have a negative impact on human health or the environment, including particulates, NOx, SOx, lead, carbon monoxide, ozone, POPs, mercury, CFCs, Halogens. Also odor is considered to be a form of air pollution. Pollution by gases covered under the Kyoto Protocol (carbon dioxide (CO2), methane (CH4), nitrous oxide (N2O), hydrofluorocarbons (HFCs), perfluorinated carbons (PFCs) and sulphur hexafluoride (SF6).) are not included in this category as this category refers to changes in the environment in addition to reductions of greenhouse gases since GHG reductions are included in all greenhouse gas reduction projects by definition.	Concentrations and Emissions of: Nox Sox Lead CO Ozone POPs Mercury CFCs Halogens Respirable Suspended Particulate Matter (RSPM) NH3 PM10 VOC Total Suspended Particulate Matter (TSPM) Dust Health (e.g. –respiratory problems, eye irritation etc.) Odour
Water quality and quantity	Water quality refers to changes compared to the baseline in: • Release of pollutants and its impacts on the environment and human health, including biological oxygen demand and chemical oxygen demand, thermal pollution, mercury, SO_2 NO_x, POPs, lead, coliforms (bacteria from animal waste). Water quantity refers to changes in water balance and availability in ground- and surface water.[46]	Levels of: Biological oxygen demand Chemical oxygen demand Thermal pollution Mercury SOx NOx POPs Lead

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[46] Note: different guidelines apply to hydropower projects.

Indicator	Description	Possible Parameter
		Coliforms (bacteria from animal waste) Quantity Water used in the process. Indirect parameters like fuel wood consumption etc. that can be proven to be linked to decreased surface water run off etc.
Soil condition	Soil condition refers to changes compared to the baseline in: • Pollution of soils, pollution of soils can be caused by lead, mercury, cadmium, possibly combined by a negative corresponding impact on human health. • Organic matter content • Erosion level	Levels of: Lead Mercury Cadmium Soil refilling Soil erosion Indirect parameters like fuel wood consumption etc. that can be proven to be linked to decreased soil erosion etc.
Other pollutants	This indicator refers to changes compared to the baseline in: • Other pollutants of the environment, which are not already mentioned. For instance level of noise/ light, frequency of noise/light and time occurrence (daytime/night-time, weekdays/ weekend) is relevant for consideration. • Visual pollution	Level of noise Frequency of noise (per day, per week, per month) Time occurrence (day/night, weekdays/weekend) Vibration from blasting activities. Solid/liquid wastes from construction stage
Biodiversity	Contribution to biodiversity refers to changes compared to the baseline in: • Number of genes (i.e., genetic diversity within a species) species and habitats existing within the project's impact boundaries. • Alteration or destruction of natural habitat • Depletion level of renewable stocks like water, forests, fisheries	Number of affected and/or threatened Plants Number of affected and /or threatened mammals, birds, reptiles, fishes, and other species and habitats
Social development		
Quality of employment	Quality of employment refers to changes compared to the baseline in: • Labor conditions, such as job-related health and Safety Qualitative value of employment, such as whether the jobs resulting from the project activity are highly or poorly qualified, temporary or permanent etc.	Training, workshops etc. Labor conditions

Indicator	Description	Possible Parameter
Livelihood of the poor	Livelihood of the poor refers to changes compared to the baseline in: • Poverty alleviation, e.g. changes in living standards, number of people living below the poverty line • Access to health care services (hospitals, doctors, medication, nurses etc.), affordability of services, reliability and quality of services, and diseases prevention and treatment, including HIV AIDS, measles, TB, malaria, cholera and others. • Access to sanitation including access to toilets/washrooms. Waste management facilities that offer the possibility of deposing waste in a sanitary way. • Access to an appropriate quantity, quality and variety of food that is a prerequisite for health. • Changes in proneness to natural disasters that may be climate change related (e.g. droughts, flooding, storms etc.) or unrelated (e.g. earthquakes, volcano outbreaks). • Long-term changes that differ from natural disasters in the sense that they occur steadily/increasingly but not suddenly (e.g. community's dependency on river water from a river with diminishing volumes of water). Changes must be directly related to the service and not an unintended impact.	Children immunized against measles Maternal mortality ratio HIV prevalence among pregnant women Condom use rate of the contraceptive prevalence rate Condom use rate for high-risk people Population with comprehensive correct knowledge of HIV/AIDS/other diseases Prevalence and death rates associated with malaria Population rate in malaria-risk areas using effective malaria prevention and treatment measures Prevalence and death rates associated with tuberculosis Proportion of tuberculosis cases detected and cured under directly observed treatment short course DOTS (Internationally recommended TB control strategy) Infant mortality rate Life expectancy Number of hospitals available Number of doctors Number of physicians Number of nurses Proportion of births attended by skilled health personnel Under-five mortality rate Infant mortality rate Quality improvement of health care services Number of population with access to improved sanitation,

Indicator	Description	Possible Parameter
		urban and rural Number of population who can access to effective waste management system Prevalence of underweight children under-five years of age Proportion of population below minimum level of dietary energy consumption Availability of Reliable disaster warning and relief system at community, local, regional, and national levels Knowledge and information dissemination regarding natural disaster Money spent to collect fuel
Access to affordable and clean energy services	Access to energy services refer to changes compared to the baseline in: • Presence, affordability of services and reliability of clean energy services in the local area or households	Change in Energy use Change in Traditional fuel consumption (% of total energy requirements) Electricity consumption per capita (kilowatt-hours) Reduced black outs, fluctuations
Human and institutional capacity	Human and institutional capacity refers to changes compared to the baseline in: • Education & skills: Access to primary, secondary and tertiary schooling as well as affordability and quality of education. Educational activities which are not part of the usual schooling system, such as environmental training, awareness raising for health or other issues, literacy classes for adults, and other knowledge dissemination. • Gender equality: Livelihood and education for women that may include special schooling opportunities as well as other woman-specific training, awareness-raising, etc. • Empowerment. Changes in the social structure, e.g. caused by a change in the distribution of income and assets. This may result in shifts in decision-making power at project level (e.g. participation in project executive board, ownership of CERs etc.), community level (e.g. community council) or at a higher level. Especially in communities with diversified ethnic or religious structures, changes in income and asset distribution may have an impact. Especially ownership of CERs or other direct involvement in the project may support participation in project decision-making. The social /community initiatives must have long-term benefits.	Female combined gross enrolment ratio for primary, secondary and tertiary schools Female Adult literacy rate Change in female earned income Change in number of jobs and positions for women Change in decision-making structures at the community, local government levels Change in income and asset distributions by region, ethnicity, religion, and socio-economic groups Women in government or decision making groups at community, regional, ministerial levels

Indicator	Description	Possible Parameter
Economic and technological development		
Quantitative employment and income generation	Quantitative employment and income generation refers to changes compared to the baseline in: • Number of jobs • Income from employment (with salaries at par or better than the average local / sector wage level) in the formal and informal sector. Other income, such as from ownership of CERs, may be included • Local employment for skilled / un-skilled and permanent jobs.	Household income generated from the project Number of jobs created
Access to investment	Access to investment refer to changes compared to the baseline in: • Investment into a country/region or technology. Without proper access to investment, projects may demonstrate credibility and reliability of loan takers and trust in the financial structure. Hence future investments into similar or other activities may be enabled. Only if financing possibilities are limited in the country/region or technology, a positive impact from demonstration of investment may exist. Investments may come from national or international sources. Bilateral and unilateral investment should be distinguished, since the former do have this effect of demonstrating the viability of the host as a destination for investment, whereas the latter have this to a much lesser extent	Amount of domestic investment Amount of foreign direct Investment
Technology transfer and technological self-reliance	Technology transfer and technological self-reliance refer to changes compared to the baseline in: • Technology development as well as adaptation of new technologies to unproven circumstances. Technology can be sourced from outside or inside the country as long as it is new to this particular region and introduced in a proven sustainable way. Demonstrating the viability of technologies new to a country/region may help in transforming the energy sector. • Activities that build usable and sustainable knowhow in a region/country for a technology, where know-how was previously lacking. This capacity building enables spill-over effects to the area by replicating similar or different projects • Amount of expenditure on technology between the host and foreign investors regarding the contribution of domestically produced equipment, royalty payments and license fees, imported technical assistance or the need for subsidies and external technical support	Number of workshops, seminars organized, and training-related opportunities held for masons/external audience who would be directly involved in replication of the technology Number of participants who attend those capacity building activities R&D Expenditures

Source: The Gold Standard Secretariat, 2012c.