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Local and Regional Pollution Reduction Co-Benefits from Climate Change Mitigation Interventions

A Literature Review

IEG
Independent Evaluation Group

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1818 H Street NW
Washington DC 20433
Telephone: 202-473-1000
Internet: www.worldbank.org

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By Leonard Ortolano

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Abbreviations

BAU	business-as-usual
CCS	carbon capture and storage
CDM	Clean Development Mechanism
CHP	combined heat and power
CO_2	carbon dioxide
GAINS	Greenhouse Gas-Air Pollution Interactions and Synergies
GHG	greenhouse gas
IEG	Independent Evaluation Group
IPCC	Intergovernmental Panel on Climate Change
kg/t	kilogram per metric ton
LCA	life cycle assessment
MW	megawatt
NO_x	nitrogen oxides
PM	particulate matter
REDD	Reducing Emissions from Deforestation and Forest Degradation
SLCP	short-lived climate pollutants
SO_2	sulfur dioxide

Preface

This literature review was conducted in the context of a major evaluation by the Independent Evaluation Group (IEG) on pollution management, *Toward a Cleaner World for All*. In this evaluation, IEG examined a decade of work in the World Bank Group on pollution management and abatement.

The literature review was a key piece of evidence for Recommendation 4 of this evaluation, which argued that the World Bank Group should "Leverage the World Bank Group's climate change portfolio to better combat local and regional air pollution and other applicable forms of pollution." However, the literature review is also useful in its own right, as a guide to the empirical literature on pollution co-benefits from climate change mitigation investments. For this reason, IEG is publishing the literature review as a working paper, to make this resource widely and publicly available to enrich thinking about this most vital development challenge

The literature review was carried out by Professor Leonard Ortolano (Stanford University), under the supervision of Stephen Hutton. We are grateful for peer review comments received from Sameer Akbar (World Bank).

The full IEG evaluation is available at
http://ieg.worldbankgroup.org/evaluations/pollution.

Summary

IEG's evaluation on pollution and the World Bank Group commissioned a review of the empirical literature on pollution co-benefits from climate change mitigation interventions, emphasizing air pollution benefits. Such pollution is defined using parameters such as sulfur dioxide (SO_2), oxides of nitrogen, and particulate matter for air emissions, and total suspended solids for water releases. The review used a multistage identification technique based on 40 keyword strings in Google Scholar, web of science, and Scopus to identify a universe of peer-reviewed articles. Papers were included only if they focused on developing countries. Additional papers were identified iteratively based on references from the initial papers. The final papers cited were based on expert judgment, with emphasis for studies published after 2010. A systematic search was conducted to locate relevant review articles and meta-analyses; no formal systematic reviews were found. Google was also used to identify non-peer-reviewed studies from reputable sources, such as the International Energy Agency, U.S. Environmental Protection Agency, and World Bank.

The paper lays out the methods and models used in calculating pollution co-benefits, and then presents sector-by-sector results for energy, buildings, industry, transportation, solid and liquid waste management, agriculture, forests/other land use, and multiple sector studies.

There exists a considerable quantitative literature estimating the local pollution co-benefits of climate change mitigation interventions. The sectors in which fuel combustion contributes to greenhouse gas (GHG) emissions—energy, buildings, industry and transport—are the ones with the most significant air quality co-benefits, and the most substantial quantitative literatures. In energy and industry, the largest co-benefits come from replacing coal combustion with less polluting fossil fuels, from replacing fossil fuels with renewable energy, from improving energy efficiency, and from improving the characteristics of coal via coal washing and briquetting. For buildings, the largest air quality co-benefits are typically linked to improvements in energy efficiency and modifications in cooking stoves. Transport studies typically aggregate the effects from a collection of interventions, including greater use of public transport and improving vehicle fuel efficiency, but transport-related studies also often aggregate effects on health outcomes from other nonpollution effects such as benefits from increased walking and cycling.

For agriculture, forestry and land use change, there are many opportunities for environmental co-benefits, but the effects are particularly location specific and do not lend themselves readily to cataloging and quantification.

Carbon capture and storage is noted as having negative effects on air pollution, because of the loss of efficiency of electricity generation and associated increased in fuel consumption. In some cases, use of biofuels also led to increases in particulate matter and nitrogen oxides.

However, the size of these effects is highly uncertain, because substantial methodological variation across studies and the lack of any common standards in results reporting makes comparisons difficult. Point estimates of tons of pollution abatement per ton of carbon dioxide equivalent from a particular intervention can vary by an order of magnitude across studies, depending on modeling assumptions (which are often opaque). Context-specific details of interventions, existing fuel mix, and geography are also very important, especially for identifying co-benefits from renewable energy. The World Bank could consider carrying out such analysis for its own projects, and working to develop and disseminate standardized methodologies.

There also remain some notable gaps in the literature: the evidence base is relatively thin on effects of climate change mitigation on water quality, or on pollution co-benefits from forestry/land use or agriculture interventions. Studies on energy efficiency in buildings are dominated overwhelmingly by cases from developed countries. Studies on improved cookstoves have looked at air pollution effects but have seldom considered GHG emission benefits. And waste sector studies do little to document possibility of air pollution benefits from conversion to sanitary landfills or incineration, focusing instead on GHG emission benefits.

1. Introduction

This literature review addresses, in broad terms, the following question: to what extent are interventions that mitigate global climate change, for example, by reducing greenhouse gas (GHG) emissions, also likely to affect local air and water pollution? Such pollution is defined using parameters such as sulfur dioxide (SO_2), nitrogen oxides (NO_x), and particulate matter (PM) for air emissions, and total suspended solids for water releases.[1] Although it is not the focus of this review, attention is also given to short-lived climate pollutants (SLCPs), a subset of climate forcers with a lifetime in the atmosphere of about 15 years or less. These include: black carbon, methane, tropospheric ozone, and some hydrofluorocarbons.[2] The SLCPs are important because of their impacts on global temperature, human health, and food security, and because their mitigation can yield local improvements in human health relatively quickly. The review emphasizes studies from developing countries.

This paper is organized as follows. Section 2 lays out the scope of the review as well as the literature search process. Section 3 provides introduction to the methods and models used in calculating co-benefits. Section 4 presents sector-by-sector results in the following order: energy, buildings, industry, transportation, solid and liquid waste management, agriculture, and forests and other land uses. Many analyses of alternative GHG reduction scenarios considered actions from more than one sector, which are also discussed. Section 5 elaborates on the quantitative estimates of co-benefits obtained from the literature, and presents conclusions.

2. Scope and Literature Search Methods

The nonclimate benefits (often termed "co-benefits") that may accompany climate change mitigation encompass a broad array of topics, including food and energy security and reduced traffic congestion. However, the scope of this literature review is limited to co-benefits in the form of effects in reducing conventional air and water pollutants. Local air quality co-benefits are dominant in the environmental co-benefits literature because local air pollutants often originate from the same sources as GHGs, such as power production, industrial processes, buildings, transport and agriculture (Apsimon et al. 2009). This review reflects the literature and emphasizes local air quality co-benefits. There are some environmental co-benefits in the form of water quality effects, and they are covered also, as are pollution-related "co-harms" that are mentioned occasionally in the literature.

To the extent that the literature provides evidence of health benefits that follow directly from reductions of conventional pollutants, those are also included herein. However, effects that do not follow directly because of changes in conventional pollution parameters are *not* included. Thus, the following health co-benefits, which are prominent in the co-benefits literature, are not covered: benefits that accompany reductions in heat stress as well as those that follow from increased walking and cycling as a result of transportation-related mitigation measures.

Discussion of climate change mitigation co-benefits began in the 1990s and the literature on the subject has since become voluminous (Mayrhofer and Gupta 2016.). One reason is that local air quality benefits of climate change policies accrue in the near term while benefits from GHG emission reductions occur over the long run.[3] The short-term reductions in local pollution provide an added incentive to undertake climate change mitigation measures. A continuing challenge in taking advantage of local air quality co-benefits to encourage mitigation activity is that they are not routinely monetized and included in benefit-cost analyses.

The climate change mitigation literature sometimes uses terms such as "ancillary benefits" or ''multiple benefits" instead of co-benefits.[4] The literature also includes the term "climate change co-benefits," and in this review that term comes up largely in the context of papers describing improved waste management systems that simultaneously reduce GHGs.

A multistage approach to searching the literature was followed. In the first stage, strings of key words (for example, "transportation, GHG mitigation, co-benefits") were used in Google Scholar as well as two relevant databases (Web of Science and Scopus) to identify an initial universe of peer-reviewed articles to be considered. (The list of key word strings is given as an endnote.)[5] In a number of the searches using key words on Web of Science and Scopus, more than 100 papers came up. In most such cases, additional key words were added to narrow the search to get the number to be examined on any one set of key words to below 50 or so. This was necessary since, as shown in endnote 6, approximately 40 strings of key words were used in searching for papers. Although the emphasis was on papers concerning developing countries published after 2010, older papers were also considered.

The next stage of the literature identification process proceeded as follows. For any one search on Web of Science or Scopus, the resulting papers were ordered by "relevance" (as opposed to "newest to oldest") and all the abstracts were read. Papers that contained information relevant to the goals of the review were downloaded and at least skimmed. Papers found valuable were read in detail and they often lead to other papers—either papers cited by the original paper (backward citation tracking) or papers that later cited the original paper (forward citation tracking using Google Scholar). For any one sector, this led to a massive amount of information, and judgment was exercised regarding what to read in depth, what to include in this review, and what to leave out or simply cite as additional illustrative studies in endnotes.

In addition, a systematic search was conducted to locate relevant review articles and meta-analyses. (These are typically for a single sector and the ones found to be the most helpful are listed in an endnote.)[6] This multistage approach allowed for broad coverage of the relevant literature. In addition, a search engine (Google) was used to identify non-peer-reviewed publications dealing with environmental co-benefits issued by reputable sources, such as the International Energy Agency, the U.S. Environmental Protection Agency, and the World Bank.[7]

The general goal of this review was to identify the extent to which interventions that reduce GHG emissions, also cut local pollution. Thus, whenever possible, quantitative study outputs are presented as "co-abatement rates" in the form of kilogram (kg) of pollutant reduced per metric ton (t) of CO_2 or CO_2 equivalent (CO_2e) abated.[8] Some co-benefits studies presented results in this form, and many others presented results that could be put in the form of kg/t by converting units. However, several quantitative co-benefits studies presented outputs in completely different units, such as percent of reduction in emissions of conventional air pollutants or concentrations of conventional pollutants. Use of different units, of course, makes it difficult to compare numerical outcomes. Moreover, even when the same units are used, it is challenging to make comparisons across studies because of a number of factors, such as differences in study location, quality of input data and overall methodology. Tables are used herein to provide perspective on numerical outcomes, and, as mentioned, the penultimate section of the paper presents an overview of the quantitative results.

3. Methods and Models Used in Analyzing Co-Benefits

Before presenting the main results of this review on a sector-by-sector basis, the methods and models used in co-benefit analysis are introduced. This provides a foundation for understanding how environmental co-benefits study results are obtained.

Co-benefit studies used a wide variety of approaches. The most straightforward studies evaluate specific GHG emission abatement projects. Typically, the projects are actual proposals or projects created by authors for analytic purposes. The most complex assessment approaches are in studies based on mathematical models describing the economy as a whole; for example, partial or general economic equilibrium models. These rest on economic theory to address impacts of energy policies on a host of variables including, for example, employment and energy security.[9] Co-benefit studies based on general equilibrium models are not emphasized herein because many are for developed countries, and often the links between the sector-related activities and local air quality benefits are either not made explicit or not estimated at all (Nemet, Holloway, and Meier 2010).

Another type of co-benefit study is one that creates and/or simulates *hypothetical* policy scenarios made up of sets of GHG mitigation activities. Papers based on policy scenario assessments commonly examine collections of interventions. There are also relevant studies based on postproject observations. However, studies based on observations of local environmental impacts do not receive much attention herein because they are relatively few.[10] Most co-benefit studies involve ex-ante assessments. Some co-benefits studies involve no formal study approach; they simply assert that air or water quality co-benefits exist. This review does not dwell on these studies because one of the goals was to characterize pollution co-benefits in quantitative terms.[11]

Since the mathematical models used in policy scenario studies are complex, a brief introduction is provided. The models fall into two main classes: optimization and simulation. Optimization models select from each of the energy systems and technologies under consideration over a multiyear period to identify the least-cost set of interventions subject to specified constraints (for example, limits on GHG emissions). Model outputs include the least-cost mix of energy suppliers and technologies to satisfy energy demand during the period under study. Optimization models are often created using well-established software packages, such as MARKAL (short for MARKet Allocation) model (Pfenninger, Hawkes, and Keirstead 2014).

Simulation models determine how a specific set of actions will perform over time in terms of costs, energy generated, emissions of GHGs and local air pollutants, and so on. Typically, multiple scenarios are examined, including a reference or "business-as-usual" (BAU) scenario and one or more "low carbon development" pathways. For any scenario, input for a simulation model includes, among other things, information on energy sources and costs, technologies, and end-use demand for energy services. As in the case of optimization models, software packages are available to simulate outcomes associated with policy scenarios. An example is the software package called LEAP, short for Long-range Energy Alternative Planning System, which is a widely used tool in climate change mitigation assessments.[12]

Some models allow the simultaneous study of GHG and local air pollutant emissions and facilitate both optimization and simulation work. An example is the Greenhouse Gas-Air Pollution Interactions and Synergies (GAINS) model. It can be operated in two modes: (i) "scenario analysis mode," that is, for any proposed set of interventions the model analyzes the pathways of emissions from sources to impacts and traces costs and environmental benefits; and (II) "optimization mode," that is, the model identifies the cost-minimizing (or net-benefit maximizing) program of interventions to achieve specified concentration targets.[13]

For any set of mitigation measures, a typical procedure for estimating GHG and conventional air pollutant emissions involves multiplying total activity levels (for example, fuel combusted) during a period by the associated "emission factors," given in mass (or weight) of emissions per unit of activity. Emission factors can be locally derived. However, often local information is not available, and in those cases factors can be taken from national emission factor databases (when they exist) or the Intergovernmental Panel on Climate Change (IPCC) database.[14] For mobile sources of air pollution, emission factors are available from several sources (for example, the European Union's COPERT software program).

In health impact assessments, air pollutant emissions (in units of mass or weight) must be converted to local pollutant concentrations (in units of mass per volume) using pollutant dispersion models. Concentration-response models from epidemiological studies are then used to determine health impacts of ambient air pollutants. Some co-benefit studies monetize results and present them in the form of dollars per unit of CO_2 (or CO_2e) avoided.

As mentioned, the emphasis herein is on studies from developing countries. This is germane to issues of methodology because co-benefits modeling studies often require a wide range of inputs, and needed input data may not be available for many developing countries. Thus, approximations must be made, and they are often based on data from developed countries.

In presenting results of a collection of environmental co-benefit studies, one of the difficulties consists in making comparisons across study outputs. This is challenging because studies vary in significant ways, including analysis approach, sector, scope, time span, and output metrics. Additional difficulties in making comparisons are highlighted in the following excerpt from an informative review paper on air quality co-benefits:

> Results from co-benefits studies are typically difficult to compare, even if study area and target year are identical, due to variations in study design. Major differences exist in the methodology used to estimate benefits…. Whereas some studies implement sophisticated modeling systems to estimate altered air quality, capturing regional differences in pollutant levels … others use simple target values with uniform pollution reductions across all spatial areas (Bell et al. 2008).

Regardless of the modeling approach, model-based studies of co-benefits are often opaque inasmuch as they rely on complex sets of modeling assumptions that are frequently not delineated in papers presenting results.

4. Results from Specific Sectors

Energy

This section on energy is the first of several sections containing results of co-benefits studies for different sectors. The burning of coal, natural gas, and oil for electricity and heat is the largest single source of global GHG emissions. The energy supply sector, including electric power generation and heat production, was responsible for about 25 percent of 2010 global GHG emissions.[15]

In addition to a discussion of policy implications, three topics are considered in this section: power sector energy efficiency, renewable energy and carbon capture and storage (CCS). Energy efficiency is treated first, but it is considered here only in the context of power generation by energy utilities. Many efficiency studies focus on individual sectors, such as buildings, industry and transport, and they are discussed in the relevant sector-oriented discussions below. A few other studies consider energy efficiency in the context of policy scenarios involving multiple sectors.

POWER SECTOR ENERGY EFFICIENCY

Within the energy sector, studies of energy efficiency have been conducted in the context of power generation, energy transmission and distribution and the transport of fossil fuels. However, many power sector efficiency studies for developing countries focus on benefits in the form of cost savings and energy security and do not emphasize local air quality co-benefits. When co-benefits are mentioned, they are typically in the form of GHG emission reductions (referred to as "climate change co-benefits") and/or energy security, not local air quality.[16]

There are exceptions in that a few power system efficiency studies for developing countries did examine local air quality co-benefits. For example, a study examined the feasibility of supply-side efficiency projects in Shanxi Province, one of China's main coal producing areas. For the power sector, the main efficiency improvement projects concerned coal washing and modification of boiler designs to include multilayer combustion systems that sort coal entering boilers. (In the Shanxi study, somewhat less than half the potential projects involved the power sector and the rest involved industrial operations.) Coal washing projects considered had the potential to reduce 9.63 kg total suspended particulate (TSP)/t CO_2 and 32.9 kg SO_2/t CO_2. For possible boiler design projects, calculated co-abatement rates were 2.66 kg TSP/t CO_2 and 8.23 kg SO_2/t CO_2.

More generally, co-benefits studies in developing countries involving the power sector sometimes grouped energy efficiency together with other measures to reduce GHGs, such as fuel switching and the introduction of renewables. This is illustrated by a study of the power system in Bangladesh that identified changes needed to meet CO_2 reduction targets at minimum cost over a 2005 – 2035 planning horizon. The Bangladesh study considered several types of measures—energy efficiency, process changes, fuel switching and renewables—and did not provide details regarding the specific contributions of energy efficiency measures to meeting targets. Air quality co-benefits were reported as percent reductions in emissions of SO_2 and NO_2. In comparison to the BAU scenario, SO_2 emissions during the planning horizon would be cut 12 percent, 26 percent and 40 percent in the scenarios for cuts in CO_2 emissions of 10 percent, 20 percent, and 30 percent respectively. The comparable NO_2 reductions were 10 percent, 21 percent and 31 percent, respectively.

RENEWABLE ENERGY

The following question must be addressed when estimating impacts of renewable energy on local air quality co-benefits: what fossil fuel sources will be displaced by a power system operator when renewable energy supplies become available? The relevant comparison is between power generation scenarios with and without renewables. Given those scenarios, the associated air pollutant emissions are determined using emission factors linked to different energy sources.

Mathematical models can simulate how power system operators will react to new power generation resources. An example is PROSYM, a widely used production cost model that allocates electricity among available generation units to satisfy demand at minimum cost. Such models help in deciding when, where and how much of each type of generation it is most economic to add to a power system. Production cost models require input data such as fuel price and load forecasts, wind and solar generation profiles, emission rates, transmission constraints, and so forth. Because models like PROSYM are so complex, efforts have been made to create easy-to-use, approximate procedures for estimating displaced fossil fuel emissions when renewables are introduced. An example is the approach developed by Synapse Energy Economics, which has been used by some US electric utilities.

As an illustration, consider a study of the power system in China's Xinjiang Uygur Autonomous Region. This study ignored the complexities of determining how power system operators would respond to the introduction of wind power by assuming annual renewable energy from the 49.5-megawatt (MW) Buerjin wind power project would replace thermal sources on a one-to-one basis. After making further simplifying assumptions and using emission factors from the literature, the study yielded the following co-abatement rates for wind power displacing thermal sources: 4.11 kg SO_2/t CO_2, 3.20 kg NO_x/t CO_2, and 0.30 kg $PM_{2.5}$/t CO_2.

Most studies of the effects of renewables in reducing local air pollution involve more than one form of renewable energy. An example is given by a study of co-benefits using renewables in the Shanghai power system. The study, which was far more sophisticated than the above-mentioned wind study, employed optimization modeling to identify which renewable energy units would replace thermal power units. The analysts used LEAP to construct a "Regional Power Generation System Optimization" model for Shanghai. Total emissions of CO_2 and various air pollution indicators were calculated for each of several planning scenarios, but results were presented in multiple, complex graphs that are not readily summarized.

Another China-based study involved estimating ex-ante co-abatement rates for projects formulated under the Kyoto Protocol's Clean Development Mechanism (CDM). The study was based on project documents for a large sample of Chinese CDM projects in the pipeline (as of 2010) as well as emissions factor data based on the previously-mentioned GAINS model. Co-abatement rates computed for energy sector projects in this study are summarized in table 1. The wide variations in co-abatement rates result from the differences in activities within a project type as well as variations in project location. The study authors explained the comparatively high SO_2 cuts per unit CO_2e reduced for "fossil fuel switch" projects in terms of the reliance on substituting gas (with low SO_2 emissions) for coal in these projects. The comparably small estimate of offsets of NO_x from the other natural gas-related projects, such as waste (that is, extracting fuel from waste) and fossil fuel switch was explained in terms of the expectation that the new gas combustion would itself involve new NO_x emissions. (Other explanations are provided in notes to table 1.) More generally, results from this study suggest that CDM projects in China have the potential to make significant reductions in SO_2 and modest, but nonetheless notable reductions in NO_x and $PM_{2.5}$.

A similar study of the energy sector in China as a whole determined a set of co-abatement rates that also allows for comparisons among CDM interventions. The study used calculation procedures involving data from multiple sources to deduce co-abatement rates for various types of CDM energy facilities (table 2). The study estimated that (for 2010) "every 1 percent CO_2 reduction in China's power generation sector resulted in the respective co-reduction of 1.1 percent, 0.5 percent, and 0.8 percent of SO_2, NO_X, and $PM_{2.5}$. Wind is the best technology to achieve the largest amount of co-abatement in most parts of China." In other words, from a mitigation option perspective, wind power technology has the highest co-abatement rates for three types of conventional pollutants. As shown in table 3, major differences exist in co-abatement rates across regions; this occurs because of variations in pollution control equipment. As the study indicated "the East China grid's co-abatement rates are comparatively lower than other regions, which corresponds to a higher deployment level of pollutant control equipment in this economically developed area."

In some co-benefits studies, renewable energy was examined together with energy efficiency measures. One such study was for Taiwan. System dynamics simulation modeling was used to develop electricity generation scenarios that differed by types of energy source. Scenarios were created for both renewable energy and energy efficiency. An illustrative output for the study period (2010-30) is that the energy efficiency scenario would cut emissions by 67.4 kg PM_{10}/t CO_2e reduced. In contrast, the renewable energy scenario would reduce emissions by 87.6 kg PM_{10}/t CO_2e reduced. Similar calculations were made for SOx, NO_x, CO, and nonmethane hydrocarbons. Table 4 contains the emission factors employed, and they are based on data from many nations, mainly Organisation for Economic Co-operation and Development (OECD) countries. Simple assumptions were used to convert from tons of emissions avoided to changes in atmospheric pollutant concentrations, which were then used to estimate associated health co-benefits.

Local air quality co-benefits of renewable energy combined with energy efficiency have also been studied in South Africa and Thailand, among other countries. Combining renewables with efficiency makes it challenging to isolate and compare effects of renewables. Moreover, co-benefits from using renewables vary dramatically by type and location of renewable energy sources and therefore must be evaluated on a location-specific basis. In addition, the sources of emission factors used in studies are taken from numerous sources, typically from developed countries.

CARBON CAPTURE AND STORAGE

CCS is often considered for use in coal- and gas-fired power plants as a way of reducing CO_2 emissions. An illustration of the many studies that have examined non-CO_2 environmental consequences associated with CCS is one comparing three types of power plants with and without CCS. The CCS technologies were found to offer some co-benefits for air pollution via the co-capture of SOx. However, the study argued that current CCS systems have significant negative impacts on power-plant-level consumption of fuel and chemical reagents, as well as on solid wastes and other environmental emissions relative to a similar plant without CCS. As an example of impacts on local air pollutants, the study found that for the three types of power plants using CCS, the NO_x emissions increased by between 0.1 and 0.18 kg/MWh.

A 2012 review paper examined 17 post-2000 CCS studies that used different approaches and varied across three capture technology routes—postcombustion, oxyfuel and precombustion. Most of the reviewed studies involved OECD countries but several took a global approach. Even though technologies and assumptions differed across the studies, the analysts reached the following conclusions: regardless of capture options or fuel used, an increase in other environmental impacts accompanied the use of CCS to make significant reductions in global warming potential. This typically occurred because of the loss in efficiency and the corresponding additional demand for fuel and operating materials (for example, solvents).

POLICY IMPLICATIONS

In terms of the relative contributions of different sources, using renewables to replace fossil fuels (especially coal) will offer relatively high local air quality co-benefits; and relatively notable reductions would also accompany use of energy efficiency to reduce demand for electricity generation.

In comparison to other developing countries, studies of air quality co-benefits in China are the most prominent in the literature. The large number of energy-related Chinese CDM projects has provided opportunities for estimating co-abatement rates. As one of the CDM-based Chinese co-benefits studies indicated, wind (compared with hydro and other renewables) is a particularly important energy source in terms of reducing local air pollution in China.

The results above also demonstrate the significance of local context in affecting co-benefits outcomes. Local context is especially important when it comes to renewables. More generally, major differences exist in models and underlying assumptions, and it is challenging to identify all key assumptions because the presentations are often opaque regarding modeling details.

Finally, CCS represents a significant step toward cutting GHG emissions. However, challenges currently exist in using CCS because of the potential adverse environmental consequences, especially in terms of conventional air pollutant emissions and local air quality impacts.

Buildings

Buildings account for about 6 percent of 2010 global GHG emissions. The sector’s emissions arise from on-site energy generation and fuels burned for heat in buildings and cooking in homes. The 6 percent figure does not reflect emissions from electricity use in buildings; those emissions are included in the energy sector. Techniques to improve building energy efficiency include, for example, better insulation; more energy-efficient systems for heating, cooling, ventilation, and refrigeration; and passive heating and lighting to take advantage of sunlight. In the context of developing countries, improvements in efficiency of biomass-burning stoves used for household cooking and heating offer major opportunities for cutting emissions of both GHGs and local air pollutants.

BUILDING ENERGY EFFICIENCY PROGRAMS

Building energy efficiency can be improved by making changes in building materials and designs, lighting, appliances and heating and ventilating systems to deliver the same, or comparably satisfactory, levels of performance for less energy input.

The extent to which energy efficiency in buildings actually cuts energy consumption has been debated because of what is termed the "rebound effect": the increase in energy consumption observed when energy is used more efficiently. The concept is intuitively clear: for example, if energy efficiency improvements in air conditioners make them less expensive to operate, people might run them longer during heat waves. Notwithstanding the clarity of the intuitive explanation, the literature demonstrates considerable "confusion around what the rebound effect is exactly, how to estimate it, and how to interpret the results."

In the context of energy efficiency in buildings, much of the literature (including rebound effects' studies) concerns households in developed countries. For example, a 2009 review of empirical literature found that for household energy services in OECD countries, "the direct rebound effect should generally be less than 30 percent" of anticipated reductions in energy use. Rebound effects in developing countries would likely be larger because of unsaturated demand for energy services. In any case, positive social welfare benefits (for example, improvements in health and comfort) are typically associated with the additional energy used.

A key concept in determining how energy efficiency links to air quality co-benefits concerns diverted fossil fuels: every unit of energy not used because of a more efficient building material, appliance or other device has its equivalent in a unit of fossil fuel that need not be used. A central question concerns the fossil fuel sources that would be displaced if energy efficiency cut the need for generating capacity. As mentioned in the discussion of renewable energy, modeling tools provide one approach to estimating fossil fuel use avoided. As an example, modeling techniques developed by Synapse Energy Economics were employed to determine air pollution emissions avoided by building schools that use 34 percent less energy due to more efficient equipment and better designs. That study estimated annual emission reductions per school, and they were converted to co-abatement rates: 2.05 kg NO_x/t CO_2, 2.23 kg SO_2/t CO_2, and 0.26 kg PM_{10}/t CO_2.

A wide range of cost savings have been reported for household energy efficiency improvements. For example, the monetary value of air pollution co-benefits was estimated in a 2003 synthesis based on numerous studies of households participating in the US Weatherization Assistance Program. The reduction of air pollutants was due to the decreases in burning of fossil fuels, either in the home (for example, natural gas) or at central power stations to produce electricity. Associated benefits included improvements to human health and ecosystems and decreases in deterioration of building exteriors. The study relied on values in the literature to arrive at the following figures for present value per household in 2001: point estimate of $869, and range $68 to $67,000. This enormous range of values was explained by noting differences in geographic contexts as well as the absence of a standard procedure for estimating these types of co-benefits.

A 2016 study estimated that increasing insulation to International Energy Conservation Code 2012 levels for all single-family homes in the US in 2013 would reduce 110 million tons of CO_2 annually. Average monetized values of local air quality and health improvement co-benefits ranged (by state) from $12 to $390 per ton of CO_2 with an average value of $49 per ton. Several empirical studies have also been conducted of residential energy efficiency programs in the UK, New Zealand and Switzerland.

Few of the building energy efficiency studies found in this review of the literature concerned developing countries. A study of energy efficiency measures in China’s residential sector was conducted, but results for local air quality benefits were not presented clearly. Another study used interviews to examine co-benefits of an insulation retrofit subsidy program in Chile and found, in qualitative terms, significant perceived benefits in terms of outdoor air quality improvements. A study in India examined co-benefits from building energy efficiency but did not separate effects of enhanced efficiency in buildings from improved transport systems and it did not provide quantitative co-abatement rates. Many studies of energy efficiency in the building sector have been included in analyses of policy scenarios involving multiple sectors, and some of those studies are discussed later in this paper. However, as in the case of the aforementioned study of building energy efficiency in India, the papers describing multiple sector scenarios generally do not isolate co-benefits for the different types of interventions (for example, energy efficiency in buildings vs. enhanced public transport and so on.).

BIOFUEL COOKING STOVES

As of 2016, about 2.7 billion people relied on traditional biomass (for example, fuelwood, dung and agricultural residues) for cooking, mainly in rural areas in developing countries. Residential solid fuel burning releases a complex mix of health- and/or climate-damaging pollutants. These include GHGs as well as indoor air pollutants that add significantly to morbidity and mortality, such as CO, PM, NO_x, benzene, and hundreds of different types of hydrocarbons. The emphasis in the relevant literature is on air pollution and health, but increasing attention is being given to the influence of cookstoves on climate change.

Studies of impacts of improved cooking stoves on air quality are illustrated by research in China comparing emissions from solid fuel combustion in a recently developed under-fire heating stove and a typical traditional over-fire version. For six tested fuel types (for example, anthracite and bituminous coal and biomass), average pollutant reductions were about 50 percent for CO_2, 79 percent for $PM_{2.5}$, and 66 percent for eight toxic elements (for example, lead copper and cadmium) in $PM_{2.5}$. Scores of studies of this type have been conducted.

Biomass stove improvements that reduce GHG emissions at the same time as improving indoor air quality are important in terms of saving lives and improving development. However, a 2015 descriptive review of 36 studies of cooking stoves interventions in natural settings in developing countries found that single interventions (for example, provision of stoves) are unlikely to reduce pollution to meet World Health Organization recommended standards if made without supplemental measures. Notwithstanding that complex sets of simultaneous interventions may be needed, research attention to multicomponent interventions has been limited.

Indeed, a 2016 assessment of a cookstove intervention program in India yielded counterintuitive results. It shows that black carbon reductions were smaller in households that received improved cookstoves as compared with a control group. Researchers suggest that this may be due to "snapback" effects with greater usage of cooking stoves or field performance of stoves that did not match laboratory effects. Results suggest that considerable effort is still needed to create household-level interventions effective in cutting PM emissions.

POLICY IMPLICATIONS

The literature on co-benefits linked to the building sector highlights a number of important gaps. The main quantitative studies of co-benefits in this sector have been for building energy efficiency programs in developed countries, and these generally do not report co-abatement rates for air pollution co-benefits. Moreover, while the developed country studies of building energy efficiency provide monetary estimates of air quality co-benefits, the values vary greatly because of differences in location and study methodology.

Another gap in the air quality co-benefits literature concerns the absence of co-abatement rates for cooking stoves. The emphasis in the cooking stove co-benefits literature is on air pollution improvements and corresponding health impacts. However, billions of people in the developing world rely on biomass for cooking, and, according to a 2011 World Bank study, in some regions, "biomass for household fuel use can be a net contributor to global warming since all biomass harvested for household fuel use is not renewable." There is an ongoing scientific debate about the flaws in the argument that burning fuelwood is carbon neutral because the GHGs from burned wood will be offset by new forest growth. The weakness in the assumption of carbon neutrality is that there is "no assurance [at] all that carbon will wind up back in trees and the ground because logged land could be put to other uses, new forests might be managed differently than the ones they replaced, and insect infestations or droughts could make it hard to reestablish trees."

There are few detailed studies of the quantitative effects of improved cookstoves on GHG emissions. That kind of information would enable a more complete assessment of cookstove improvements, including not only air quality–related health impacts but also climate change mitigation effects. Many cookstove improvement projects already have favorable benefit-cost ratios, but those ratios would be even higher if reductions in emissions of both conventional air pollutants and GHGs were taken into account.

Industry

In 2010, industry accounted for 21 percent of global GHG emissions. These mainly involved fossil fuels burned on-site for energy at industrial facilities. Other emissions from the industry sector are from chemical, metallurgical, and mineral transformation processes not associated with energy consumption. The 21 percent figure does not include emissions from electricity use, which are instead viewed as part of the energy sector.

Co-benefits in industry have been a subject of study in several countries, including India and Thailand, among others. However, the largest and most sophisticated segment of the industrial sector co-benefits literature (and thus the emphasis in this section) concerns China. A study of industry in South Africa is also discussed because it introduces notable trade-offs between GHG reductions and possible increases in conventional air pollutants.

CHINA

Cement is the most widely covered item in the co-benefit studies of China's industries. As an example, a spatially disaggregated study of China's cement industry was conducted using a geographic information system coupled with the GAINS model. Energy efficiency measures in cement and clinker production were found to have the potential to decrease 38 percent of CO_2, 23 percent of SO_2, 33 percent of NO_x, and 26 percent of PM emissions by 2020 in the seven key provinces engaged in the sector. In a follow-up study, co-benefits (including air pollution reductions and health improvements) were found to be about twice the cost of energy efficiency measures. As another example, a study of 23 control measures (for example, use of high efficiency motors) that could have been applied at 16 cement plants in Shandong Provence in 2008 were estimated to have had the following potential co-abatement rates: 1.08 kg PM/t CO_2 and 5.15 kg SO_2/t CO_2.

The steel sector in China is also important in terms of global CO_2 emissions and it has received attention from researchers. For example, one study used an advanced form of a MARKAL model (called the "China-TIMES" model) to analyze a BAU steel sector scenario and three alternative carbon mitigation scenarios for 2010 to 2050. Results from this study are illustrated by the "carbon tax scenario": an increasing carbon tax of \$15–80/t CO_2 (2015–50) plus "more effective application" of the 28 energy saving and emission reduction technologies in China's steel sector in the BAU scenario (for example, recovery of waste heat during hot-rolling). Relative to BAU, the carbon tax scenario in 2050 would potentially provide the following co-abatement rates: 1.20 kg SO_2/t CO_2, 0.57 kg NO_x/t CO_2, and 0.21 kg PM_{10}/t CO_2.

Additional examples include an analysis of co-benefits of possible projects to improve efficiency in the industrial sector in China's Shanxi Province. Project types involved: co-generation, boiler replacements, improved boiler management and briquetting. As an illustrative study output, co-abatement rates for co-generation were: 8.67 kg SO_2/t CO_2 and 4.00 kg TSP/t CO_2. Other results from the Shanxi study are shown in table 5.

For the whole of China, a 2006 review of 24 studies involving different types of interventions (including individual projects and scenarios based on actions covering multiple sectors) reported the median and 15/85 percentiles for co-abatement rates. The results are summarized in table 6 for two groups of studies: all 24 studies reviewed, and the subset of studies for boiler improvement projects only. The boiler improvement projects are relevant to both the energy and industry sectors.

Still other relevant studies of industry in China include modeling to forecast co-benefits of: energy efficiency measures in China's ammonia industry; reduction of coal use in multiple sectors (including industry); improvements in industrial sectors in the Yangtze River Delta and Shanghai's Baoshan District; and waste reduction and recycling.

SOUTH AFRICA

A study of industries in Durban, South Africa is notable for highlighting the need for improved coordination between officials managing conventional air pollutants and those addressing energy policies. The study indicated that petroleum refining industries in the region switched from using predominantly heavy fuel oil (3.5 percent sulfur content) in heaters and boilers to using refinery gas (0.0001–0.015 percent sulfur content) and methane rich gas (0.0003–0.0008 percent sulfur content). In doing so, the refining industries were able to cut their SO_2 emissions from fuel combustion sources significantly over the period from 2002 to 2008. However, fuel switching to meet air quality goals also led to an increase in CO_2 emissions at the very end of that period.

Another illustration of linkages between air quality goals and GHG emissions in the Durban area concerns the use of “scrubbers” and other end-of-pipe air pollution control technologies to meet air quality targets. Industries made considerable progress toward meeting SO_2 ambient air quality requirements by switching to coal with a lower sulfur content, but that proved insufficient to meet SO_2 targets. Many operations found that meeting the SO_2 targets required scrubbers. The combination of using a lower sulfur coal as well as scrubbers and other pollution control devices contributed to cuts of up to 70 percent in SO_2 from certain industrial facilities. However, energy needed to operate the air pollution control devices increased fuel use by 1 to 3 percent, thereby adding additional GHG emissions, particularly from industrial facilities using carbon-based fuels.

One of the main points of the Durban study was that relationships exist between meeting SO_2 targets set by local air pollution control authorities and reducing GHG emissions. At the time of the study (2011), air quality and energy policies in Durban were executed independently, without consideration of the trade-offs or synergies of interventions being implemented. The study urged a much higher degree of coordination among officials concerned with local air quality and energy policies.

The opportunities associated with a more coordinated approach to air quality and energy policies are demonstrated in a study of the Seoul, South Korea, metropolitan area. Using optimization modeling techniques, the study produced a scenario that achieved goals for both air quality improvement and CO_2 reduction at a minimum cost. The study emphasized that for megacities in developing countries facing significant air quality problems and having limited resources, the cost savings attainable by an integrated approach to managing conventional air quality and GHG emissions simultaneously could be significant.

POLICY IMPLICATIONS

Of all the co-abatement rates for the China-related studies noted in this section, the largest are for coal washing and briquetting (table 5). The boiler-project related rates are smaller, but also significant. The 15/85 percentile spreads of values reported in table 6 are also notable.

Notwithstanding the range of values reported, the monetized values of health-related co-benefits were greater than the project costs for many of the projects studied. The challenge is that the costs are paid by enterprises and the benefits are spread among the population that would breathe less polluted air. Therefore, the societal advantages of these projects may not be recognized and accounted for by enterprises considering the projects.

The work in South Africa demonstrates that there are unexploited opportunities for cost savings in improving air quality and cutting GHG emissions because policies for air quality management and energy are often not well coordinated. Moreover, tensions may exist inasmuch as policies that are effective at reducing conventional air pollutants may wind up increasing GHG emissions and vice versa. Improved coordination between energy and air quality officials would at least recognize the possibilities for synergies that are present and the trade-offs that may need to be made.

Transportation

In 2010, transportation accounted for 14 percent of global GHG emissions. These mainly involved fossil fuels burned for road, rail, air, and marine transportation. About 95 percent of the world's transportation energy comes from petroleum-based fuels, largely gasoline and diesel.

The section first considers air quality co-benefits of strategies for decarbonizing the ground transport sector. This is followed by a discussion of air quality–related health co-benefits of transport emission reductions linked to decarbonizing strategies.

GROUND TRANSPORTATION

Road transport scenario studies that examine GHG emission reductions and associated conventional air pollution co-benefits have been conducted in a number of places. Quantitative studies are discussed below, but numerical results cannot be compared meaningfully because studies employ different time frames and report results in varying formats and units (for example, percent emission reduction, kg of pollutant/t CO_2, and change in pollutant concentration in $\mu g/m^3$).

A 2016 paper surveyed co-benefit modeling studies that estimated quantitative environmental and health co-benefits for scenarios that encouraged mode shifts to public transport. Using a set of criteria to select from papers published from 2004 to 2015, a total of 153 transport-air quality–related articles were identified for further study; about half were qualitative, only nine satisfied all selection criteria, and only five included air quality issues involving developing countries. Those five studies are noted below to illustrate the kinds of results available from co-benefits studies in the transport sector.

- Delhi—An extension of the Delhi Metro was proposed to increase ridership. An analysis using a "first-order screening tool" determined potential co-benefits in terms of CO_2 reductions and cuts in local air pollution. Assuming all anticipated mode shifts took place, potential co-abatement rates were: 1.99 kg PM_{10} /t CO_2, 80.4 kg CO/t CO_2, 17.7 kg NO_x/t CO_2, and 23.9 kg hydrocarbon/t CO_2.
- Indonesia—An analysis of co-benefits associated with proposed improvements in the quality of the Trans-Jogja bus system in Yogyakarta Special Region Province, Indonesia used conventional transportation air-quality analysis procedures and assumptions about emission factors associated with projected system changes. Potential co-abatement rates for 2010–24 were as follows: 2.58 kg PM_{10}/t CO_2, 47.2 kg CO/t CO_2, 15.1 kg NO_x/t CO_2, and 1.09 kg SO_2/ t CO_2.
- Malaysia—Information on the national automotive fleet in Malaysia (for example, fuel consumption, and average speed for several vehicle categories) was used to analyze four emission reduction strategies. They involved changes of 10 percent in users of: passenger cars shifting to public transport, motorcycles shifting to public transport, and passenger cars shifting to natural gas vehicles. The fourth scenario assumed that 10 percent of vehicle renewals would meet Euro 4 emission standards. The following is a typical form of the results: "With renewal of 10 percent in the oldest [passenger] cars, the CO, NO_x, and hydrocarbon emissions can be reduced to 88.5 percent, 89 percent and 89.4 percent, respectively from the baseline [year, 2007]."
- Mexico City—Two studies involved Mexico City. One assessed a baseline scenario and two climate change mitigation scenarios. Results showed a decrease in both conventional air pollutants and CO_2 emissions if a bus rapid transit system is introduced along with strict standards for vehicle emission controls and fuel economy. A second Mexico City assessment relied on prior air quality management studies to evaluate five pollution reduction options, three of which involved transport: taxi fleet renovation, extension of the metro network and introduction of hybrid buses. Implementation of all three transport measures was projected to cut PM_{10} exposure by almost 1 percent (0.52 $\mu g/m^3$), maximum ozone

exposure by nearly 3 percent (4.02 μg/m^3), and CO_2e emissions by more than 620,000 tons per year.

The aforementioned 2016 literature review said little about air quality co-benefits in the above-noted studies apart from pointing out limitations. For example, the review mentioned that the output parameter "vehicle distance traveled" underestimated emissions from vehicles trapped in congestion and traveling at low speeds.

Another dimension of the transportation-climate change literature concerns air-quality effects from use of biofuels (for example, ethanol) in motor vehicles. As the discussion in the agriculture section below makes clear, the effectiveness of biofuels in reducing GHGs is a controversial subject. In addition, a 2016 study of ethanol in motor vehicle fuel in São Paulo State, Brazil argued that evidence on whether air quality is improved or degraded by use of ethanol is still unclear, partly because of "marked sensitivity to the vehicle studied (age and type), operating conditions and blend ratio, and possibly to the biofuel's feedstock crop."

HEALTH CO-BENEFITS RELATED TO TRANSPORT EMISSIONS

Health impacts receive considerable attention in the transport co-benefits literature. Three main sources of transport-related health co-benefits have been identified: improvements in air quality; increased physical activity from "active travel" (that is, walking and cycling); and reduced traffic injury. Only the first category is considered here because the others have not been tied directly to conventional air pollutants. In general, evidence exists that public health and associated economic co-benefits related to GHG mitigation strategies are substantial and probably underestimated because of difficulties in quantifying health impacts.

Typical approaches to estimating health co-benefits (but not generalizable findings) are illustrated by a comparative risk assessment of ground transport scenarios in London and Delhi. For each city, a BAU 2030 scenario (which lacked policies to cut GHGs) was compared with alternative scenarios: lower-carbon-emission motor vehicles, increased active travel, and a combination of the two. Mathematical modeling was used to link changes in air pollution with the transport scenarios. A strategy that combined active travel and lower-emission motor vehicles was found to give the largest benefits (7,439 disability-adjusted life-years in London, and 12,995 in Delhi). The health burden from urban outdoor air pollution would decrease if lower-emission vehicles were used in both cities, but reductions in distance traveled by motor vehicles were expected to have a greater effect. Several articles provide additional examples of this type of study; many analyses of transport GHG reductions emphasize the health-related co-benefits of active travel.

A 2014 literature review examined empirically-based ex post studies of health co-benefits of urban transport GHG mitigation interventions. Notwithstanding that the review used keywords in 12 standard databases for papers published from January 1992 to March 2011, the authors found only 13 studies that provided empirical evidence for co-benefits (as opposed to assertions based on ex-ante modeling studies of the type described above). They found 12 of the 13 studies to be seriously flawed.

The only study that the 2014 review considered valid involved the "The Stockholm Trial," a set of changes in Stockholm during six months in 2006 that consisted of: new bus lines, a congestion tax, and more park-and-ride sites. The main empirical work involved counting vehicles to measure traffic flow and calculating the number of vehicle-km traveled in affected areas before, during, and after the trial changes. Account was taken of traffic increases outside the congestion tax zone when calculating emission reductions. Emissions were calculated based on emission factors. Dispersion models were used to compute concentrations, and these were checked against field measurements. Overall, in the inner city, traffic-related CO_2 emissions dropped by about 14 percent during the trial, and annual average cuts in population-weighted concentrations were 10 percent and 7.6 percent for NO_x and PM_{10}, respectively. It was estimated that "206 years of life would be gained over 10 years per 100,000 people following the trial if the effects on exposures were to persist."

POLICY IMPLICATIONS

A major complexity in comparing results from different studies concerns the use of varying units to report outcomes. The Malaysia study reported results in the form of percent of emission reductions for conventional pollutants. The Mexico City studies reported results in terms of percentage of reduced exposure to conventional pollutants and changes in pollutant concentration in $\mu g/m^3$. Results of studies in India and Indonesia were in the form of co-abatement rates (kg of conventional pollutants decreased/t of CO_2 reduced). Comparisons among study outcomes are also made complicated by variations in local context, data available, modeling methods used and assumptions made.

Numerous studies have emphasized the reductions in morbidity and mortality linked to changes in transport systems, including health benefits of local air pollution reductions that accompany efforts to cut GHG emissions by improving mass transit systems. Estimates of health benefits from decreased air pollution associated with transportation are often difficult to isolate, however, because air pollution in cities results from many causes, not just transportation. That said, relationships between changes in transportation systems and health co-benefits have been documented. For example, one review paper isolated papers describing how improved air quality will reduce respiratory illnesses. But that study, along with other similar studies also emphasize the health co-benefits associated with reductions in "lifestyle" diseases, such as obesity, cardiovascular disease, and social isolation. In short, while some of the health co-benefits are a result of reduced conventional air pollution, others are linked to land use/transportation system changes that encourage walking and cycling instead of relying on motor vehicles.

Solid and Liquid Waste

GHG emissions from wastewater and postconsumer waste contribute about 3 percent to total global anthropogenic GHG emissions. About 90 percent of waste sector emissions come from methane (CH_4) in landfills and wastewater treatment facilities, collectively. Methane is a particularly potent GHG: pound for pound, the comparative impact of CH_4 on climate change is more than 25 times greater than CO_2 over a 100-year period, and its impacts (compared with CO_2) are even greater over shorter time frames.

SOLID WASTE

The literature on solid waste management strategies to reduce GHG emissions emphasizes mitigation in the context of three technologies:

- Landfilling—capture and use of CH_4 within landfill gas for either electricity generation or combined heat and power (CHP) production.
- Incineration—direct use of energy recovered from waste incineration for electricity generation or CHP production.
- Anaerobic digestion—recovery of released gas (60-70 percent CH_4) for use as fuel or to generate electricity in biogas power plants.

In addition to reducing GHG emissions and providing associated local air quality co-benefits, by capturing CH_4 these technologies provide a renewable energy resource.

Open dumping and sanitary landfilling without gas recovery are common solid waste disposal methods in many developing countries, and those approaches result in significant releases of CH_4. Well-designed and operated sanitary landfills with gas recovery systems provide opportunities to generate renewable energy. A paper on Muangklang Municipality, Thailand, focuses almost entirely on GHG reduction. However, it makes a convincing qualitative argument that local air quality co-benefits from improved solid waste management with gas recovery would result since renewable energy would displace the burning of fossil fuels in producing electricity.

Much of the literature on co-benefits of modifying solid waste management systems emphasizes reducing GHGs (referred to in this context as "climate change co-benefits"), not improving local air quality. Examples of climate change co-benefits studies exist for

China; Malaysia; Vietnam; and Thailand. The health co-benefits of improved municipal waste management in cutting CH_4 and black carbon have been estimated by Robinson.

Determining local air quality co-benefits as a result of fossil fuel displaced by energy captured from waste management systems requires analyzing existing energy generating production systems and operating rules to determine benefits from displaced fossil fuel generation. In that sense, some steps involved in estimating co-benefits are similar to those used in determining co-benefits from energy efficiency and renewable energy.

The general approach involved is demonstrated in a study to determine air quality impacts from using biomass and incineration facilities at the Stockholm district heating utility run by Fortum, a major Scandinavian energy company. The study found, for example, that a biomass CHP unit (currently under construction) would cut fossil fuel use at other facilities, yielding: a net reduction of 158 kt/yr of CO_2, no overall change in SOx, and a total increase in NO_x of 178 t/year (much of which would be outside the high-density service area). The study also found that when two plants – the above-mentioned biomass CHP plant and a proposed incineration CHP unit – are introduced in Stockholm, systemwide NO_x emissions are reduced, but SOx emissions remain the same. The study emphasized that the "impact of waste incineration and biomass CHP plants is strongly connected to existing production," …. [and] which existing production plant is replaced."

WASTEWATER

Notable GHG emissions also accompany wastewater treatment plant operations. Energy used to run plants generates CO_2 and CH_4, and treatment unit processes release CO_2, CH_4 and N_2O.

Co-benefits studies of wastewater treatment plants do not emphasize local air quality co-benefits; instead they focus on identification and reduction of GHG emissions. Assessments of how best to cut GHG emissions from municipal sewer treatment plants are illustrated by studies of Jordan and Mexico. More generally, many GHG reduction studies have been conducted for both municipal and industrial wastewater treatment facilities. Use of captured CH_4 to generate electricity cuts in GHG emissions would be accompanied by local air quality co-benefits, but those co-benefits were not often mentioned in the studies of GHG reduction in wastewater treatment plants that were reviewed. For example, a study of sewer treatment in Surat, India demonstrated that CH_4 capture and use generated significant quantities of electricity, but no attempt was made to estimate local air quality co-benefits.

POLICY IMPLICATIONS

The possibilities for generating local air pollution co-benefits by capturing GHGs after converting from open dumping sites and basic landfills to sanitary landfills or incinerators with the ability to capture and use GHGs for electricity production have not been well documented in the co-benefits literature. Indeed, much of the attention related to co-benefits and solid waste management has been directed at demonstrating possibilities for GHG reduction.

The literature on co-benefits in wastewater management also focuses on GHG reduction. As in the case of solid waste management, capture of GHGs during wastewater treatment to generate electricity would result in displaced use of fossil fuels in electricity generation, with consequent air quality co-benefits. More generally, a gap exists in the literature on co-benefits in solid and liquid waste management in developing countries inasmuch as the quantitative, local air quality benefits have not been carefully investigated.

Agriculture

In comparison to other sectors considered in this paper, the agriculture sector and the one considered in the section below on "forestry and other land use" are unique because climate change mitigation potential is derived from two (sometimes overlapping) sources: (i) decreases in global atmospheric carbon that occur because of the ability to capture and store (sequester) carbon in vegetation and soils; and (ii) reductions of GHG emissions.

Because agricultural land is often created by clearing forests, agriculture, forestry and land use change are often combined in doing accounting for sectoral contributions to GHG emissions. Using that combined framework, agriculture, forestry and land use change contributed around 24 percent to global annual emissions in 2010. GHG emissions from this combination of sectors come mostly from agriculture (cultivation of crops and livestock) and land use change that involves converting forested land to agriculture and other uses. Forested land is a key GHG sink.

CARBON SEQUESTRATION AND REDUCTIONS IN GHG EMISSIONS

Carbon sequestration methods include the following:

- Agroforestry; that is, integration of trees and shrubs on agricultural land.
- Restoration of degraded lands (for example, using nutrient amendments).
- Improved management of cropland and grazing land.

- Changes in land use and cropping patterns that increase soil carbon.
- Conservation tillage.
- Production and use of “biochar.”

Notable options for reducing agricultural GHG emissions include the following:

- Reduced frequency or intensity of on-farm biomass burning.
- Abatement of emissions from livestock (for example, dietary management of cattle to cut CH_4 emissions and manure management to decrease N_2O and ammonia releases).
- Improved fertilizer management.
- Use of agricultural biomass as a substitute for fossil fuels in energy production.
- Reduced on-farm fuel consumption.
- Enhanced water and rice management.
- “Set-asides” (that is, allowing cultivable land to revert to vegetation similar to native cover).

The effectiveness of agricultural GHG reduction practices differs among climate regions and even across sites within a region, and there is no universally applicable set of agricultural GHG mitigation practices. A 2007 IPCC report summarizes the possible co-benefits (including water quality and soil quality) and trade-offs for over 20 mitigation options in agriculture.

The 2007 IPCC report also lists the following practices as often improving water quality: nutrient and fire management; use of set-asides and land use changes; restoration of degraded lands (for example, via erosion control and nutrient amendments); and efficient use of manure as a nutrient source. The summary also lists the following as generally improving local air quality: nutrient management; set-asides and land use changes; anaerobic digestion of manure and bio-solids; and more efficient use of manure as a nutrient source.

Many measures aimed at reducing GHG emissions from agriculture are adopted for reasons unrelated to climate change mitigation. For example, avoiding erosion and improving soil structure are measures undertaken to enhance agricultural productivity, and they also promote carbon sequestration. Such productivity enhancing measures may also have negative environmental impacts. As an illustration, measures to enhance wheat yields in Australia simultaneously increased rates of acidification and salinization of soil and reduced stream quality.

BIOFUELS

The existence of both positive and negative effects of GHG mitigation efforts in agriculture is made clear in studies of biofuels. Many life cycle assessments (LCAs) have claimed a net reduction in fossil energy consumption and GHG emissions when bioenergy replaces fossil energy. However, these studies have been questioned for ignoring the GHG emissions associated with conversion of forest and grassland to new agricultural use by farmers who replace cropland diverted for use in producing biofuels. For example, a study using a worldwide agricultural model to estimate GHG emissions from such land use changes found that corn-based ethanol, instead of producing a 20 percent savings in GHG emissions (as expected without considering land conversions), would nearly double GHG emissions over 30 years. This concern regarding land conversion would not apply, however, if the biofuels used as feedstock involved waste products or carbon-poor lands.

Life cycle studies of bioenergy typically do not consider issues related to local air quality changes. A 2011 review of 74 LCAs for bioenergy found that few of the reviewed LCAs provided any information about changes in local emissions of conventional air pollutants. Also, in a 2013 analysis, only two of the 19 reviewed LCAs of biofuel considered environmental impacts unrelated to GHGs, and both studies were tentative about those impacts. In particular, a study accounting for water use impacts in an LCA of biofuels in Argentina identified water consumption as a potential major concern that could offset GHG mitigation benefits of biofuel use. A second LCA indicated general concerns about increases in acidification and eutrophication linked to biofuel production.

POLICY IMPLICATIONS

As a sector, the analysis of local environmental co-benefits in agriculture is complex for two reasons: (i) the effectiveness of agricultural GHG reduction practices depends on location-specific variables and thus there is no universally applicable set of agricultural GHG mitigation practices; and (ii) with the exception of biofuels, measures that provide co-benefits in the agriculture sector may be undertaken for reasons unrelated to climate change. More generally, co-benefits studies in the agriculture sector do not contain quantitative estimates of the type found in the sectors above: energy, buildings, industry, transportation and waste management.

The subject of biofuels is controversial for a number of reasons, not the least of which is the debate within the biofuels LCA literature on whether biofuels yield net reductions in GHGs. In addition to issues tied to land conversion and GHGs (for example, farmers replacing cropland diverted to biofuels), biofuels as a policy has elicited debate on its impact on food security, food prices and poverty in general.

Forestry and Other Land Use

When forests are cut down, two things happen: (i) carbon absorption by trees and other vegetation stops, and (ii) the carbon stored in the removed trees and vegetation is released into the atmosphere as CO_2. This release takes place quickly if the wood is burned and gradually if it is left to rot after the deforestation process. Logged wood used in construction and wood products retains the sequestered carbon.

Forests currently contribute about one-sixth of global carbon emissions when cleared, overused or degraded; and they have the potential to absorb and store about one-tenth of global carbon emissions projected for the first half of the 21st century into their biomass, soils and products.

MITIGATION MEASURES AND CO-BENEFITS

Three main types of mitigation projects exist for the sector:

- Afforestation (that is, converting long-time nonforested land to forest)—This strategy, which often involves planting monocultures, can increase carbon storage rates. However, planting trees where they were not present recently can lower groundwater tables and cause soil erosion on hill slopes. Moreover, afforestation generally reduces streamflow because trees use more water than grass or crops. If afforestation includes the addition of nitrogen fertilizer, emissions of N_2O may increase.
- Reforestation (that is, converting recently nonforested land to forest)—This is generally done by planting near-native species and focusing on restoration of "nature like" ecosystems. A defining difference between afforestation and reforestation is the period during which the land was without forest.
- Avoided Deforestation—This approach protects existing forest carbon stocks by avoiding the conversion of forests to nonforest land. Deforestation is the source of a multitude of changes in both air and water quality, many of which are widely considered as adverse.

Significantly, the (often illegal) practice of intentionally burning forests (or forest residue) to clear land for agricultural purposes is a direct source of emissions of both GHGs and conventional air pollutants. Although effects at a global level are not fully quantified, the associated GHG emissions from using fires in the process of clearing forests for agriculture is of mounting concern, especially in the tropics. Avoiding the burning of forests to clear land for agriculture eliminates the fire-related GHG emissions and maintains continued use of forests to sequester carbon.

Afforestation and reforestation generally cause small yearly changes in carbon stocks over long periods, but not engaging in deforestation has immediate positive impacts by retaining stored carbon. Avoiding deforestation also preserves biodiversity and protects watershed and soil quality. In addition, avoiding deforestation eliminates drawbacks associated with monoculture plantations, which are often favored in afforestation and reforestation projects.

The United Nations' program on Reducing Emissions from Deforestation and Forest Degradation (REDD) represents a key strategy to mitigate climate change impacts in the forest and other land use sector. "REDD+" strategies go beyond avoiding deforestation and forest degradation by including roles for conservation, sustainable management of forests and enhancement of forest carbon stocks in reducing GHGs. The literature on REDD and REDD+ characterizes the major environmental co-benefits of those approaches as conservation of biodiversity and ecosystem services (for example, avoiding adverse effects on water quantity and quality). However, the extent to which REDD+ approaches can deliver co-benefits is context-dependent.

An example of a study that examined water quality when deforestation was avoided involves Tapantí National Park in Costa Rica. In comparison to deforested watersheds near the park, the amount of sediments in the river flowing from Tapantí National Park was five times lower; this provided an important advantage in terms of use of the river for drinking water.

Air quality co-benefits are also discussed in the forest sector literature, primarily in the context of maintaining forests and tree cover in and near cities. For example, a study in Bangalore, India compared segments of roads with and without trees to identify air quality differences linked to the presence or absence of street tree cover. In addition to having lower temperatures, streets with tree cover also had significantly lower values of SO_2 and TSP.

As another example, a study in Barcelona, Spain found that maintenance of urban forests in the city contributed significantly to lower concentrations of PM_{10}, and to a lesser extent NO_2. In cities where urban forests decrease warm-weather street temperatures, the maintenance of urban tree cover can indirectly avoid CO_2 emissions and add to air quality co-benefits through energy saving in buildings for heating and cooling. Impacts of urban green space on air pollution and GHG emissions may be substantial in areas with notable tree cover, yet modest when compared with city-wide levels of air pollution and GHG emissions.

POLICY IMPLICATIONS

A major mitigation strategy in the forest and other land use sector is the avoidance of deforestation to both eliminate GHG emissions from forest burning and allow carbon sequestration in forested areas to continue. The REDD program and REDD+ strategies play major roles in avoiding deforestation and forest degradation.

The effects of mitigation measures in forestry on reducing conventional air pollutants are often indirect because avoiding deforestation, a principal mitigation strategy, does not involve cutting GHG emissions directly. The effects involve emissions of GHGs and conventional air pollution avoided inasmuch as the deforestation process often involves forest land conversion to agriculture and associated burning. These indirect effects on conventional air pollution are real, but the literature on quantifying effects in a way useful for policy making is not voluminous.

Maintenance of green space in and near urban areas has been linked to direct improvements of air quality in forested areas. One of the main mechanisms through which avoiding deforestation directly impacts conventional pollutants involves enhancing particle deposition on vegetation, thereby decreasing PM concentrations. Lesser reductions have also been reported for other conventional air pollutants.

The pollution-related co-benefits of climate change mitigation measures in the forest sector are situation specific, and generalizations on effects (including magnitudes of effects) cannot be made. Research on quantification of some effects (for example, effects of urban forests in cutting air pollution) is emerging.

Multiple Sector Studies

Multiple sector papers examined in this review are challenging to interpret because they report aggregate outcomes; the papers do not generally indicate contributions of individual interventions to specific reductions in either GHGs or conventional air pollutants. This makes it difficult to identify the impacts of particular mitigation measures. This section makes note of a few of the many multiple sector policy assessments for three commonly studied geographic units: cities, countries, and the Earth.

An illustrative city-level study of Beijing is notable because it demonstrates the possibilities for cutting emissions of both GHGs and local air pollutants by employing what the study termed “climate-friendly air quality management policies in urban areas.” The study used the GAINS-City model to analyze three policy scenarios for Beijing: baseline, “Air Quality,” and “Strict Air Quality” for 2005, 2020, and 2030. Five sectors were included: power, industrial processes, industrial combustion, households and transportation. A total of 77 interventions across the five sectors were ranked based on the ability to provide low-cost ways to meet both air quality and CO_2 reduction targets; highly ranked interventions were used to create the Air Quality and Strict Air Quality scenarios. An illustrative result is as follows: In 2030, in comparison to the baseline scenario, implementation of Air Quality and Strict Air Quality scenarios could result in emission reductions of 39-48 percent for SO_2, 38–42 percent for NO_x, 37–55 percent for $PM_{2.5}$ and 5–22 percent for CO_2. Other Chinese multisector air quality co-benefits studies have been conducted at the city, provincial and national levels.

An air quality co-benefits study of Nepal illustrates a country-level multisector analysis of co-benefits. The Nepal study is notable because it focused on a single policy instrument: a time-variant, nation-wide carbon tax. MARKAL software was used to create an integrated energy system model with a 2005–50 horizon. The carbon tax gradually increased from \$13/t CO_2e in 2015 to \$200/t CO_2e by 2050. The tax reduced cumulative emissions of CO_2e by 12 percent compared with outcomes with a reference scenario. More than two-thirds of the total GHG reduction was a result of interventions in the industrial sector, mostly due to the substitution of fuelwood for coal and improvements in energy efficiency. Another noteworthy shift was the introduction of an additional 945 MW of hydropower, in comparison to the reference scenario. Co-benefits are illustrated by results for the carbon tax scenario: the 2050 emissions of SO_2, NO_x, and nonmethane volatile organic compounds were projected to be cut by 12 percent, 7 percent, and 1 percent, respectively.

At the global scale, the multiple sector co-benefits literature is dominated by studies of air quality and health. As an example, a 2012 study developed several increasingly stringent policy scenarios created from combinations of 14 interventions to mitigate CH_4 (an ozone precursor) and black carbon. Examples of the mitigation interventions include: reducing gas leakage from long-distance transmission pipelines to control CH_4, and banning open field burning of agricultural waste to control black carbon. Impacts in terms of conventional air pollution parameters and health indicators were determined for each scenario. The study estimated that various combinations of intervention measures "could reduce global population-weighted average surface $PM_{2.5}$ and ozone concentrations by 3.98–4.92 μg/m3 (23.0–33.7 percent) and 4.71–11.0 ppb (6.5–17.0), respectively, and avoid 0.6–4.4 and 0.04–0.52 million annual premature deaths globally in 2030."

Environmental co-benefits studies that involve multiple sectors are useful for many purposes, but the papers reporting on the studies provide only limited information on the ways in which interventions produce co-benefits. As mentioned, those papers typically report aggregate values of local air pollutant reductions, but they do not link those reductions to particular interventions.

Short-Lived Climate Pollutants

SLCPs have a strong influence on global climate change, and have relatively brief atmospheric lifetimes. The main SLCPs include black carbon, methane and tropospheric ozone, and they are key anthropogenic contributors to the global greenhouse effect.

In terms of co-benefits, black carbon and ozone are particularly concerning because they are linked to major adverse health effects. Black carbon is not a GHG, but it is a major climate warmer. Black carbon consists of small, dark particles that affect the way the sun's rays are absorbed and reflected. The small particle size of black carbon is such that it is a significant contributor to $PM_{2.5}$, particles with a diameter of less than 2.5 µm. $PM_{2.5}$, is known to cause major health problems such as: respiratory and cardiovascular morbidity, including aggravation of asthma; and mortality from cardiovascular and respiratory diseases and from lung cancer. Many components of $PM_{2.5}$ attached to black carbon play a role in causing adverse health impacts; examples include organic compounds such as polycyclic aromatic hydrocarbons that are known carcinogens.

Tropospheric ozone is linked to a variety of health problems, such as chest pain, coughing, throat irritation, and airway inflammation. It also can also worsen bronchitis, emphysema, and asthma. Methane influences human health primarily through its role as a precursor in the formation of tropospheric ozone. In addition to reducing ozone formation, methane mitigation also provides an opportunity to decrease global climate change.

Black carbon is emitted directly as a result of incomplete combustion processes, including fossil fuel and biomass burning during residential and commercial combustion and transport; these sources accounted for about 80 percent of anthropogenic emissions in 2005. Other important sources include industrial processes and the burning of agricultural waste. Important regional variations in emissions exist. While Europe and the United States dominated emissions patterns in the last century, rapid future growth is expected in Asia and Africa.

Tropospheric ozone is formed by the interaction of sunlight with hydrocarbons and nitrogen oxides. Key anthropogenic sources of hydrocarbons and nitrogen oxides include motor vehicles, gasoline vapors, fossil fuel power plants, and refineries and other industries. As mentioned, methane is a precursor in ozone formation. Over 90 percent of anthropogenic methane in 2005 originated in agriculture (livestock rearing and rice production), fossil fuel production and distribution, and municipal waste and wastewater management.

Globally, emissions of methane are expected to increase, despite current and planned regulations; this is expected because of fossil fuel production that will accompany anticipated economic growth. In contrast, global emissions of black carbon and accompanying co-emitted pollutants are expected to remain relatively constant through 2030.

Many options exist for reducing emissions of black carbon and methane. A few of the methane mitigation measures are illustrated by:

- Extended recovery and utilization, rather than venting, of associated gas (and improved control of unintended fugitive emissions) from the production of oil and natural gas
- Reduced gas leakage from long-distance transmission pipelines
- Upgrading primary wastewater treatment to secondary and/or tertiary treatment with gas recovery
- Control of methane emissions from livestock, mainly through farm-scale anaerobic digestion of manure from cattle and pigs
- Intermittent aeration of continuously flooded rice paddies

Among the promising black carbon mitigation measures are the following:

- Diesel particle filters for road and off-road vehicles
- Introduction of clean-burning biomass stoves for cooking and heating in developing countries
- Replacing traditional coke ovens with modern recovery ovens, including improvement of end-of-pipe abatement measures in developing countries
- Ban of open field burning of agricultural waste

A 2012 study examined the air quality and health co-benefits of 14 specific emission control measures targeting black carbon and methane. The measures were selected because of their potential to slow the climate change rate over a few decades. The study, which took a global approach, analyzed three policy scenarios created based on a preliminary analysis of approximately 2,000 mitigation measures. Results were used to identify 14 methane and black carbon control measures expected to achieve approximately 90 percent of the climate benefits feasible for all measures under consideration. Using the 14 mitigation measures, three increasingly stringent policy scenarios were created for 2030. The first scenario included only methane control options, and the second and third scenarios added black carbon controls. Global climate models were then used to estimate ground level concentrations of various air quality parameters. These were then used to project changes in health outcomes. Key results were "that implementing all measures would avoid 0.6–4.4 million $PM_{2.5}$-related deaths … and 0.04–0.52 million ozone-related deaths … in 2030.

Health co-benefits from the 2012 study need to be tempered by subtleties and uncertainties associated with the complex sets of chemical substances associated with black carbon, particularly sulfates, which are co-emitted with many releases of black carbon. A meta-analysis that examined interactions among black carbon, ozone and sulfates found: "Associations among these pollutants make drawing conclusions about their individual health effects difficult at present."

5. Implications

Numerical Estimates of Air Quality Co-Benefits

The lack of uniformity in the way quantitative results are reported makes it challenging to interpret the co-benefits literature. As demonstrated herein, some studies report co-abatement rates (kg of conventional pollutant reduced/t CO_2 emissions avoided). Others report results as decreases in local air pollutant emissions (typically as percentage or mass). Still other studies report on changes in ambient air pollutant concentrations (for example, in $\mu g/m^3$).

Of all the reporting metrics mentioned above, the co-abatement rate is the one that lends itself to possibilities for comparisons across studies. The most robust source of data on co-abatement rates has been a set of studies on CDM projects in China. Results from these studies were consistently presented in units of kg of conventional pollutant reduced/t CO_2 emissions avoided. In addition, a number of the studies discussed herein presented results using metrics that could, after suitable unit conversions, be presented as co-abatement rates in kg/t units.

Ranges for co-abatement rates are presented in table 7. Five aspects of table 7 are notable. First, the co-abatement rates are difficult to compare because they are presented in different terms; some are in units of kg/t CO_2 and others are in units of kg/t CO_2e; similarly, different units are used for particulate matter (TSP, PM, PM_{10}, and $PM_{2.5}$). Second, even when considering interventions using comparable units, the difference co-abatement rates across interventions are sometimes quite large, especially for SO_2. Third, the largest range for a given intervention is for fossil fuel switching, which reflects the ability to drive SO_2 levels down by substituting natural gas for coal. Fourth, the data is not robust enough to rank order the interventions, but co-abatement rates are relatively large for projects involving coal washing and briquetting and boiler improvements; and, as mentioned, SO_2 reductions can be substantial for fuel switching projects. Fifth, some biomass projects used to generate values in table 7 increase conventional air pollutant emissions because they involve agricultural waste that is only partially open burned in the reference scenarios and fully combusted in the CDM projects used to generate the biomass figures in the table.

Although the previous sections did not emphasize quantitative values of the health benefits associated with air pollution co-benefits, the subject has been treated by many researchers and a few illustrative values are provided here. In this context, a 2010 review paper is particularly helpful because it examined 37 peer-reviewed air quality co-benefit studies and identified 29 that contained results using a monetary value of air quality co-benefits: \$/t of CO_2 avoided. Some studies were based on general or partial economic equilibrium models and others were benefit-cost analyses of particular interventions. Moreover, the studies covered different economic sectors and time spans. In the 22 (of 24) developed country studies that included monetary estimates, values varied from \$2 to \$128/t CO_2 (with an average \$44/t CO_2). Seven (of 13) developing country studies reported monetary values, and they ranged from \$27 to \$196/t CO_2 (with an average of \$81/t CO_2). Notwithstanding the wide range in reported values, the analysts noted "that the magnitude of [air quality] co-benefits of climate change mitigation are nontrivial and have been observed across varied geographies, time periods, and sectors."

Average economic values of co-benefits above \$50/t CO_2 are not uncommon in the literature. For example, a 2013 study used a global atmospheric model and future scenarios to examine air quality and health co-benefits. Relative to a reference scenario, the study found: global GHG mitigation scenarios would avoid 1.3±0.5 million premature deaths in 2050. Monetized global average marginal co-benefits of avoided mortality ranged between \$50 and \$380/t CO_2, depending on estimates used for value of a statistical life. Similarly, a 2015 paper analyzed (mostly) air quality co-benefits data for the top 20 GHG-emitting countries. Results showed that for domestic co-benefits (that is, excluding global climate change mitigation benefits), the average "second-best domestic price" was \$57.5 per ton of CO_2 (for 2010), "reflecting primarily health co-benefits from reduced air pollution at coal plants and, in some cases, reductions in automobile externalities net of fuel taxes/subsidies." Slightly less than half the nations in the study were developing countries.

An interesting aspect of the monetary values reported here is that they are larger than most of current values in carbon pricing schemes based on carbon taxes and emissions trading systems. These schemes employ what is sometimes called a "social cost" of carbon (that is, the economic damage caused by a ton of CO_2 emissions). According to a 2016 World Bank study, about 40 national jurisdictions and over 20 cities, states, and regions are putting a price on carbon. The majority of emissions (75 percent) in these carbon tax or trading schemes were priced at less than \$10/t CO_2e. While it is tempting to make comparisons with the monetary values of CO_2 emissions avoided reported in the previous few paragraphs, that is not simply done because monetary values in previously noted papers are reported as \$/t CO_2 not \$/t CO_2e.

Discussion

Environmental co-benefits studies have considered the following actions to mitigate climate change by reducing or preventing GHG emissions: switching from fossil fuels to low (or zero) carbon energy sources such as wind, solar and hydropower; reducing emissions associated with coal (for example, by using technologies involving coal washing and briquetting); improving energy efficiency (for example, by improving the efficiency of boilers used in the energy and industry sectors); improving energy efficiency in the buildings sector; and relying more heavily on public transportation and fuel-efficient motor vehicles. Co-benefits studies have also considered actions to protect natural sources of carbon sequestration by avoiding deforestation and interventions to create new sources of carbon storage by, for example, engaging in reforestation and environmentally-friendly agricultural practices.

Substantial global health co-benefits would accompany efforts to cut concentrations of tropospheric ozone levels and PM, particularly black carbon. Some have noted that cutting SLCPs early would also help achieve several the UN Sustainable Development Goals; and others have argued that cutting SLCPs will slow sea level rise and lead to slowing global average temperature rise within a generation or two. (In contrast, some climate modeling specialists have concluded that even with maximally feasible reductions phased in from 2015 to 2035, global mean temperatures in 2050 would be reduced by only 0.16 °C on average.) In addition, cutting black carbon is believed to have the potential for yielding positive local health effects as well as impacts on regional climate.

The regional effects of black carbon reduction are illustrated by a 2011 study: "In areas with high emissions of [black carbon], the resulting extensive brown haze can affect temperature and precipitation. Early evidence is suggesting that large BC emissions in India and China have caused shifts in the Indian monsoon and in Chinese rainfall patterns." The author also notes that cutting black carbon emissions from diesel and coal has beneficial local health effects at the same time that it reduces global warming.

Indeed, many analysts believe the health co-benefits of measures to cut black carbon and other SLCPs would be sufficient to justify many of those interventions on their own, and that insufficient attention has been given to positive health impacts of cutting SLCPs. Finally, as one World Bank sponsored publication indicated, "[l]imiting these [SLCPs] through smart development enhances economies, stimulates production, leaves populations healthier and slows the rate of climate change."

Notwithstanding these advantages, concerns have been raised about interventions to target SLCP reductions. These concerns center on the possibility that slowing global average temperature rise in the short term by cutting SLCPs would take political pressure off of cutting CO_2, which is central to the long-term control of global average temperature. Indeed, a number of climate modeling specialists worry that emphasizing SLCP reductions would detract from what they see as the central goal in stabilizing temperature: acting early in decreasing emissions of CO_2 and other long-lived climate pollutants. Climate models appear to show that near-term climate benefits of policies to reduce SLCPs would be both modest and uncertain, and, in any case, they would be similar to climate benefits from a climate policy directed at cutting CO_2 and other long-lived GHGs in the near-term.

Some researchers have tried to strike a balance by urging what they call a hybrid strategy: "reducing SLCPs in parallel with long-lived CO_2 to achieve climate goals, as well as health and food security benefits, associated with some of the SLCPs." The discussion among researchers is not on the technical aspects of forecasting the likely climate effects of SLCP emission reductions, but rather on different views around the strategies for mustering political will to move forward with GHG mitigation policies. The sectors that have received the greatest attention in terms of quantitative environmental co-benefit assessments include energy, buildings, industry, and transportation. Co-benefits studies in the waste sector place more attention on climate change mitigation as a co-benefit of reducing GHG emissions than they do on local air quality co-benefits. There are many opportunities for environmental co-benefits in the agriculture and forestry and other land use sectors, but environmental co-benefits in those sectors are particularly location specific and do not lend themselves readily to simple cataloging and quantification. More generally, the literature reviewed herein demonstrates that environmental co-benefits vary significantly by type and geographic coverage of GHG mitigation interventions and, consequently, impacts are most appropriately evaluated on a location-specific basis. Local context is especially important when it comes to identifying air quality co-benefits from renewable energy.

A notable complexity in comparing results from different studies concerns the use of varying units to report outcomes; for example, kg of conventional pollutants cut/t of CO_2

reduced; percentage of reduced exposure to conventional pollutants; and changes in pollutant concentration in μg/m3. More generally, differences among study outcomes are to be expected because of variations in factors such as local context, data available, modeling methods used and assumptions made. In a few instances, key assumptions cannot be identified because papers reporting on co-benefits studies are opaque regarding modeling details.

In comparison, to water quality co-benefits, air quality co-benefits have received much greater attention in studies of pollution-related co-benefits. Strategies designed to cut GHG emissions by reducing fuel combustion (for example, by relying more heavily on zero-emission renewables, increasing energy efficiency or switching from coal to less polluting fuels), also have an influence on curbing conventional air pollutants, such as SO_2, NO_x, PM and volatile organic compounds. This follows because the source of GHG and local air pollutant emissions is the same: the combustion of fuels, such as coal, oil, gas and biofuels. Therefore, the sectors in which fuel combustion contributes to GHG emissions—energy, buildings, industry and transport—are the ones with the most significant air quality co-benefits. Opportunities for air quality co-benefits exist in forestry (for example, via decreased land clearing via forest burning) and agriculture (improved agricultural burning practices), but publications providing quantitative co-abatement rates are not common.

In terms of the relative contributions of different sources, data suggest the following climate change mitigation measures as having especially notable air quality co-benefits in the sectors for energy and industry: replacing coal with less polluting fossil fuels, replacing fossil fuels with renewables, improving energy efficiency to reduce demand for electricity generation and thereby reduce the need for burning fossil fuels, enhancing the performance of boilers, and improving the characteristics of coal via coal washing and briquetting. For buildings, the air quality co-benefits are typically linked to improvements in energy efficiency and modifications in cooking stoves used by billions of people in developing countries.

The transportation sector is a major source of air quality co-benefits and associated health benefits. However, it is difficult to distinguish the impacts of individual transport-related interventions in producing co-benefits because the transport-related studies (as well as studies involving multiple sectors) often aggregate outcomes from a collection of interventions. In addition, while some transport -related health benefits are tied to reducing conventional air pollution, other health improvements are linked to transportation system related changes that encourage walking and cycling and reduce use of motor vehicles.

Although adverse co-impacts are not mentioned frequently in the co-benefits literature, it is notable that CCS was characterized as having negative environmental impacts (for example, increased NO_x emissions). This typically occurred because of an overall loss in energy efficiency of electricity generation and an associated increase in the demand for fuel and operating materials (for example, solvents). In addition, in some cases increased use of biofuels led to a rise in $PM_{2.5}$ and NO_x.

There is wide recognition that reduction of fossil fuel consumption to cut GHG emissions provides potential opportunities for the simultaneous reduction of conventional air pollutants. However, in many instances, policies for air quality and energy are designed and implemented independently. This absence of coordination ignores the synergies (or trade-offs) of the policies being implemented. The consequence is the incomplete assessment of interventions in both the air quality and climate change mitigation domains. More coordination between officials responsible for air quality and energy policies could offer opportunities to increase both climate change mitigation and air quality improvement.

Notwithstanding the wide range of values reported for monetized health co-benefits ($/t CO_2), those values (often in excess of $50 per ton of CO_2) were greater than the project costs for many of the individual projects mentioned in the literature (for example, many CDM projects in China). The challenge is that project costs are paid by enterprises and the benefits are spread among the large numbers of people who would breathe less polluted air. The societal advantages of these projects may therefore not be recognized and accounted for by enterprises considering the projects or by the governments in a position to help subsidize those projects.

Finally, this review identified three notable gaps in the existing co-benefits literature. First, the literature on co-benefits linked to energy efficiency in the building sector is dominated by studies from industrialized countries; relatively few studies concern developing nations. Second, studies in the building sector have been concerned with health impacts, which is appropriate, but that literature has not been particularly concerned with quantifying opportunities for cutting GHG emissions associated with cookstoves. That kind of information would make cookstove improvement projects, which are already important because of the health impacts, even more important because of climate change mitigation possibilities. Third and finally, literature on the waste sector contains little documentation of the possibilities for generating local air pollution control co-benefits by converting open dumping sites and basic landfills to sanitary landfills or incinerators capable of capturing and using GHGs for electricity production. In addition, literature on co-benefits in wastewater management emphasizes GHG reduction but does not elaborate on local air quality co-benefits.

Conclusions

Air quality co-benefits have received far more attention than those for water quality in studies of pollution-related co-benefits of GHG reductions. Measures to cut GHGs in the energy and industry sectors have particularly notable air quality co-benefits (for example, replacing fossil fuels with renewables, and improving energy efficiency). For buildings, air quality co-benefits are typically linked to improvements in energy efficiency and modifications in cooking stoves.

The transportation sector is a major source of air quality co-benefits. However, it is difficult to isolate co-benefits of individual transport-related interventions because the transport-related studies (as well as studies involving multiple sectors) often aggregate outcomes from a collection of interventions. In addition, while some transport-related health benefits are tied to reducing conventional air pollution, others are linked to changes that encourage walking and cycling and reduced use of motor vehicles.

There is wide recognition that reduction of fossil fuel consumption to cut GHG emissions provides potential opportunities for the simultaneous reduction of conventional air pollutants. However, opportunities for gains are not fully exploited when policies for air quality and energy are designed and implemented in isolation from each other.

A notable complexity in comparing results from different studies is that different units are used to report outcomes; for example, kg of conventional pollutants cut/t of CO_2 reduced and changes in pollutant concentration in μg/m3. More generally, differences among study outcomes are to be expected because of variations in local context, data available, and modeling methods and assumptions.

Notwithstanding the wide range of values reported for monetized health co-benefits (often >50$/t CO_2), they were greater than project costs for many of the individual GHG reduction projects mentioned in the literature. The social advantages of private-sector projects are unaccounted for either because they do not accrue to enterprises considering the projects or they are not recognized by governments that might help subsidize them.

Finally, while evidence exists for notable global health co-benefits in decreasing concentrations of SLCPs, the strategy of focusing on SCLPs has been controversial in the literature because of fears that slowing global average temperature rise in the short term by cutting SLCPs would take political pressure off cutting CO_2, which is central to the long-term control of global average temperature. Advocates for short-term attention to cutting SLCPs argue that that reducing SLCPs need not detract from the need to cut CO_2 and other long-lived pollutants, and that many relatively short-term and local health benefits can be gained.

Table 1. Co-abatement Rates for CDM Power-Related Projects in China (kg/t CO_{2eq})

CDM Project Type	Example	$PM_{2.5}$	SO_2	NOx	Projects *(no.)*
Zero-emission renewables	New Wind or Hydro	0.31 (0.23–0.45)[a]	4.5 (3.5–5.7)	1.5 (1.1–2.1)	149
Biomass	237	0.74 (−0.039[b]–1.1)	5.6 (−0.73 [b]–10)	1.5 (−0.017 [c]–2.3)	70
Waste	Biogas recovery for power generation	0.042 (0.007–0.49)	0.79 (0.33–2.0)	0.082 (0–0.51)	83
Fossil fuel switch	Switch from coal to gas	0.79 (0.51–1.60)	12 (2.9–24)	0.12 (0.096–2.3)	27
Energy efficiency	Waste heat for power generation	0.35 (0.28–0.40)	4.9 (4.1–5.8)	1.50 (1.1–1.7)	n.a.

Source: Based on Rive and Aunan 2010.

Note: Rates are based on national averages and wide variations exist across regions. Regional co-abatement rates by project type were not reported. CDM = Clean Development Mechanism CO_2e = carbon dioxide equivalent; kg/t = kilogram per ton; NOx = nitrogen oxides; PM = particulate matter; SO_2 = sulfur dioxide; t = ton.

a. Values in parentheses are very approximately indicative of the range of values. Data presented were for weighted average values of co-abatement rates for seven regions examined in the study: Central, East, Hainan, North, North East, North West and South.

b. Based on data presented, a few biomass facilities a single facility in North West China showed negative co-abatement rates for $PM_{2.5}$ (-0.039) and SO_2 (-0.017). Biomass projects tend to have increased emissions because they take agricultural waste that is only partially open burned in the reference scenarios and fully combusted in the CDM projects.

c. As in the case of biomass, there were a few waste projects that had negative average co-abatement values. These included average rates for NO_x that were -0.22 for waste projects in the East and -0.017 for waste projects in the North West. The study's authors, Aunan and Rive, provided no explanations for these outcomes.

Table 2. Co-abatement Rates for CDM Projects in a Chinese Grid Emission Factor Study (kg/t CO_2)

CDM Power Facility Type	$PM_{2.5}$	SO_2	NO_x
Wind	0.42	2.76	2.77
Hydro	0.35	2.34	2.06
Solar Photovoltaic	0.26	2.19	1.96
Biomass	0.24	1.46	0.48
Fuel Switch	0.29	0.79	0.73

Source: Based on Cai et al. 2013.

Note: Rates are based on national averages and wide variations exist across regions. Regional co-abatement rates by facility type were not reported. CO_2 = carbon dioxide; kg/t = kilogram per ton; NOx = nitrogen oxides; PM = particulate matter; SO_2 = sulfur dioxide.

Table 3. Co-abatement Rates Estimated in a Chinese Grid Emission Factor Study (kg/t CO_2)

Power Facility Type	$PM_{2.5}$	SO_2	NO_x
North	0.36	2.46	2.49
Northeast	0.49	2.07	2.33
East	0.36	1.45	1.25
Central	0.35	2.21	1.90
Northwest	0.29	2.63	2.37
South	0.36	2.20	1.86

Source: Based on Cai et al. 2013.

Note: Rates based on regional averages and (unreported) regional variations exist across facility types. Differences across regions are due to differences in levels of pollution control. CO_2 = carbon dioxide; kg/t = kilogram per ton; NOx = nitrogen oxides; PM = particulate matter; SO_2 = sulfur dioxide.

Table 4. Emission Factors Used in Taiwan Power Sector Study (g/kWh)

Power Facility Type	PM_{10}	SO_x	NO_x	CO
Coal	0.09	0.78	1.54	0.37
Solar photovoltaic	0.05	0.11	0.11	0.75
Onshore wind	0.01	0.05	0.05	0.09
Hydro	0.02	0.07	0.08	0.05

Source: Based on Shih and Tseng 2014.

Note: CO = carbon oxide; g/kWh = grams per kilowatt hours; NOx = nitrogen oxides; PM = particulate matter; SOx = sulfur oxides.

Table 5. Co-abatement Rates for Potential Coal-Related Industrial Projects in Shanxi, China (kg/t CO_2)

Intervention	Details	SO_2	TSP
Co-gen	Paper and textile industries	8.67	4.0
Modified boiler design	Multilayer combustion system to sort coal before entering boiler	8.23	2.66
Boiler replacement	Replace old, inefficient industrial boilers with state-of-the-art boilers	8.24	3.64
Improved boiler management	Changes in management practice, maintenance, etc., and small investments	8.22	3.62
Coal washing	removes coal dust and impurities; sulfur rich particles washed away	32.94	9.63
Briquetting binds coal together	Eliminates coal dust—addition of lime reduces SO_2	28.82	13.29

Source: Based on Aunan et al. 2004.

Note: CO_2 = carbon dioxide; kg/t = kilogram per ton; SO_2 = sulfur dioxide; TSP = total suspended particulate.

Table 6. Co-abatement Rates for Boiler Improvement Projects and Other Interventions in China

Co-abatement Rates	Set of Interventions	Mean	15–85 Percentiles
kg SO_2/t CO_2	All 24 studies	10.8	6.7–18.2
kg SO_2/t CO_2	Boiler Improvements	5.9	4.5–8.2
kg TSP/t CO_2	All 24 studies	5.3	2.7–12.2
kg TSP/t CO_2	Boiler Improvements	4.8	3.1–10.2

Source: Based on Vennemo et al. 2006.

Note: CO_2 = carbon dioxide; kg = kilogram; SO_2 = sulfur dioxide; t = ton; TSP = total suspended particulate.

Table 7. Range of Co-abatement Results (kg/t CO_2; or CO_2e)

Sector(s)	Intervention Type	SO_2	NO_x	TSP	PM	PM_{10}	$PM_{2.5}$
Energy/Industry	Coal washing/ Briquetting	28.8–32.9		9.63–13.29			
Energy/Industry	Boiler improvements	4.5–8.2		2.66–10.2			
Energy	Zero-emission renewables	3.5–5.7[a]	1.1–2.1[a]				0.23–0.45[a]
Energy	Biomass	–0.73–10[a]	–0.017–2.3[a]				–0.039–1.1[a]
Energy	Waste	0.33–2.0[a]	0–0.51[a]				0.007–0.49[a]
Energy	Co-generation	8.67		4.0			
Energy	Fossil fuel switch	2.9–24[a]	0.096–2.3[a]				0.51–1.60[a]
Energy	Efficiency	4.1–5.8[a]	1.1–1.7[a]				0.28–0.4[a]
School Buildings (1)	Efficiency	2.23	2.05			0.26	
Cement	Mixed	5.15			1.08		
Steel	Carbon tax	1.20	0.57			0.21	
Transport (2)	Mixed		17.7			1.99	
Transport (3)	Mixed	1.09	15.1			2.58	

Source: Tables 1, 5, and 6 and values cited earlier in this literature review.

Note: All studies are for China except (1) = USA; (2) = Delhi, India; and (3) = Indonesia. CO_2 = carbon dioxide; CO_2e = carbon dioxide equivalent; kg/t = kilogram per ton; NOx = nitrogen oxides; PM = particulate matter; SO_2 = sulfur dioxide; TSP = total suspended particulate.

a. Indicates the units are CO_2e.

References

Anenberg, S. C., J. Schwartz, D. Shindell, M. Amann, G. Faluvegi, Z. Klimont, and L. Emberson. 2012. "Global Air Quality and Health Co-Benefits of Mitigating Near-Term Climate Change through Methane and Black Carbon Emission Controls." *Environmental Health Perspectives* 120 (6): 831.

Apsimon, H., M. Amann, S. Åström, and T. Oxley. 2009. "Synergies in Addressing Air Quality and Climate Change." *Climate Policy* 9 (6): 669–680.

Aunan, K., J. Fang, H. Vennemo, K. Oye, and H. M. Seip. 2004. "Co-benefits of Climate Policy—Lessons Learned from a Study in Shanxi, China." *Energy Policy* 32 (4): 567–581.

Bell, M. L., D. L. Davis, L. A. Cifuentes, A. J. Krupnick, R. D. Morgenstern, and G. D. Thurston. 2008. "Ancillary Human Health Benefits of Improved Air Quality Resulting from Climate Change Mitigation." *Environmental Health* 7 (1): 1.

Bollen, J., B. van der Zwaan, C. Brink, and H. Eerens. 2009. "Local Air Pollution and Global Climate Change: A Combined Cost-Benefit Analysis." *Resource and Energy Economics* 31 (3): 161–181.

Bongardt, D., M. Breithaupt, and F. Creutzig. 2010. "Beyond the Fossil City: Towards Low Carbon Transport and Green Growth." Paper presented at the Fifth Regional Environmentally Sustainable Transportation Forum, Bangkok, Thailand, August 23–25. http://www.uncrd.or.jp/content/documents/5EST-P1-BGP.pdf.

Cai, W., C. Wang, Z. Jin, and J. Chen. 2013. "Quantifying Baseline Emission Factors of Air Pollutants in China's Regional Power Grids." *Environmental Science & Technology* 47 (8): 3590–3597.

Chang, Z., K. X. Pan, and H. X. Zhu. 2017. "Power Generation System Optimization with Emission Co-benefits Analysis: A Case Study of Shanghai." In *Advances in Energy Systems Engineering,* edited by Georgios M. Kopanos Pei Liu, and Michael C. Georgiadis, 355–386. Springer International Publishing.

Floater, G., C. Catarina Heeckt, M. Ulterino, L. Mackie, P. Rode, A. Bhardwaj, M. Carvalho, D. Gill, T. Bailey, and R. Huxley. 2016. "Co-benefits of Urban Climate Action: A Framework for Cities." A working paper by the Economics of Green Cities Programme Working Paper, LSE Cities, London School of Economics and Political Science. http://www.c40.org/researches/c40-lse-cobenefits.

Klaassen, G., and K. Riahi. 2007. "Internalizing externalities of electricity generation: An analysis with MESSAGE-MACRO." *Energy Policy* 35 (2): 815–827.

Kumar, M., S. Kumar, and S. K. Tyagi. 2013. "Design, Development and Technological Advancement in the Biomass Cookstoves: A Review." *Renewable and Sustainable Energy Reviews* 26: 265–285.

Malla, S. 2009. "CO_2 Emissions from Electricity Generation in Seven Asia-Pacific and North American Countries: A Decomposition Analysis." *Energy Policy* 37 (1): 1–9.

Mayrhofer, J. P., and J. Gupta. 2016. "The Science and Politics of Co-benefits in Climate Policy." *Environmental Science & Policy* 57: 22–30.

Mondal, M. A. H., M. Denich, and P. L. Vlek. 2010. "The Future Choice of Technologies and Co-Benefits of CO_2 Emission Reduction in Bangladesh Power Sector." *Energy* 35 (12), 4902–4909.

Nápoles, P. R. 2012. "Low Carbon Development Strategy for Mexico: An Input-Output Analysis." Final report published by United Nations Environment Programme

Nemet, G. F., T. Holloway, and P. Meier. 2010. "Implications of Incorporating Air-Quality Co-benefits into Climate Change Policymaking." *Environmental Research Letters* 5 (1): 014007.

Pfenninger, S., A. Hawkes, and J. Keirstead. 2014." Energy Systems Modeling for Twenty-First Century Energy Challenges." *Renewable and Sustainable Energy Reviews 33*: 74–86.

Promjiraprawat, K., and B. Limmeechokchai. 2012. "Assessment of Thailand's Energy Policies and CO_2 Emissions: Analyses of Energy Efficiency Measures and Renewable Power Generation." *Energies*, *5*(8), 3074–3093.

Rive, N., and K. Aunan. 2010. "Quantifying the Air Quality Co-benefits of the Clean Development Mechanism in China." *Environmental Science & Technology* 44 (11): 4368–4375; suppl. 7–9.

Shaw, C., S. Hales, P. Howden-Chapman, and R. Edwards. 2014. "Health Co-benefits of Climate Change Mitigation Policies in the Transport Sector." *Nature Climate Change* 4 (6): 427–433.

Shih, Y. H., and C. H. Tseng. 2014. "Cost-Benefit Analysis of Sustainable Energy Development Using Life-Cycle Co-Benefits Assessment and the System Dynamics Approach." *Applied Energy* 119: 57–66.

Simon, G. L., A. G. Bumpus, and P. Mann. 2012. "Win-Win Scenarios at the Climate–Development Interface: Challenges and Opportunities for Stove Replacement Programs through Carbon Finance." *Global Environmental Change* 22 (1): 275–287.

Sims, R. E., W. Mabee, J. N. Saddler, and M. Taylor. 2010. "An Overview of Second Generation Biofuel Technologies." *Bioresource Technology* 101 (6): 1570–1580.

Singh, A. 2009. "Climate Co-benefit Policies for the Indian Power Sector: Domestic Drivers and North—South Cooperation." *Climate Policy* 9 (5): 529–543.

Stohl, A., B. Aamaas, M. Amann, L. H. Baker, N. Bellouin, T. K. Berntsen, M. Dusinska. 2015. "Evaluating the Climate and Air Quality Impacts of Short-Lived Pollutants." *Atmospheric Chemistry and Physics* 15 (18): 10529–10566.

Ürge-Vorsatz, D., S. T. Herrero, N. K. Dubash, and F. Lecocq. 2014. "Measuring the Co-benefits of Climate Change Mitigation." *Annual Review of Environment and Resources* 39: 549–582.

Vennemo, H., K. Aunan, F. Jinghua, P. Holtedahl, H. Tao, and H. M. Seip. 2006. "Domestic Environmental Benefits of China's Energy-Related CDM Potential." *Climatic Change* 75 (1–2): 215–239.

Zhang, X., X. Y. Wang, Z. P. Bai, and B. Han. 2013. "Co-Benefits of Integrating PM_{10} and CO_2 Reduction in an Electricity Industry in Tianjin, China." *Aerosol Air Quality Res* 13: 756–70.

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[1] The review does not present a specific analysis of the effects of the World Bank Group's climate change interventions on management of conventional air and water pollutants.

[2] Black carbon and ozone are particularly concerning because they are linked to major adverse health effects. Black carbon consists of small, dark particles that affect the way the sun's rays are absorbed and reflected. Black carbon is not a greenhouse gas (GHG), but it is a major climate warmer. Tropospheric ozone can act both as a direct greenhouse gas and as an indirect controller of the lifetimes of other GHGs, particularly methane. The latter is a GHG and also a precursor of ozone. For a review of health effects, see Anenberg et al. 2012. For details on climate and air quality impacts of STLPs, see Stohl et al. 2015.

[3] Some researchers (for example, Mayrhofer and Gupta [2016]) refer to a "co-benefits approach to development" to highlight the idea that mainstreaming climate concerns into development allows for the possibility of leveraging climate finance to meet development objectives. This concept is illustrated by Simon, Bumpus and Mann (2012), who emphasize possibilities for "win-win" climate and development outcomes by using carbon finance to meet development objectives (in this case, in financing improved cooking stove technologies to deduce emissions of both GHGs and indoor air pollution).

[4] For example, Ürge-Vorsatz et al. (2014) "argue for reframing the co-benefits concept co-benefits in a multiple-objective/multiple-impact framework rather than in a single-purpose co-benefit one."

[5] Strings of key words used in searching the literature: climate change co-benefits transportation GHG emissions air pollution co-benefits; public transport GHG emissions air pollution co-benefits; air pollution control and carbon reduction co-benefits; compact cities GHG emissions air pollution co-benefits; co-benefits health CO_2 mitigation climate; energy efficiency co-benefits CO_2 mitigation climate; energy efficiency buildings co-benefits climate mitigation; air pollution co-benefits cook stoves; coal power energy efficiency co-benefits; supply side energy efficiency co-benefits; industry climate change mitigation environmental co-benefits; agriculture GHG mitigation environmental co-benefits; forests GHG mitigation environmental co-benefits; wastewater climate mitigation co-benefits; solid waste treatment and disposal climate mitigation co-benefits; renewable energy, co-benefits, climate mitigation, air quality; renewable energy climate change mitigation environmental co-benefits; renewable energy co-benefits; review climate co-benefits; meta-analysis climate co-benefits; CCS co-benefits; bioenergy co-benefits; cogeneration climate mitigation; coal efficiency co-benefits; electricity generation efficiency co-benefits; co-benefits carbon tax; co-benefits agriculture; forest mitigation co-benefits water; forest mitigation co-benefits air; REDD co-benefits air; waste climate change mitigation co-benefits; wastewater climate change mitigation co-benefits; waste to energy co-benefits; wastewater co-benefits; sewage treatment GHG emission reduction; sewage treatment GHG emission reduction co-benefits; carbon taxes co-benefits; energy fuel switch co-benefits; coal-fired to gas-fired electricity generation co-benefits; motor vehicle fuel efficiency standards co-benefits; motor vehicle fuel efficiency standards pollution; and transport pollution Climate Change co-benefits.

[6] The most important review papers cited herein include Bell et al. 2008; Nemet, Holloway, and Meier 2010; Shaw et al. 2014; Floater et al. 2016; and Kumar, Kumar, and Tyagi 2013.

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[7] The focus throughout is on GHG-emission-intense sectors, such as energy, transport and buildings. The types of interventions included consist of those with direct effects in reducing GHG emissions (for example, retrofitting thermal power plants with emission control devices and reducing deforestation) as well as those with indirect effects (for example, displacing fossil fuel generation with renewables). The review does not cover the wide array of specific policy or other interventions that could lead to these effects (for example, renewable energy feed-in tariffs, forest governance reforms, and energy subsidy reforms).

[8] CO_2e is short for "carbon dioxide equivalent." It is used because there are several greenhouse gases (GHGs) in addition to CO_2. The impact of each different GHG is expressed in terms of the amount of CO_2 that would create the same amount of warming; those individual amounts are added to the value of CO_2 emissions to determine CO_2e.

[9] These studies are illustrated by (i) a dynamic environmental input-output model that estimated the Mexican economy's annual performance and its GHG emissions through time in Nápoles 2012 and (ii) an approach that combines the MERGE model (an integrated assessment model for global climate change) with models that consider local air pollution and shows that "policies mitigating the emissions of CO_2 and PM_{10} largely outweigh the costs of these policies, even while they induce important reallocations of resources to new (for example, renewable) energy technologies and end-of-pipe abatement techniques (rendering fossil fuel usage clean)"in Bollen et al. 2009. These types of macroeconomic models are discussed in a review paper by Mayrhofer and Gupta 2016.

[10] This paragraph is based, in part, on Vennemo et al. 2006.

[11] Qualitative arguments take the form of assertions that co-benefits will accompany GHGs emission reduction but without presenting supportive quantitative evidence. This is illustrated by Bongardt, Breithaupt, and Creutzig who observed that low-carbon transportation infrastructure that follows the principle of sustainable development "not only mitigates climate change but also … reduces traffic congestion, and consequently air pollution and noise are reduced, having a positive impact on the environment and human health …." Bongardt, Breithaupt, and Creutzig 2010.

[12] For an introduction to Long-range Energy Alternatives Planning System (LEAP), see LEAP Introduction. Accessed at https://www.energycommunity.org/default.asp?action=introduction on November 28, 2016.

[13] For more on the GAINS (Greenhouse Gas-Air Pollution Interactions and Synergies) model, see International Institute for Applied Systems Analysis website. Accessed at http://gains.iiasa.ac.at/models/ on December 5, 2016.

[14] Default emission factors are given in Intergovernmental Panel on Climate Change (IPCC) technical reports, such as the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (accessed at http://www.ipcc-nggip.iges.or.jp/public/2006gl/index.html as of November 30, 2016) and the 2013 supplement (accessed at http://www.ipcc-nggip.iges.or.jp/ as of November 30, 2016).

[15] U.S. Environmental Protection Agency, global emissions by sector. Accessed at https://www.epa.gov/ghgemissions/global-greenhouse-gas-emissions-data#Sector on January 21, 2017.

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[16] As an example, supply-side efficiency options were explored and found to improve electric power system efficiency in India; co-benefits were described in the form of greenhouse gas (GHG) reductions, but local air quality was not mentioned. For example, in Singh (2009), the focus on links between GHG reduction and supply side efficiency is apparent in many papers identified in a search on Web of Science, Scopus and Google Scholar using key words of "electricity generation efficiency co-benefits."

For most of the studies of supply-side efficiency found in this way, the co-benefits highlighted were not air quality co-benefits. Examples include Malla 2009; Mondal, Denich, and Vlek 2010; Sims et al. 2010; and Promjiraprawat and Limmeechokchai 2012.

Some studies investigated co-benefits as GHG emission reductions that would occur if electric power systems improved efficiency to meet local air quality targets. Examples include Zhang et al. 2013; Chang, Pan, and Zhu 2017; and Klaassen and Riahi 2007.