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Outlook for clean air in the context of sustainable development goals

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ABSTRACT

Air pollution is linked with many of the United Nations Sustainable Development Goals. Strategies aiming at the improved air quality interact directly with climate mitigation targets, access to clean energy services, waste management, and other aspects of socio-economic development. Continuation of current policies in the key emitting sectors implies that a number of sustainability goals will likely not be met within the next two decades: emissions of air pollutants would cause 40% more premature deaths from outdoor air pollution than today, carbon emissions would rise globally by 0.4% per year, while nearly two billion people would not have access to clean cooking. This paper examines integrated policies to put the world on track towards three interlinked goals of achieving universal energy access, limiting climate change and reducing air pollution. Scenario analysis suggests that these goals can be attained simultaneously with substantial benefits. By 2040, emissions of main pollutants are projected to drop by 60–80% relative to today, and associated health impacts are quantified at two million avoided deaths from ambient and household air pollution combined. In comparison to costs needed for the decarbonization of global economy, additional investments in air pollution control and access to clean fuels are very modest against major societal gains. However, holistic and systemic policy assessment is required to avoid potential trade-offs.

1. Introduction

Air pollution is the fourth greatest overall risk factor for human health worldwide, after high blood pressure, dietary risks and smoking. Recent estimates attribute 6.5 million premature deaths to air pollution (WHO, 2016). In addition to human health, air pollution poses risks to the environment, economy and food security. Air pollution crisis cannot be addressed in isolation: it is closely linked to policies for energy, climate, transport, trade, agriculture, biodiversity and other issues. Well-designed air quality strategies have major co-benefits for other policy goals (Anenberg et al., 2012; Rafaj et al., 2006; Schmale et al., 2014; Shindell et al., 2012). Improving air quality, via greater efficiency and increased deployment of renewables, goes hand-in-hand with the broader energy sector transformation and decarbonization commitments adopted within the Paris agreement (Mace, 2016; McCollum et al., 2013; Rafaj et al., 2013). Reducing pollutant emissions improves water and soil quality, crop yields and, in turn, food security (Emberson et al., 2001). Tackling household air pollution (HAP), via the provision of modern energy for cooking and lighting, helps development efforts dealing with poverty, education and gender equality (Amegah and Jaakkola, 2016; Lam et al., 2016; Rao and Pachauri, 2017).

In September 2015, 193 countries, developing and developed countries alike, adopted the Sustainable Development Goals (SDG), known officially as the 2030 Agenda for Sustainable Development (UN, 2015). Air pollution is recognized as a pressing sustainability concern and is directly mentioned in two SDG targets: SDG 3.9 (substantial reduction of health impacts from hazardous substances) and SDG 11.6 (reduction of adverse impacts of cities on people). Interlinkages of air pollution with other SDGs are described in detail in Supplementary material (Section S1). Action in the energy sector, including industry, transport and domestic subsectors, is essential to the attainment of the air pollution related SDGs (Amann et al., 2013; IEA, 2017). The majority of sulfur dioxide (SO_2) and nitrogen oxides (NO_x) emissions to the atmosphere are energy-related, as are some 85% of emissions of particulate matter (PM). Within the energy sector, power generation and industry are the main sources of SO_2. Oil-products use in vehicles and power generation are the leading emitters of NO_x. Consumption of

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biomass, kerosene and coal in the buildings sector, along with industrial combustion and process emissions, are responsible for the bulk of PM reaching the atmosphere. These three key pollutants are responsible for the most widespread impacts of air pollution, either directly or once transformed into other pollutants via chemical reactions and transport in the atmosphere. Fine particulate matter ($PM_{2.5}$) is the most damaging to human health, and sulfur and nitrogen oxides (a precursor of ozone) are associated with a range of illnesses and environmental damages (Cohen et al., 2017; Kiesewetter et al., 2015).

Each of the main pollutants is linked to a main fuel and source. In the case of $PM_{2.5}$, this is the wood and other solid biomass that some 2.7 billion people use for cooking and kerosene used for lighting (and in some countries also for cooking), which incurs indoor pollution that is associated with around 3.5 million premature deaths each year (Balakrishnan et al., 2013; Smith et al., 2014). These effects of energy poverty are felt mostly in developing countries in Asia and sub-Saharan Africa (Marais and Wiedinmyer, 2016). Fine particles, whether inhaled indoors or outdoors, are particularly harmful to health as they can penetrate deep into the lungs. Exposure to $PM_{2.5}$ may not be regarded as solely an urban problem (Zhang and Day, 2015); poor air quality severely affects many rural communities, moreover, significant share of secondary pollutants can be transported over large distances from their sources (Brauer et al., 2012; Klimont et al., 2017). The main fuel associated with sulfur emissions is coal (although high-sulfur oil products, such as those still permitted for use in maritime transport, are also a major contributor): SO_2 is a cause of respiratory illnesses and a precursor of acid rain. Fuels used for transport, first and foremost diesel, generate more than half the NO_x emitted globally, which can trigger respiratory problems and the formation of other hazardous particles and pollutants, including ozone. These emissions are linked with industrialization and urbanization, and coal and oil are the main sources (natural gas emits far less air pollution than other fossil fuels, or biomass). The unabated combustion of coal and oil in power plants, industrial facilities and vehicles is the main cause of the ambient/outdoor pollution linked to around 3 million premature deaths each year (IEA, 2016; Landrigan et al., 2017).

As the predominant source of air pollution and climate forcers, the fuel combustion must be at the forefront of action to improve air quality around the world. A range of proven policies and technologies are available to do so. In the United States, European Union and Japan, regulations have helped to achieve a major drop in emissions in some sectors, although challenges remain (Henneman et al., 2017; Rafaj et al., 2014; Wakamatsu et al., 2013). In developing Asia, less stringent regulations relating to fuel quality, energy efficiency and post-combustion treatment technologies generally mean that pollutant emissions have risen in line with very rapid growth in energy demand seen in recent years, though improvements in air quality are becoming an increasingly urgent policy priority in many Asian countries (Rafaj and Amann, 2018; Jin et al., 2016; Wang et al., 2014; Zhao et al., 2016). In other regions, particularly in Sub-Saharan Africa, urban air quality has been identified as a major threat to human health driven by rapid population growth and expanded transport and industry sectors, whereas lack of political will and institutional engagement poses major challenges to tackle impacts of air pollution (Amegah and Agyei-Mensah, 2017).

Since the SDG policy context has been introduced only recently, the scenario literature on the air-pollution-related SDGs interactions in medium/long-term is rather scarce and does not reflect yet, inter alia, the recent evolution in climate negotiations (see, e.g., Rao et al., 2016; van Vuuren et al., 2015; Roehrl, 2012). More recent studies, however, address implications of meeting the Paris agreement on a set of SDGs, including air pollution and health impacts (Grubler et al., 2018; McCollum et al., 2018), and suggest substantial co-benefits due to a rapid decarbonization of global economy and changes to consumption patterns. Evaluation of impacts – including potential tensions and trade-offs (Bowen et al., 2017; Klausbruckner et al., 2016) – of attaining multiple SDGs on the future air quality and associated health indicators requires an integrative and novel approach capable of quantifying interactions between key policy domains covered in this paper: access to clean energy carriers, climate change mitigation and abatement of air pollutant emissions. Using the policy scenario assessment, we attempt to contribute to this research area by quantifying and highlighting implications of multi-objective approach for sustainable development in contrast with a single-goal-oriented air pollution strategies.

Description of scenarios analyzed in this study together with key assumptions are provided in the next section; thereafter, the methodology and modelling tools are summarized. Subsequently, quantitative results are discussed in terms of future emissions of air pollutants, concentrations of fine particles, health impacts, and investment cost. Finally, conclusions and policy insights are drawn based on the numerical results.

2. Scenarios

This analysis is conducted on the basis of three scenarios: the New Policies Scenario (NPS), which assumes the continuation of existing and planned policies, the Clean Air Scenario (CAS), in which the implementation of additional measures achieves a significant reduction in air pollutant emissions, and the Sustainable Development Scenario (SDS), the aim of which is to address the three interlinked sustainability goals of achieving universal energy access, limiting climate change and reducing air pollution. Analysis of the NPS and SDS scenarios has been initially presented by the International Energy Agency's World Energy Outlook 2017 (IEA, 2017), and the first version of the CAS scenario has been reported in 2016 by the IEA's special report on energy and air pollution (IEA, 2016). For each scenario, underlying assumptions, policies and technological measures that determine emission levels from key sectors, are summarized in Table ST1 in the Supplementary material.

The New Policies Scenario (NPS) is the central scenario of this analysis, and aims to provide a sense of the direction in which latest policy ambitions could take the energy and industrial sectors. In addition to incorporating policies and measures that governments around the world have already put in place (Table ST1), it also takes into account the effects of announced energy, climate and air pollution policies, as expressed in official targets and plans. The Nationally Determined Contributions (NDC) of the Paris Agreement provide important additional guidance regarding energy policy intentions. Given that "new policies" are by definition not yet fully reflected in legislation or regulation, the prospects and timing for their full realization are based upon our assessment of the relevant political, regulatory, market, infrastructural and financial constraints.

The policies in place and under consideration to tackle air pollution vary considerably by country and region, with the state of economic development being an important variable. They encompass efforts that specifically target a reduction in pollutant emissions (e.g. setting upper limits for the concentration of individual pollutants in the flue gas stream). They also include broader policy efforts that change the pattern of energy consumption and thereby also have an impact on emissions trends (e.g. policies that support renewable energy or improve energy efficiency, or put a price on carbon).

The Clean Air Scenario (CAS) sets out a plausible strategy based on existing technologies and proven policies, to cut 2040 pollutant emissions by more than half compared with NPS. This policy path is one in which the energy sector takes determined action, coordinated effectively with others, to deliver a comprehensive overall improvement in air quality. Key areas for policy actions comprise a) setting an ambitious long-term air quality goal, to which all stakeholders can subscribe and against which the efficacy of the various pollution mitigation options can be assessed; b) putting in place a package of clean air policies for the energy sector to achieve the long-term goal, drawing on an efficient mix of best available practices, direct emissions controls, regulation and other measures, giving due weight to the co-benefits for other energy policy objectives; c) ensuring effective monitoring, enforcement, evaluation and communication, while recognizing the need for reliable data, a continuous focus on compliance and on policy improvement, and timely and transparent public information.

The scenario builds on the success already achieved in different parts of the world in improving air quality, by municipal and regional governments (which have often played a pioneering role in developing a policy response to air pollution) and through national and international efforts. The scenario combines policy and technology best-practices to reduce air pollutant emissions through post-combustion control measures with an accelerated clean energy sector transition towards the use of cleaner fuels. For the latter, the scenario aims to ramp up ambition over NPS in key areas, such as increasing energy efficiency; decreasing the use of inefficient coal-fired power plants; and increasing investments in renewable energies. CAS is also mindful of some cautionary tales: for example, the large gap between test data and the higher real-world pollutant emissions from diesel vehicles, which underlines the essential nature of adequate enforcement and compliance. The measures proposed in CAS are tailored to different national and regional circumstances, and include effective action to achieve full, universal access to cleaner cooking fuels and to electricity by 2040. Given the diversity of local, national and regional circumstances, the scenario rests on tailored combinations of policy measures that can bring about the targeted improvement in air quality.

The Sustainable Development Scenario (SDS) builds on the selected SDGs of the United Nations and aims to provide a pathway that integrates three closely associated but distinct policy objectives: to ensure universal access to affordable, reliable and modern energy services by 2030 (SDG 7.1); to substantially reduce the air pollution which causes deaths and illness (SDG 3.9); and to take effective action to combat climate change (SDG 13). The objective of the SDS is to lay out an integrated strategy for the achievement of these important policy objectives, alongside energy security, in order to show how the respective objectives can be reconciled, dealing with potentially conflicting priorities, so as to realize mutually-supportive benefits. A key distinction between CAS and SDS is the stated ambition of reaching energy access and climate goals in the latter, which requires a more comprehensive and faster clean energy transition than the one achieved in CAS. Actions on one of the three SDGs can often assist in achieving another. Therefore, the approach adopted in SDS is to focus first on universal access, while low-carbon technologies provide a suitable route in many instances to achieve energy access. Developments in all countries are modelled to remain within the required carbon constraint, guided by the policy and technology preferences that countries have today. The mixture of technologies deployed to meet climate objectives is also shaped by the requirement to reduce air pollution.

In terms of air quality, SDS does not aim at the achievement of a specific universal pollution exposure targets within the projection period 2020-2040. Instead, the scenario suggests a mix of measures for a maximal reduction of air pollutants. For this purpose, the scenario assumes highest feasible application rates for abatement technologies and policy practices to reduce pollutant emissions. It also assumes that policy signals are sufficiently strong and aligned to ensure that energy investment decisions take into account air pollution and climate goals at the same time, in order to avoid undesired lock-in effects and reduce the overall costs of compliance. For example, retrofitting existing inefficient coal-fired power plants with scrubbers or filters to reduce air pollution today is not economic if the plants are to be retired tomorrow to meet the shared climate goal.

3. Methods

In a first step of the scenario analysis, we use the IEA's World Energy Model (WEM) to project the evolution of the global energy system. WEM is an energy system model with 25 world regions that comprises a detailed representation of the energy sector from supply to transformation, transmission, distribution and use. It builds sectoral and regional energy balances by looking in detail into questions such as the evolution of activities by sector (e.g., vehicle-kilometers driven in transport, or the evolution of demand for steel or aluminum in industry, or the demand for lighting, cooking and heating in the buildings sector) and assesses technological performance, efficiencies, investment needs and fuel costs, as well as the prices that are needed to satisfy demand. For the analysis of electricity access, WEM combines cost-optimization with geospatial analysis that takes into account current and planned transmission lines, population density, resource availability and fuel costs. Among the key outputs of the model are projections of energy-related greenhouse-gases (GHGs), however, the model does not, in isolation, generate projections for air pollution (OECD/IEA, 2017).

In a second step, we consider scenario-specific implications and requirements to reach universal access to modern energy, to address climate change and ambient air pollution (AAP). Our analysis takes these environmental goals as equally important and does not weigh short-term benefits against longer term gains. In terms of climate change, the point of departure for SDS is a pathway that meets key objectives of the Paris Agreement through 2040, i.e., a peak in emissions as soon as possible and a steep decline thereafter. This target requires taking ambitious action, using all available technologies (even if not commercially available today at significant scale), to keep the world on track through the projection period towards the long-term objectives of the Paris Agreement. The temperature target achieved by 2100 depends on further progress in emissions reductions after 2040, and action taken outside the energy sector. By 2040, the energy- and process-related CO_2 emissions of the SDS are at the lower end of a range of publicly available decarbonization scenarios, all of which estimate a temperature increase of around 1.7–1.8 °C in 2100. The resulting activity projections in SDS, however, differs to climate-only pathways, as the required additional achievements of universal access and reduced air pollution lead to different outcomes; for example, higher demand for energy services from universal access, higher fuel input in thermal combustion processes resulting from the use of air pollution control devices, and differences in technology choices to encompass the different policy goals in an optimal fashion (IEA, 2017).

Analytically, we approach the second step of the analysis by running WEM in iterations with the Greenhouse Gas and Air Pollution Interactions and Synergies (GAINS) model over the implications for air pollutant emissions that arise from the achievement (or absence) of climate goals and clean energy access. GAINS is a widely recognized model which estimates emissions of air pollutants by country, using international energy and industrial statistics, emission inventories and data supplied by countries. It uses the WEM outputs to assess the future path of pollutant emissions by country in five-year intervals through to 2040 for different scenarios and policy packages (Amann et al., 2011). The purpose of multi-model iterations is to identify a portfolio of least-cost technology options that achieve various goals and policy objectives. For instance in SDS, measures are selected for each country individually, according to specific national circumstances, with two intentions: first, to increase the pace of the energy transition towards the use of low-carbon technologies, essential to meet climate as well as air pollution goals, and, second, to ensure that existing policy and technology best-practices for reducing air pollution accompany the low-carbon carbon transition so as to significantly improve air quality.

The GAINS model calculates the effects of levels of emissions on ambient air quality, and the subsequent impacts on human health and ecosystems. GAINS captures the impact of primary PM, as well precursors to secondary PM (i.e., SO_2, NO_x, ammonia and volatile organic compounds) emissions on ambient $PM_{2.5}$ concentrations. Emissions of all air pollutants are computed globally for 174 regions, countries or provinces. Concentrations and health impacts are calculated for a subset of countries covering Europe, East Asia (China, Korea, Japan), India and South-East Asia (Indonesia, Thailand, Vietnam, others), Latin

America (Argentina, Brazil, Mexico) and South Africa. Since the chemistry transport model simulations underlying the atmospheric dispersion calculations in GAINS are computationally expensive, ambient pollution levels are not yet computed globally. The impact regions covered by GAINS in this study, however, correspond to almost 70% of current global premature deaths due to outdoor air pollution (WHO, 2016). Additional regions (e.g., Nigeria, the US) are under implementation in a forthcoming model version. Besides anthropogenic sources, suspended soil dust, sea salt, and forest fires are considered in the model as natural sources of emissions. Forest fires are based on gridded emission data reported by (Wiedinmyer et al., 2011), averaged in 2005–2015 to compensate for the high spatial and seasonal variability. These emissions are kept constant across scenarios.

Our analysis uses transfer coefficients derived from sensitivity simulations with a full atmospheric chemistry transport model on a $0.5^\circ \times 0.5^\circ$ grid (Simpson et al., 2012). To capture the level of concentration of $PM_{2.5}$ in cities, grid concentrations are calculated separately for the urban and rural parts of each grid cell, which are identified using urban extent shapes from the Global Rural-Urban Mapping Project (CIESIN, 2017). A downscaling approach similar to that described by (Kiesewetter et al., 2015) is used, which distributes $PM_{2.5}$ emissions from household combustion and road traffic to population using a 100 × 100 m resolution from the Worldpop project (Tatem, 2017). The resulting $PM_{2.5}$ concentration levels are used to estimate population exposure. Spatially explicit projections of future population density are computed by applying country specific urbanization rates from the UN World Urbanization Project (UNDESA, 2014) to gridded urban and rural population.

The calculation of premature deaths from AAP and HAP follows the methodology used by the Global Burden of Disease (GBD) 2013 study (Forouzanfar et al., 2015), calculating the fractions of deaths attributable to AAP and HAP by disease and age within total disease and age-specific deaths. Integrated exposure-response relationships (the same for AAP and HAP), adopted from (WHO, 2016; Forouzanfar et al., 2015), are used to derive the relative risk at a given concentration of $PM_{2.5}$ for five illnesses: chronic obstructive pulmonary disease, ischemic heart disease, acute lower respiratory infection, lung cancer, and stroke. Projected age-specific baseline death rates are taken from the UN World Population Projections (UNDESA, 2011). It is assumed that while the overall life expectancy might increase over time, age-specific contributions from individual diseases to total deaths within each age group remain constant. For HAP, it is assumed that users of traditional solid fuel-based cook-stoves are exposed to annual average indoor concentration levels of 300 μg per cubic meter ($\mu g/m^3$) – within the range reported by (Smith et al., 2014) and (Balakrishnan et al., 2013), and users of clean solid fuel stoves to 70 $\mu g/m^3$. Following the GBD approach, HAP is treated as an independent risk factor and is therefore calculated separately from AAP; resulting numbers of AAP and HAP related premature deaths are not additive.

4. Results

4.1. Current status

The energy sector is the largest source of air pollution emissions from human activity. They come primarily from the combustion of fossil fuels and bioenergy (Fig. 1), but also from mining and fuel extraction, processing and transportation of fuels, oil refining and charcoal production, industrial process activities, as well as from non-exhaust sources in the transport sector (e.g., road dust and abrasion, tire and brake wear). Taking each of the main pollutants in turn, we estimate that, in 2015, the energy sector was responsible for over 80 million tons (Mt) of SO_2 emissions, with over 45% from industry and one-third from the power sector. In recent years, global emissions of NO_x continued to increase and they stood at 110 Mt in 2015, with transport accounting for the largest share (over 50%), followed by industry (26%) and power (14%). More than half of global energy-related fine particulate matter emissions come from the residential sector, however, non-energy sectors, such as waste treatment and agriculture, contribute significantly to the current $PM_{2.5}$ emission levels.

Over one-quarter of total SO_2 emissions arose in China (22 Mt), where industry accounts for nearly two-thirds of the total, the power sector having moved rapidly to install various forms of emissions abatement technology over the last decade. India was the next largest source of SO_2 emissions (9 Mt); a development that is spurring increased regulatory efforts to tackle emissions from a coal-dominated power sector. Increases in NO_x emissions in many developing countries have been rapid and they volumetrically outweighed the declines seen in a number of developed countries. China (23 Mt) and the United States (13 Mt) account for one-third of global NO_x emissions (Fig. 2). Transport, including land- and ocean-based, is the largest emitter of NO_x in many world regions, but China is a notable exception with industry being the largest source. India's NO_x emissions are on an upward path, now having reached a level similar to that of Europe – albeit with a population that is more than twice as large. The regional picture for $PM_{2.5}$ is heavily skewed towards Africa and Asia (China and India, in particular), with 80% of the global total. In these regions, $PM_{2.5}$ emissions are due mainly to incomplete combustion of fuels in households, particularly for cooking (bioenergy), heating (bioenergy and coal) and lighting (kerosene). More so than many other major energy-related pollutants, emissions of $PM_{2.5}$ are heavily concentrated in developing countries and in one sector.

4.2. Emission trends

Efforts to reduce air pollution span all key sectors in the NPS scenario. With the strong policy focus on renewables in particular, and with additional policies to increase air pollution control and monitoring in many countries, power sector emissions of all air pollutants fall, despite a rise in electricity demand. Today, at a global level, air pollutant emissions from power generation mostly relate to the use of coal; the exception is SO_2, to which oil also makes an important contribution, for example in the Middle East. In 2040, in NPS, SO_2 emissions from the power sector are globally more than 40% lower than today, as the use of oil for power generation declines. NO_x emissions decline by 20% and $PM_{2.5}$ emissions fall by around one-third.

Policies considered in NPS for the transport sector also successfully reduce emissions of NO_x and SO_2. Transport-related SO_2 emissions stem mostly from the use of heavy fuel oil in shipping and they fall by nearly 60% following new regulations by the International Maritime Organization. NO_x emissions, which come mostly from road vehicles, fall by nearly 20% to 2040, despite a doubling of the vehicle fleet. One reason is the increasing uptake of electric cars, which rises to 280 million by 2040 (from 2 million today); the other reason is that vehicle emissions standards in the major global car and truck markets are becoming increasingly stringent.

$PM_{2.5}$ emissions from transport essentially stay flat, as improvements in emissions standards for trucks are offset by the overall increase in the global car and truck fleet (pushing up $PM_{2.5}$ emissions associated with abrasion, brakes and tires). The industry sector is the only one in which, at a global level, there is no reduction in any of the main air pollutants. Although regulations, often stringent, are in place in many countries, the rise in industrial production and the lack of success in decarbonizing fuel use in NPS (which assumes existing and announced policies) means that industry-related SO_2 emissions grow slightly by 2% through 2040, NO_x emissions by 3% and $PM_{2.5}$ emissions by around 25%. The primary contributors to growing industrial $PM_{2.5}$ emissions are process-related emissions from cement, iron and steel production.

The buildings sector is the main contributor to $PM_{2.5}$ emissions at a global level, largely as a result of the traditional use of biomass for cooking in developing countries. These emissions fall significantly as an

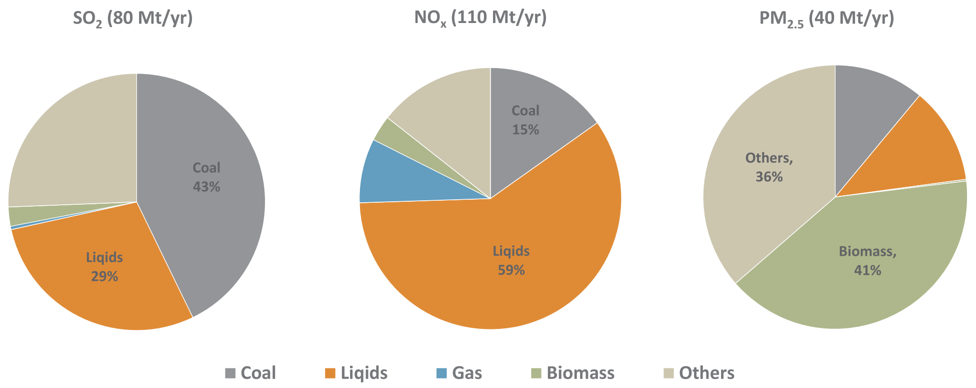

Fig. 1. Estimated anthropogenic emissions of the main air pollutants by source, 2015.

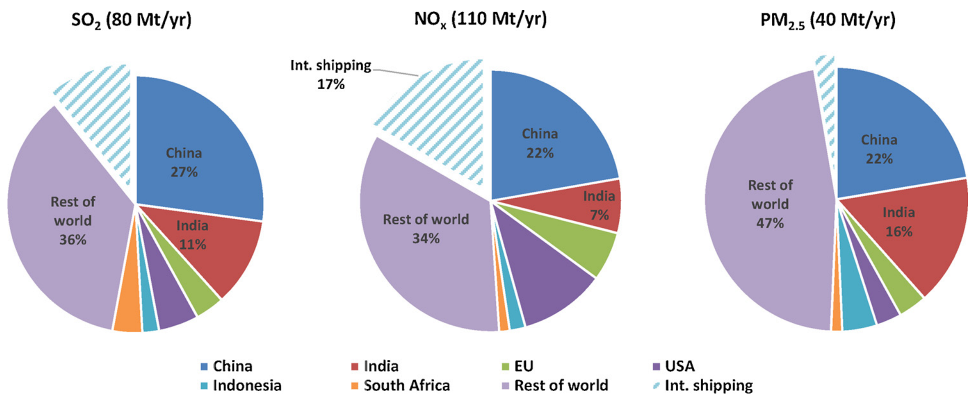

Fig. 2. Estimated anthropogenic emissions of the main air pollutants by region, 2015.

increasing number of people get access to other means of cooking, although they still constitute the largest source of $PM_{2.5}$ emissions in 2040 in NPS. SO_2 emissions fall by 40%– in 2040, also driven by increasing access to clean cooking facilities. NO_x emissions fall only modestly, as increasing emissions in the services sector partially offset the global decline in the residential sector.

In CAS, policies to avoid emissions (i.e., through energy sector transformation) and to reduce emissions (i.e., through mandating emissions controls) contribute substantially to the emissions savings relative to NPS (Fig. 3). Most of the decline of SO_2 emissions rests on measures to cut emissions from fuel combustion through end-of-pipe measures, smaller reductions come from process-related emissions savings in the industry and transformation sectors. Half of the combustion-related savings occur in the power sector and are in large part achieved by emissions controls and the remainder being from increased use of renewables. Around one-third of combustion-related emissions savings are secured in the industry and transformation sectors, in particular by reducing sulfur emissions from coal combustion (through imposing tighter pollution standards in the iron and steel industry) and oil combustion (particularly in the chemicals industry).

Around 70% of the NO_x emissions reductions in 2040 in CAS relative to NPS are from policies and technical measures that cut emissions from the combustion of fuels; the remainder come from structural improvements in energy and industrial sectors. About half of the combustion-related emissions savings are achieved in the transport sector and originate mainly from more stringent pollutant emissions standards in CAS, which are particularly effective in reducing NO_x emissions from road freight vehicles. For passenger cars, measures to avoid or reduce urban traffic contribute around 5% of all transport-related NO_x emissions savings in CAS relative to NPS, while energy

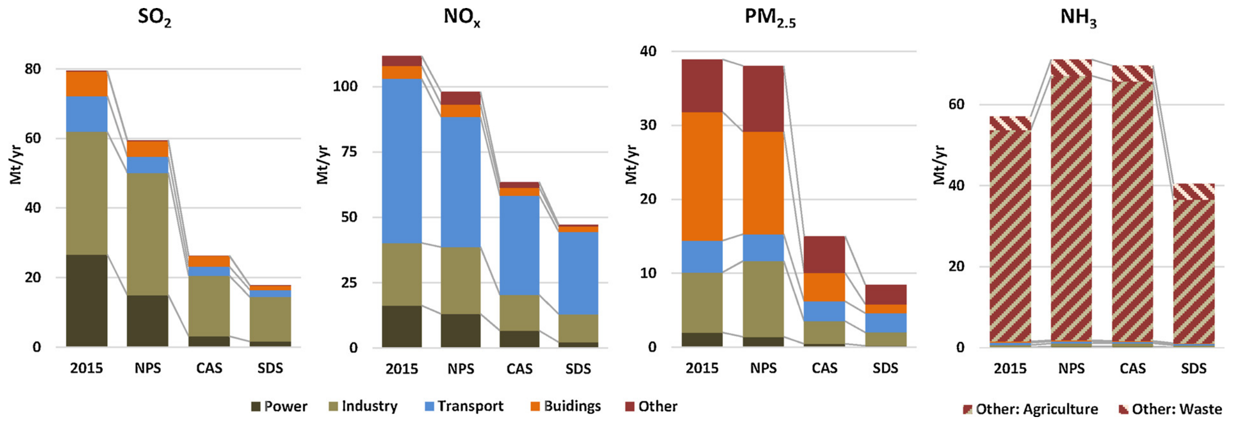

Fig. 3. Global air pollutant emissions by sectors in 2015 and by scenarios in 2040.

efficiency policy plays a cost-effective, complementary role.

Almost half of the global reductions in $PM_{2.5}$ emissions in CAS rests on measures to avoid emissions in the residential sector through fuel mix changes favoring low-emitting alternatives and efficiency improvements including a faster uptake of clean cook-stoves. A large share of the $PM_{2.5}$ emissions savings in CAS are achieved by reducing emissions from industrial processes, in particular in the iron and steel, and cement sectors. 10% of the global reduction of $PM_{2.5}$ emissions comes from emission control strategies related to the combustion of fuels in the industry and transformation sectors, while transport contributes another 6% (mostly road transport).

Although open burning of agricultural residues causes non-negligible emissions of particulates, which are relevant especially for regional air pollution, agriculture sector contributes mostly to ammonia (NH_3) emissions, an important precursor of ambient PM (Kirkby et al., 2011). In NPS and CAS scenarios, NH_3 emissions increase following increased demand for food and associated livestock and crop production, because there are no additional policies assumed beyond current legislation, which is limited to only few countries and some very large farms. The development of agricultural production is modelled based on projections by (Alexandratos and Bruinsma, 2012).

Achievement of the three SDG goals simultaneously is the intention of the SDS scenario. The overall objective of SDG 7 is universal access to affordable, reliable, sustainable and modern energy services by 2030. According to our analysis, achieving this goal accounts for about a quarter of the reduced $PM_{2.5}$ emissions in SDS. However, its relevance for human health is even greater than this. Securing universal energy access basically eliminates HAP by 2030 and is the main reason why related premature deaths fall (Section 4.4). The long-term transition to a low-carbon energy sector modelled in SDS is a decisive factor to the mitigation of climate change and at the same time contributes in an efficient way to minimize the impact of energy/industry sectors on human health through avoiding related air pollutant emissions altogether. Cumulative energy-related CO_2 emissions to 2040 in SDS are 195 Gt lower than in NPS, falling to 18.3 Gt in the year 2040.

All air pollutant emissions fall in SDS: SO_2 drops by 70% in 2040 relative to NPS, NO_x emissions fall by more than 50%, $PM_{2.5}$ emissions are reduced by 80%, while NH_3 by about 40% due to measures in agriculture, including improved fertilizer application and manure management options. For comparison, respective reductions over CAS in 2040 are reported at 30% for SO_2 and NO_x, and 45% for $PM_{2.5}$ emissions. The significant emissions declines in SDS are facilitated by the package of adopted cost-effective policies, although the degree to which each individual policy contributes to the decline in CO_2 and air pollutant emissions varies. In contrast to CO_2, the global decline in air pollutant emissions is attributable to all three pillars of SDS (Fig. 4).

The achieved reductions in CAS and SDS for key air pollutants vary significantly across countries and regions. Detailed description of regional emission trends in all scenarios is provided in the Supplementary material (Section S2).

4.3. Outlook for air quality

While no clear indication of a lower concentration threshold for health impacts from $PM_{2.5}$ has been found so far (Crouse et al., 2012), the WHO air quality guideline recommends a maximum annual mean concentration of $PM_{2.5}$ at 10 $\mu g/m^3$ (WHO, 2006). The WHO has introduced a series of interim targets that are less stringent, but represent an attainable set of milestones on the path to better air quality: Interim target-1 (25–35 $\mu g/m^3$), Interim target-2 (15–25 $\mu g/m^3$) and Interim target-3 (10–15 $\mu g/m^3$). In Fig. 5, we characterize ambient air quality by the shares of population living above and below these interim targets, as well as the population-weighted mean $PM_{2.5}$ concentrations. In NPS, large parts of the population in many countries continue to live in 2040 with a level of air quality that does not comply with the WHO guideline for average annual $PM_{2.5}$ concentrations. Worse, in many countries, large parts of the population will be living with air quality that does not meet even the WHO interim target-1 (Fig. 5). For example in India, in NPS, despite the current policy attention to the issue, 72% of the population in 2040 are projected to live at a concentration level above the WHO target-1 (seven percentage points above today's level), and only 1% at a level that is compatible with the ultimate WHO guideline.

In China, the national air quality standard for $PM_{2.5}$ is an annual mean concentration of 35 $\mu g/m^3$ (comparable with WHO interim target-1). In NPS, the share of the population that lives at a concentration above it in 2040, at 46%, is only nine percentage points lower than today, while the share of the population living below the concentration level of the ultimate WHO guideline increases by only one percentage point, to 4% in 2040.

In Indonesia, the level of exposure to $PM_{2.5}$ concentrations in 2040 increases relative to today: 30% of the population lives above the WHO interim target-1 (compared with 25% today), while about one-quarter of the population remains to live in areas meeting the ultimate WHO guideline. In South Africa, the population exposed to a $PM_{2.5}$ concentration above the WHO interim target-1 is reduced from 27% today to about 10% in 2040, and the ultimate WHO guideline is reached for more than 40% of the population across the country. In contrast, policy efforts of the EU are expected to bear more fruit: by 2040 in NPS, more than 80% of the population are projected to live in areas meeting the WHO guideline (from just above half today) and almost no part of the population is exposed to levels above WHO interim target-2. It is noted that modelled concentrations in South America (e.g., Brazil) are not discussed here being comparatively lower than in other regions, while some major emitting countries (Nigeria, the US) were not covered by atmospheric transfer calculations in GAINS (see Section 3).

In CAS, the implementation of additional policies to avoid and reduce air pollutant emissions results in significant improvements is air

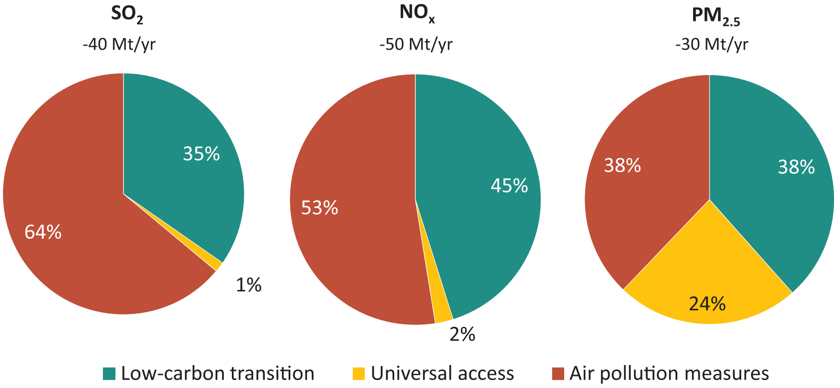

Fig. 4. Air pollutant emissions savings by policy area in SDS relative to the NPS scenario, 2040.

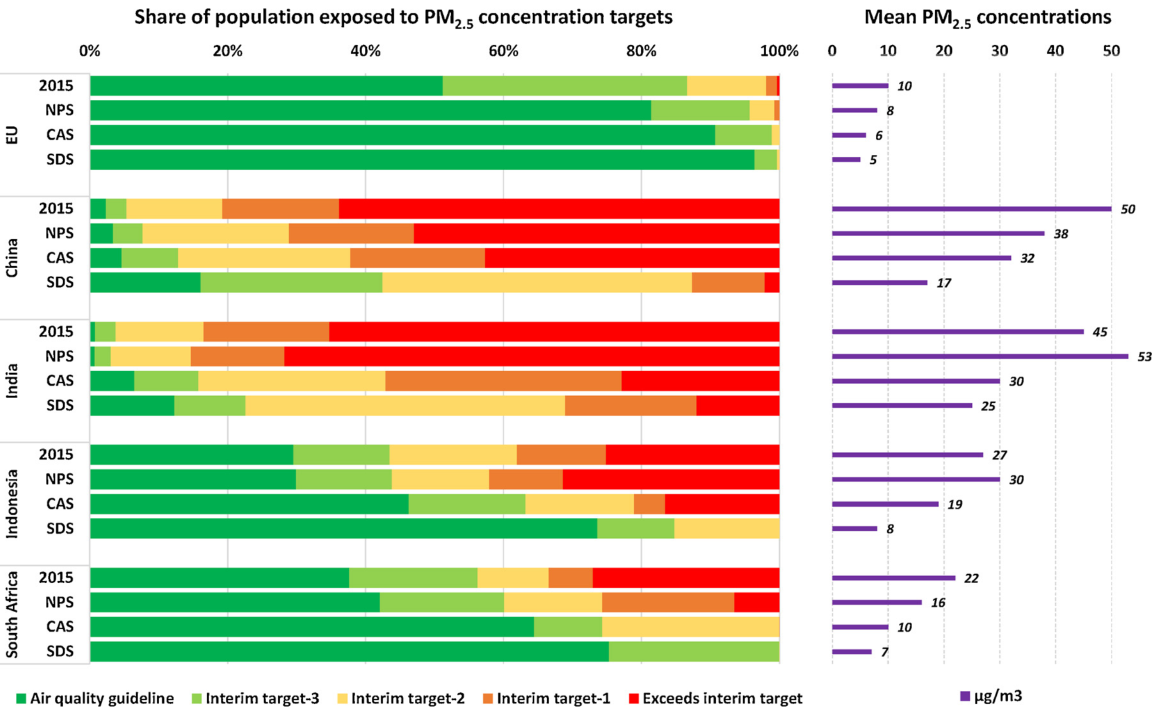

Fig. 5. Shares of population exposed to various $PM_{2.5}$ concentrations by WHO interim targets/guidelines (left panel), and population-weighted mean $PM_{2.5}$ concentrations (right panel) in selected regions by scenario in 2040.

quality. India sees the share of the population exposed to average annual concentrations of $PM_{2.5}$ above the WHO interim target-1 fall below 25% in 2040. China reaches its national air quality target of 35 µg/m^3 already during the 2020s and the share of the population living above it shrinks to 40% in 2040. In Indonesia, CAS implies that more than 80% of the entire population could live at concentrations of $PM_{2.5}$ that are compatible at least with the WHO target-2 by 2040; about half would live at a level compatible with the ultimate WHO guideline. Similarly, in South Africa, no part of the population is exposed to $PM_{2.5}$ concentration levels worse than WHO target-2, although the ultimate WHO guideline is not met.

The SDS scenario brings about further significant improvements in air quality, even if a pollution-free environment is not fully achieved. India sees the share of the population exposed to average annual concentrations of $PM_{2.5}$ above the WHO interim target-1 fall to 12% in 2040. In Indonesia, SDS implies that the entire population could be subject to concentrations of $PM_{2.5}$ that are compatible at least with the WHO target-2 by 2040; three-quarters would have a level compatible with the air quality guideline. Similarly, in South Africa, no part of the population is exposed to $PM_{2.5}$ concentration levels worse than WHO target-3 and the majority lives in areas compatible with the air quality guideline.

4.4. *China in focus*

We illustrate our results further by focusing on China. The Chinese government has long recognized the extent of air pollution and the data reflect the impact of recent policies to address the issue (Mao et al., 2014; Zhao et al., 2016). A notable tightening of China's policy in this area came in 2013 with the Action Plan for Air Pollution Prevention and Control (Jin et al., 2016). The Action Plan is a roadmap at provincial level for efforts to improve air quality over the period 2013–2017. It aims to reduce $PM_{2.5}$ pollution towards the National Ambient Air Quality Standard of 35 µg/m^3. It also contains detailed measures to address other pollutants. Although the Action Plan is national in scope, it focuses on three regions in particular: the Beijing-Tianjin-Hebei area, the Yangtze River Delta and the Pearl River Delta. These regions have $PM_{2.5}$ reduction targets of 25%, 20% and 15% by 2017 (compared with 2012 levels), with the $PM_{2.5}$ concentration for Beijing capped at an annual average 60 µg/m^3.

Nevertheless, air quality remains an acute problem in many parts of the country (Fig. 6). According to the Ministry of Environmental Protection, almost three out-of-four Chinese cities have not yet met the required domestic air quality criteria. The main industrial centers, in particular Beijing, Tianjin and the Hebei province, continue to register the presence of high levels of all major air pollutants (Gao et al., 2017). In December 2016, the State Council published the 13th Five-Year Plan for Ecological and Environmental Protection (2016–2020). According to the plan, China's 338 largest cities must meet "good" levels of air quality 80% of the time by 2020, compared with 77% in 2015, and large cities that did not meet standards for $PM_{2.5}$ concentrations by 2015 have to cut their average by 18% by 2020, compared with their 2015 level.

We estimate that currently only about 2% of the population in China breathes air with a level of $PM_{2.5}$ concentrations that complies with the WHO guideline, and only one-third of the population breathes air that meets the national standards. Under the NPS assumptions, emissions of all air pollutants fall and concentrations of fine particulate matter drop. In 2040, almost half of the population lives in areas compatible with the national air quality standard (from 36% today); but only 3% live in areas that comply with the WHO guideline. As shown in Fig. 6, the SDS scenario provides considerable further improvements to air quality in China. By 2040, nearly all the population live in areas where air quality is compatible with the National Air Quality Standard, while the share of the population living above WHO interim target-1 shrinks to 2%.

4.5. *Impacts on human health*

Despite significant improvements in air quality in NPS, air pollution remains a major issue particularly in developing Asia by 2040, mainly because a) the population ages and becomes more vulnerable to the impacts of air pollution, and b) urbanization increases, thus placing more people in highly polluted areas. This finding has been already observed by other studies, e.g., (Lelieveld et al., 2015). As a result, the

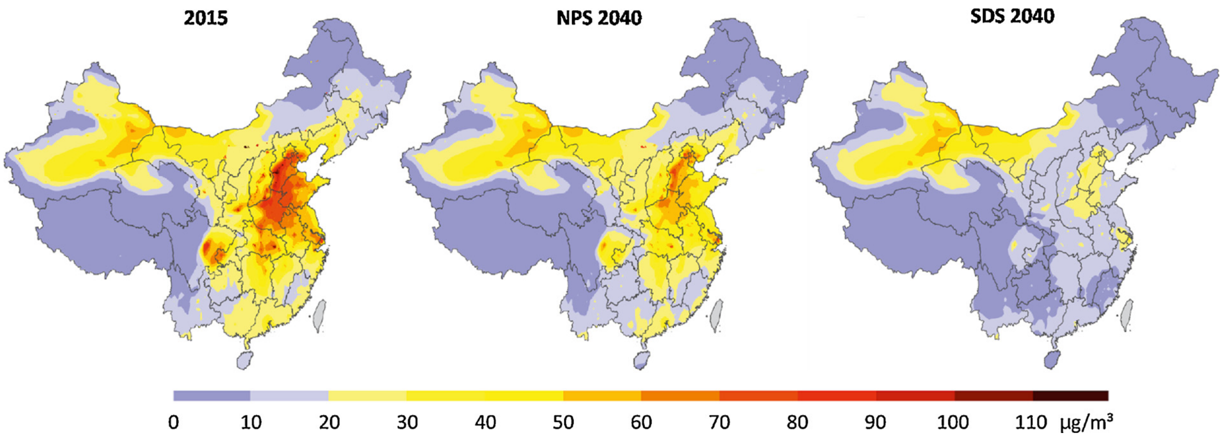

Fig. 6. Concentration of $PM_{2.5}$ in China by scenario.

number of people in China dying prematurely from AAP increases from just below 1 million today to 1.4 million in 2040. In India, the deteriorating air quality in NPS results in a death toll that keeps rising: by 2040, 0.9 million die prematurely each year from AAP, compared with 0.5 million today. Similarly, in Indonesia air pollution remains a serious health concern, expecting 0.14 million die prematurely from AAP in 2040, compared with 0.1 million today. In contrast, the number of premature deaths in the EU decreases by one-quarter by 2040, relative to current levels.

In NPS, the decreasing use of coal heating and solid biomass for cooking reduces $PM_{2.5}$ emissions by around 20% worldwide, contributing to a decline of half a million in the number of people dying prematurely from HAP in developing countries by 2040. The biggest part of this reduction is achieved in China with the move to cleaner fuels in households (Fig. 7). The reduction is less prominent in India. Although the reduction in the use of traditional stoves by 2040 is substantial in India, premature deaths do not fall by a similar amount as the benefits are partially offset by strong population growth and aging, as well as by the continued reliance of many people on biomass with improved (less emitting) cook stoves.

Air-quality-oriented policies assumed in CAS induce significant reductions of impacts from both ambient and household air pollution on human health. By 2040, this scenario delivers about 0.2 million avoided deaths in China and nearly 0.5 million in India, from outdoor and indoor exposure combined. Corresponding mortality impacts are reduced by 40% and 50% in Indonesia and South Africa, relative to NPS. The SDS results in even more dramatic health improvements. By 2040, there are nearly 0.5 million fewer people in China who die prematurely from the impacts of outdoor air pollution than in NPS, stabilizing the health impact of AAP at just below today's level despite an ageing and urbanizing population. Meanwhile the impact of HAP is reduced by three-quarters as the use of polluting fuels for cooking in rural areas declines. In India, about 0.6 million premature deaths are avoided by 2040, and this decline is equally distributed among lower exposure to AAP and HAP. The universal access to clean energy – as projected in SDS - helps to minimize HAP in the whole developing world with important benefits for human health, reducing the related premature deaths by 1.8 million in 2030 and 1.5 million in 2040, over NPS.

4.6. *Implications for costs of pollution abatement*

Pursuit of the policy goals of SDS comes with important development, climate and health benefits as described above. However, its achievement requires significant additional investment in the energy sector itself, an additional \$9 trillion net through 2040, relative to the investment needs in the NPS case (Fig. 8). Around two-thirds of this increment is used to improve the energy efficiency and fuel mix of end-use sectors, while the remainder are investments in low-carbon power sector. These investment requirements are partially offset by the resulting lower need for investment in fossil-fuel supply and power generation. Additional energy system investments are about 70% lower in the CAS scenario, which misses the climate mitigation aspirations of SDS.

The level of incremental investment needed in developing countries to achieve universal access to modern energy is minor and amounts to around \$0.8 trillion cumulatively to 2040 in both CAS and SDS scenarios. The additional investment needed for pollution control in SDS is of a similar magnitude to that for access, however, it is just about two-

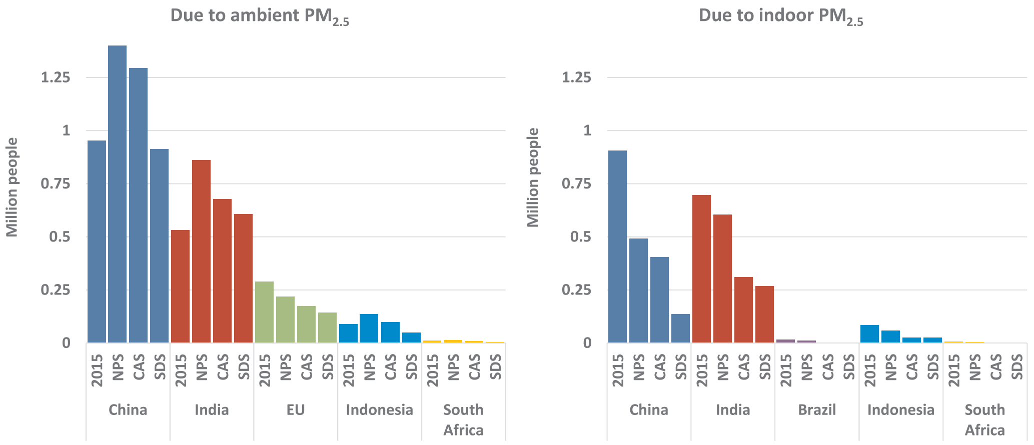

Fig. 7. Premature deaths from ambient and indoor air pollution in selected regions by scenario in 2040.

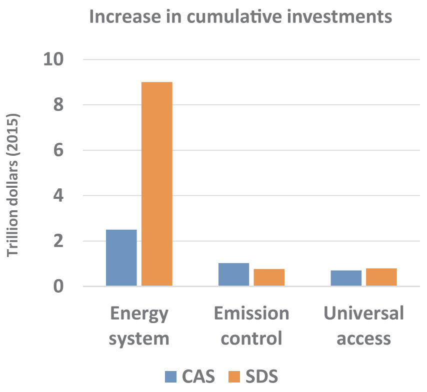

Fig. 8. Increase in cumulative investments (2015–2040) relative to the NPS scenario.

thirds of cumulative expenditures reported for the CAS scenario with a significantly larger share of fossil energy consumption by 2040.

Majority of additional investment in post-combustion control measures is required in the transport sector (mostly in road transport), followed by the buildings sector. Investments in end-of-pipe technologies in the power sector increase only marginally, due to lower electricity demand and higher use of non-fossil sources, relative to NPS, cutting the investment needs for coal-fired power plants. Around two-thirds of the additional investment in the SDS and CAS scenarios is required in developing countries, in particular in Asia. Among the industrialized countries, the United States and the EU require most of the investment.

It is noted that each country has different investment needs over NPS: the investment focus in most industrialized countries is on additional measures to avoid air pollution through energy sector transformation, while the investment focus in developing countries is on increasing measures to reduce emissions through post combustion control and reducing process-emissions. To secure funding to meet investment needs in developing regions might be particularly challenging due to competing development goals, and will most likely require a portfolio of domestic and international entities, as well as foreign development programs (Amegah and Agyei-Mensah, 2017; McCollum et al., 2018).

5. Summary

The approach of treating individual sustainability goals in isolation has limitations. The 17 SDGs of the 2030 Agenda for Sustainable Development formally came into force in early 2016. The SDGs, for the first time, integrate multiple policy objectives, recognizing, for example, that ending poverty must go hand-in-hand with strategies that build economic growth and address a range of social needs, while also tackling climate change and strengthening environmental protection. Just a few months later, in November 2016, the Paris Agreement entered into force, and around 170 countries have now ratified it. It builds on the NDCs offered by those countries, primarily to address climate change, though many countries place their contribution within other policy goals, including ending poverty or reducing air pollution. In this context, there is a clear need to shift towards systems approach: focusing on a specific goal individually might risk a lock-in of economies in pathways that impede the achievement of other SDGs, or at least makes their attainment more expensive or more difficult.

The multiple benefits of a joint approach towards achieving air pollution-related SDGs are quantified through scenario analysis and presented in this paper. Current policy efforts, as simulated by the New Policies Scenario, result in significant improvements relative to the recent past in terms of managing energy demand, CO_2 emissions and local pollution. However, NPS falls short of achieving three key SDGs: universal access to clean energy, substantial GHGs reduction, and minimized impacts from air pollution. By 2030, there are still more than 2 billion people without access to clean cooking facilities and 0.7 billion people remain without electricity. Global CO_2 emissions rise by 0.4% per year through to 2040, driven upwards by emerging economies, suggesting the world is not on track to achieve the temperature goals of the Paris Agreement. Furthermore, despite progress in reducing air pollution in many countries, there are still 4.2 million premature deaths - projected by 2040 - linked to outdoor air pollution and 2.5 million premature deaths from the impact of indoor air pollution.

A single-objective policy agenda focused on air pollution abatement is illustrated by the Clean Air Scenario, which sets out a pragmatic strategy, based on existing abatement technologies and proven policies, to cut 2040 pollutant emissions by more than half compared with NPS. This target requires interactions with other SDGs: by 2030, CAS delivers access to electricity to 0.5 billion more people, and above 1 billion people than otherwise projected adopt cleaner cooking. Additionally, CAS achieves sizeable CO_2 reductions as a side benefit of increasing share of renewables and energy efficiency improvements. In combination with the implementation of the best available pollution controls, this policy scenario achieves its objectives in terms of emission reductions and resulting health benefits.

The Sustainable Development Scenario that addresses three SDG targets simultaneously, delivers even more. Gains in energy efficiency and up-scaled renewable energy play almost equal roles in reducing CO_2 emissions by more than 13 Gt despite rising energy service demand. CO_2 emissions from energy and industrial processes peak before 2020 and show a steep decline through 2040, indicating the GHG trajectory is consistent with the global temperature growth target of the Paris Agreement. Climate mitigation target and access to clean energy reinforce each other. Universal access is achieved in 2030 in SDS, implying two million fewer people than today die prematurely in 2040 from HAP, and compared to NPS, 1.5 million fewer people die prematurely due to HAP. The pursuit of policies directed to reduce AAP also brings about significant improvements in human health, reducing the number of people dying prematurely from the impacts of AAP by 1.6 million in 2040, relative to NPS.

The significant investment needs required by the three objectives of the SDS scenario should be viewed against the background of changes in total expenditures and benefits within the energy system. The avoidance of energy demand, due to efficiency gains, is rewarded in terms of avoided energy expenditure, higher levels of energy security, and avoided investments in new energy supply assets and in pollution controls. Reduced fossil-fuel use, stemming from energy efficiency and renewable energy, delivers lower GHG emissions, lower fuel import bills for importing countries, better buildings, reduced air pollution and associated health improvements. Additional investment costs for achieving universal access and for post-combustion pollution control measures are modest when compared to the additional investments needed for the transformation of the global energy system. However, the societal benefits due to improved air quality and human health are worth many times more than the additional costs.

Rates of turnover in the energy and industrial sectors are slow. This makes the combined use of abatement technologies and policy instruments the best practice to achieve a meaningful decline in air pollutant emissions through 2040. Although post-combustion control technologies are readily available and cost-effective, their use typically hinges on the existence of appropriate and stringent regulatory frameworks, including not only setting emissions limits, but also monitoring and enforcement. The use of these measures is effective both to cut air pollutant emissions in the near-term and to facilitate their longer term decline, as many of the installations subjected to controls might still be in operation by 2040. Thus, multiple benefits can be realized only through concerted and coordinated policy action accompanied by economic and institutional considerations.

When considering implications of various SDGs, policy-makers need to be wary of some potential trade-offs. Measures to address climate change could, for example, lead in some instances to more air pollution: an isolated focus on reducing CO_2 emissions by encouraging the use of wood stoves, diesel cars or biofuels, could increase human exposure to fine particles. Similarly, an exclusive focus on direct emissions controls, rather than the package of measures, could result in increased commitments to high-carbon energy infrastructure, such as coal-fired power plants. Integrated policy approaches in this area are essential.

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