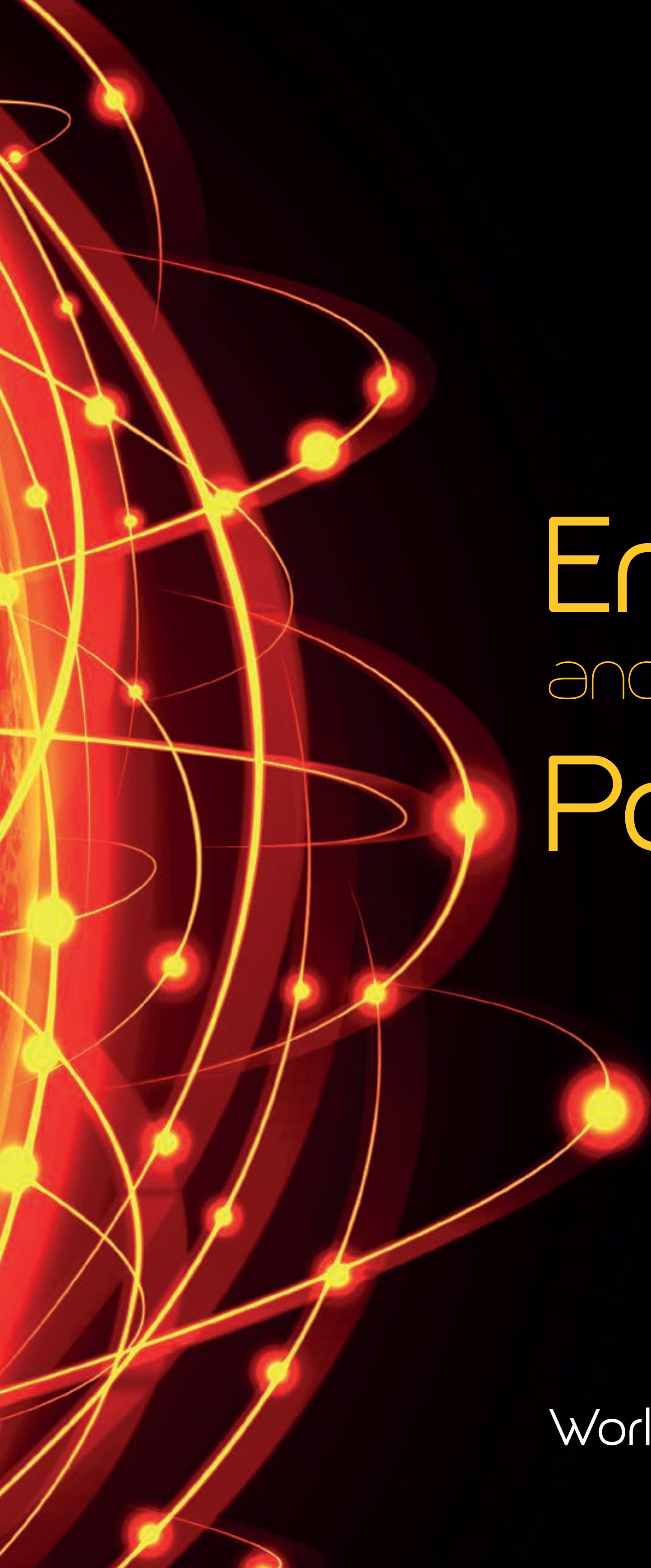

International Energy Agency
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# Energy and Air Pollution

World Energy Outlook
Special Report

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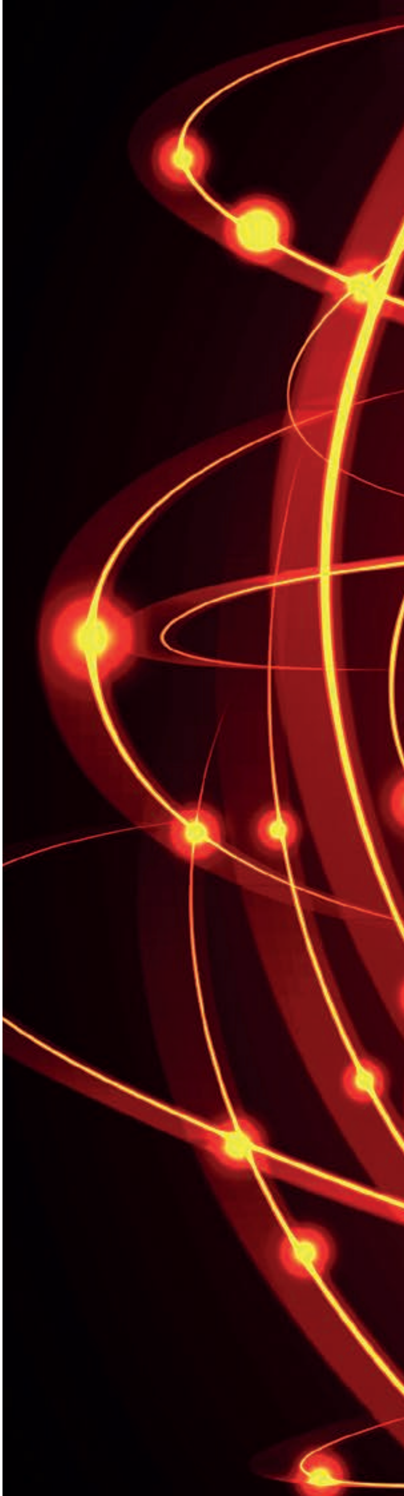
## World Energy Outlook Special Report



## INTERNATIONAL ENERGY AGENCY

The International Energy Agency (IEA), an autonomous agency, was established in November 1974. Its primary mandate was – and is – two-fold: to promote energy security amongst its member countries through collective response to physical disruptions in oil supply, and provide authoritative research and analysis on ways to ensure reliable, affordable and clean energy for its 29 member countries and beyond. The IEA carries out a comprehensive programme of energy co-operation among its member countries, each of which is obliged to hold oil stocks equivalent to 90 days of its net imports. The Agency's aims include the following objectives:

- Secure member countries' access to reliable and ample supplies of all forms of energy; in particular, through maintaining effective emergency response capabilities in case of oil supply disruptions.
- Promote sustainable energy policies that spur economic growth and environmental protection in a global context – particularly in terms of reducing greenhouse-gas emissions that contribute to climate change.
- Improve transparency of international markets through collection and analysis of energy data.
- Support global collaboration on energy technology to secure future energy supplies and mitigate their environmental impact, including through improved energy efficiency and development and deployment of low-carbon technologies.
- Find solutions to global energy challenges through engagement and dialogue with non-member countries, industry, international organisations and other stakeholders.

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Around 18 000 people die each day as a result of air pollution. In fact, the number of deaths attributed to air pollution each year – 6.5 million deaths – is, according to the World Health Organization (WHO), much greater than the number from HIV/AIDS, tuberculosis and road injuries combined. Air pollution also brings major costs to the economy and damage to the environment. Energy production and use is the most important source of air pollution coming from human activity and so, for these reasons, the IEA has – for the first time – undertaken a major study on the role of energy in air pollution.

This study – released as a *World Energy Outlook (WEO) Special Report* – reflects the IEA's new vision. An IEA that is truly international in its outlook must tackle the issues of greatest concern to developing, as well as developed, countries. No country can claim to have fully overcome the air pollution challenge, and the IEA is uniquely placed to bring decision makers together and provide evidence-based analysis and policy advice. In establishing itself as a global hub for clean and efficient energy, the IEA is seeking to help all countries of the world overcome the negative environmental impacts of energy use.

Our energy system contributes vitally to economic and social progress around the world. But there are costly side-effects. Millions of tonnes of energy-related pollutants are released each year, be it the harmful emissions from using traditional biomass for cooking, as is still common practice today for 2.7 billion people; or the emissions from cars and trucks, factories, power plants and other sources. This is not a problem that economies can expect to grow out of as they become wealthier, but one that will endure until concerted transformative action is taken.

Fortunately, there are solutions at hand. This is what this *WEO Special Report* demonstrates. It presents a strategy – in the form of a Clean Air Scenario – in which the energy sector pushes air pollution levels into a steep decline in all countries. The technologies for doing so exist and are in widespread use today. They can be applied at great net economic benefit. Concerted efforts, across areas of responsibility and between nations are required. First and foremost, a more concentrated effort needs to be made to tackle energy poverty in developing countries. Second, steps must be taken to reduce pollutant emissions through post-combustion control technologies. And third, emissions can be avoided entirely, through promoting clean forms of energy around the world. Such actions can help avoid millions of pollution-related deaths. Greenhouse-gas emissions would also be cut and fossil-fuel import bills reduced. To achieve all of this, cumulative investment in energy supply, end-use energy efficiency and pollution controls from now to 2040 needs to be no more that 7% higher than otherwise expected. This can be achieved.

One of the main conclusions of this study is that the energy sector must work closely with a range of stakeholders to tackle air pollution successfully. I am pleased to say that this *WEO Special Report* has been conducted in precisely this vein, with the co-operation of many emerging countries, research institutions and distinguished experts from around the world helping to make this groundbreaking study possible. I would like to thank the *WEO* team at the IEA for their excellent work and Herculean effort.

Modern energy is hugely important, but clean air is our most precious resource.

**Dr. Fatih Birol**
**Executive Director**
**International Energy Agency**

This report was prepared by the *World Energy Outlook* (*WEO*) team in the Directorate of Sustainability, Technology and Outlooks (STO) in co-operation with several divisions of the IEA. The Director of STO, **Kamel Ben Naceur**, provided guidance throughout the project. The study was designed and directed by **Laura Cozzi**, Head of the *WEO* Energy Demand Outlook Division. **Timur Gül** led overall modelling, Chapter 2 and all the country profiles. **Dan Dorner** and **Tim Gould**, Head of the *WEO* Energy Supply Outlook Division, co-led Chapters 1 and 3. Principal contributors to the report were: **Ali Al-Saffar**, **Elie Bellevrat**, **Philippe Benoit**, **Stéphanie Bouckaert**, **Pierpaolo Cazzola**, **Hannah Daly**, **Olivier Durand-Lasserve**, **Matthew Gray**, **Sixten Holm**, **Peter Janoska**, **Fabian Kęsicki**, **Claudia Pavarini**, **Kristine Petrosyan**, **Jacob Teter**, **Johannes Trüby**, **David Wilkinson** and **Shuwei Zhang**. Other contributors were Zakia Adam, Liwayway Adkins, Carlos Andrade, Ian Cronshaw, Araceli Fernandez Pales, Nathan Frisbee, Vincenzo Franza, Bartosz Jurga, Markus Klingbeil, Atsuhito Kurozumi, Paul Hugues, Rodolfo Lobato, Christophe McGlade, Luis Munuera, Paweł Olejarnik, Rakyung Park, Andrew Seah, Toshiyuki Shirai, Benjamin Smith and Brent Wanner. **Teresa Coon** provided essential support.

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The individuals and organisations that contributed to this study are not responsible for any opinions or judgements it contains. All errors and omissions are solely the responsibility of the IEA.

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**Air pollution is a major public health crisis, with many of its root causes and cures to be found in the energy sector.** Around 6.5 million deaths are attributed each year to poor air quality, making this the world's fourth-largest threat to human health, behind high blood pressure, dietary risks and smoking. Without changes to the way that the world produces and uses energy, the ruinous toll from air pollution on human life is set to rise. That is why this *World Energy Outlook (WEO) Special Report* is dedicated, for the first time, to the links between energy, air pollution and health. It sets out in detail the scale, causes and effects of the problem and the ways in which the energy sector can contribute to a solution.

**Energy production and use, mostly from unregulated, poorly regulated or inefficient fuel combustion, are the single most important man-made sources of air pollutant emissions**: 85% of particulate matter and almost all of the sulfur oxides and nitrogen oxides. These three pollutants are responsible for the most widespread impacts of air pollution, either directly or once transformed into other pollutants via chemical reactions in the atmosphere. They are emitted mainly as a result of:

- **Poverty**: the wood and other solid fuels that more than 2.7 billion people use for cooking, and kerosene used for lighting (and in some countries also for cooking), create smoky environments that are associated with around 3.5 million premature deaths each year. These effects are felt mostly in developing Asia and sub-Saharan Africa, where incomplete burning of biomass accounts for more than half of emissions of particulate matter. Finer particles, whether inhaled indoors or outdoors, are particularly harmful to health as they can penetrate deep into the lungs.
- **Fossil fuel-intensive development and urbanisation:** coal and oil have powered economic growth in many countries, but their unabated combustion in power plants, industrial facilities and vehicles is the main cause of the outdoor pollution linked to around 3 million premature deaths each year. Coal is responsible for around 60% of global combustion-related sulfur dioxide emissions – a cause of respiratory illnesses and a precursor of acid rain. Fuels used for transport, first and foremost diesel, generate more than half the nitrogen oxides emitted globally, which can trigger respiratory problems and the formation of other hazardous particles and pollutants, including ozone. Cities can easily become pollution hotspots, as they concentrate people, energy use, construction activity and traffic. The impact of urban vehicle emissions is heightened by the fact that they are discharged not from the top of tall chimneys but directly into the street-level air that pedestrians breathe.

## The solutions are well known, but the problem is far from being solved

**Growing attention to air pollution, together with an accelerating energy transition post-COP21, puts aggregate global emissions of the main pollutants on a slowly declining trend to 2040.** Fuel combustion increases steadily in our main scenario, to help meet a one-third rise in global energy demand. But global emissions of particulate matter are projected to fall by 7%, sulfur dioxide by 20% and nitrogen oxides by 10% over the period to 2040. This de-coupling of trends is due, in roughly equal measure, to the application of air pollution control technologies and the broader global transition to cleaner energy. Pollution controls are applied with increasing rigour in the centres of rising energy demand, mostly in Asia, where air quality regulation has struggled to keep pace with rapid industrial development and urbanisation. In parallel, the broader transformation of the energy sector – boosted by the Paris climate agreement – means that more than one-third of the projected growth in energy use is met by sources that do not emit air pollutants: wind, solar, hydro and nuclear power. Another 30% comes from natural gas, which emits less air pollution than other fossil fuels or biomass.

**Continued reductions in pollutant emissions across the industrialised world, and the onset of declines in China, are accompanied in our main scenario by modest growth in India and Southeast Asia and more rapid rises in parts of Africa.** Emissions of most major pollutants are already falling in many OECD countries, and this trend continues as total energy demand falls, the growth of low-carbon alternatives accelerates and increasingly stringent combustion-control regulations take effect. In China, a strong policy focus on air quality bears fruit and the recent dip in pollutant emissions becomes a long-term trend: emissions of particulate matter are 40% lower by 2040, as energy consumption growth slows, the energy mix diversifies away from coal and strict pollution controls are enforced. In India, the air pollution outlook worsens to 2040 as energy demand rises by 150%, although tighter standards in the power and transport sectors, the replacement of traditional cooking fuels with LPG and ambitious targets for wind and solar, all help to limit the growth in pollutant emissions to around 10%. In the absence of stronger regulation, economic growth in sub-Saharan Africa (excluding South Africa) is set to be accompanied by a steady deterioration in air quality: per capita indicators for GDP and air pollutants in 2040 reach the levels of India today, even though the projected energy mix in sub-Saharan Africa is much less dependent on coal.

**Despite the intensified policy efforts, regional demographic trends and rising energy use and urbanisation, especially in developing Asia, mean that the number of premature deaths attributable to outdoor air pollution continues to grow, from 3 million today to 4.5 million in 2040**. Asia accounts for almost 90% of the rise in premature deaths: air pollution in many of the region's growing cities continues to be a major public health hazard and, indeed, to affect a larger share of an increasingly urban population. In China, for example, an ageing population becomes more vulnerable to the effects of air pollution on human health, even though aggregate pollutant emissions are in decline. The health impacts from household air pollution improve somewhat, but remain severe. Provision of improved cookstoves and alternatives to solid biomass means that the number of people without access to clean cooking facilities is projected to fall by almost 1 billion, to 1.8 billion; as a result, the number of premature deaths attributable each year to household pollution falls from around 3.5 million today to under 3 million in 2040.

## A pragmatic, tailored alternative: a Clean Air Scenario

**The IEA proposes a cost-effective strategy, based on existing technologies and proven policies, to cut pollutant emissions by more than half compared with our main scenario.** This policy path is one in which the energy sector takes determined action, co-ordinated effectively with others, to deliver a comprehensive overall improvement. This *WEO* special report identifies three key areas for government action:

1. 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.
2. Putting in place **a package of clean air policies for the energy sector** to achieve the long-term goal, drawing on a cost-effective mix of direct emissions controls, regulation and other measures, giving due weight to the co-benefits for other energy policy objectives.
3. Ensuring effective **monitoring, enforcement, evaluation and communication:** keeping a strategy on course requires 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. It 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 the Clean Air Scenario are tailored to different national and regional circumstances, and include effective action to achieve full, universal access to cleaner cooking fuels and to electricity.** Given the diversity of local circumstances there can be no uniform policy prescription to improve air quality. The Clean Air Scenario rests instead on a suite of policy measures that – adapted in tailored combinations to reflect different national and regional settings – can bring about the targeted improvement in air quality. Organised in a simple A-I-R typology, these measures:

- **Avoid** pollutant emissions by providing energy services more efficiently or in a way that does not involve fuel combustion. Measures include higher efficiency standards, increased support to non-combustion renewable energy and alternatives to liquids fuels for transport, and improvements in public transport and urban planning.
- **Innovate** to reduce pollution abatement costs via technology improvements that will also reduce costs for the post-Paris energy transition.
- **Reduce** pollutant emissions to the atmosphere, via stringent emissions limits on combustion plants and vehicles, controls on industrial processes, fuel switching to less-polluting fuels and strict regulation of fuel quality.

**With only a 7% increase in total energy investment over the period to 2040, the Clean Air Scenario produces a sharp improvement in health compared with our main scenario: premature deaths from outdoor air pollution are 1.7 million lower in 2040 and, from household pollution, 1.6 million lower.** Investment in the Clean Air Scenario includes an extra $2.3 trillion in advanced pollution control technologies (two-thirds of this to comply with higher vehicle emissions standards) and $2.5 trillion in a more rapid transformation of the energy sector. The resultant benefits are many times more valuable. In 2040, global emissions of sulfur dioxide and nitrogen oxides are more than 50% lower, while emissions of particulate matter fall by almost three-quarters. These reductions are largest in developing countries. As a result, the share of India's population exposed to air with a high concentration of fine particles (higher than the least stringent of the World Health Organisation's interim targets) falls to less than 20% in 2040 from more than 60% today; in China, this figure shrinks below one-quarter (from well over half), and in Indonesia and South Africa it falls almost to zero. Access to clean cooking for all is instrumental in securing life-saving reductions in particulate emissions. The extra impetus to the energy transition means that global energy demand is nearly 15% lower in 2040 than in our main scenario, thanks to improvements in energy efficiency, while the use of renewables (except biomass) increases more quickly. Of the energy that is combusted, three-quarters is subject to advanced pollution controls by 2040, compared with around 45% today.

**Well-designed air quality strategies will have major co-benefits for other policy goals: the Clean Air Scenario provides for an early peak in carbon dioxide emissions, a central objective of the Paris climate change agreement.** Air pollution policy cannot be viewed in isolation: it is closely linked not only to policies for energy, but also to those dealing with climate, transport, trade, agriculture, biodiversity and other issues. Reducing pollutant emissions improves water and soil quality, crop yields and, in turn, food security. Improving air quality, via improved efficiency and increased deployment of renewables, goes hand-in-hand with the broader energy sector transformation agreed at COP21. Tackling household air pollution, via the provision of modern energy for cooking and lighting, promotes sustainable development goals dealing with poverty, education and gender equality. Policy makers have to co-ordinate their actions to take into account the potential impacts of action in one area on others and the benefits and disadvantages of the interactions. Measures to address climate change could, for example, lead in some instances to more air pollution: an isolated focus on reducing carbon dioxide 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 proposed in the Clean Air Scenario, could result in increased commitments to high-carbon energy infrastructure, such as coal-fired power plants. A solution to the world's pressing air pollution problem is within reach, but it must be grasped in a way that avoids impeding progress in other domains. Integrated policy approaches are essential and will continue to be promoted by the IEA as it strengthens its role as a global hub for clean and efficient energy: a Clean Air Scenario will bring much more than clean air.

# PART A
# GLOBAL ENERGY AND AIR POLLUTION TRENDS

## PREFACE

Part A of *Energy and Air Pollution: World Energy Outlook Special Report* presents three chapters.

Chapter 1 provides a concise primer on energy and air quality, first outlining the main causes and effects of air pollution and then focusing on the specific role and responsibilities of the energy sector. It covers the different sources and types of energy-related air pollution, the degree to which the pollutants disperse in different settings and the extent to which their concentrations in the air results in harmful exposure and measurable impacts and damages.

Chapter 2 examines the future prospects for energy and its related emissions, and concludes with an assessment of the costs of substantially eliminating energy-associated air pollutants, compared with the value in terms of human health. This reflects a first-of-a-kind assessment of the outlook for energy-related air pollution by country, sector and pollutant to 2040. The objective is to provide a clear and transparent picture of where the world is heading and guidance on possible areas for future improvement. The analysis is conducted on the basis of two scenarios: the New Policies Scenario, which includes the energy-related components of the Intended Nationally Determined Contributions pledged at COP21, and all existing and planned policies that directly or indirectly contribute to reducing air pollution; and the Clean Air Scenario, which offers a pragmatic set of measures to achieve significant additional reductions in pollutant emissions, using proven energy policies and technologies and tailored to national circumstances.

Chapter 3 builds on the analysis presented in previous chapters to highlight three key areas for action if energy-related air pollution is to be pushed into a steep decline around the world. It also explores the desirable co-benefits – in terms of climate change, energy poverty and energy security – that can be realised through positive action tackling air pollution.

# Energy and air pollution

How are they linked?

## Highlights

- Air pollution is the fourth greatest overall risk factor for human health worldwide, after high blood pressure, dietary risks and smoking. Latest estimates attribute 6.5 million premature deaths to air pollution. Among the major air pollutants, fine particulate matter is the most damaging to human health, and sulfur oxides, nitrogen oxides and ozone are associated with a range of illnesses. In addition to human health, air pollution poses risks to the environment, the economy and food security.
- Air pollutants arising from human activity overwhelmingly derive from energy production and use, mainly the combustion of fossil fuels and biomass. Three key pollutants are examined in detail in this report. Almost all sulfur dioxide and nitrogen oxides emissions to the atmosphere are energy-related, as are some 85% of emissions of particulate matter. Within the energy sector, power generation and industry are the main sources of sulfur dioxide, mostly from coal use. Oil use in vehicles and power generation are the leading emitters of nitrogen oxides. Consumption of biomass, kerosene and coal in the buildings sector, along with industrial use, are responsible for the bulk of the particulate matter reaching the atmosphere.
- The concentration of people, economic activity and energy demand in the world's growing cities means that poor air quality is often regarded as an urban problem. Yet poor air quality also affects many rural communities, particularly where households continue to rely on solid biomass for cooking and kerosene for lighting. Moreover, the major pollutants – including secondary pollutants formed by chemical reactions in the atmosphere – can be transported large distances from their sources.
- As the predominant source of air pollution, the energy sector 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. 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. No jurisdiction can claim that the task of tackling air pollution is complete.

# Introduction

More than eight-out-of-ten people in the world's urban areas live where the concentration of air pollutants – whether chemicals, soot or other damaging substances introduced into the atmosphere (Box 1.1) – exceeds the World Health Organization's (WHO) Air Quality Guidelines (WHO, 2006). The result is millions of premature deaths each year and huge costs to the global economy. The energy sector is a motor of economic and social progress, but it is also the largest source of air pollution resulting from human activity, mainly from the combustion of fossil fuels and bioenergy[1] (Figure 1.1). Accordingly, the energy sector must be at the forefront of any strategy to improve air quality and, indeed, such considerations are increasingly motivating policymaking in many countries. In recognition of both the gravity of the problem and the importance of the energy sector in its resolution, the International Energy Agency (IEA) has devoted this *World Energy Outlook Special Report* to the exploration of all facets of this critical issue, working with energy and air quality experts from around the world. Major efforts have been taken to bring together harmonised data, policy assessments, modelling and analysis to provide critical insights for relevant decision makers, particularly in the energy sector.

**Box 1.1 ▹ What is air pollution?**

Air pollution is the effect caused by concentrations of solids, liquids or gases in the air that have a negative impact on the surrounding environment and people. There are many such pollutants and they may occur naturally (from dust, wildfires and volcanoes) or from human activity, be visible or invisible, emit an odour or be odourless. Various air pollutants can stay in the atmosphere from minutes to years and, while often considered a local issue, may have a range that is local, national, regional or global.

Primary pollutants are those emitted directly as a result of human activity or natural processes, while secondary pollutants are created from primary pollutants, sunlight and components in the atmosphere reacting with one another. Some examples of air pollutants from human activity include:

- **Sulfur oxides ($SO_X$),** in particular sulfur dioxide ($SO_2$): Fossil fuels, coal and oil contain sulfur to differing degrees and, if not removed beforehand, $SO_X$ are released at combustion such as in power generation or industrial processes. If not treated or captured, $SO_X$ emissions are released to the atmosphere. Such emissions are linked to adverse health and environmental effects, as well as being a precursor to the formation of secondary particulate matter.
- **Nitrogen oxides ($NO_X$)**, nitrogen oxide (NO) and nitrogen dioxide ($NO_2$): $NO_X$ stem from high-temperature combustion, mainly in transport and power generation, or from the oxidation of NO to $NO_2$ in the atmosphere. $NO_2$ is a toxic gas and can lead to the formation of particulate matter and ozone.

[1] Bioenergy is energy content in solid, liquid and gaseous products derived from biomass feedstocks. It includes solid biomass (wood, charcoal, agricultural and animal waste etc.), biofuels and biogas.

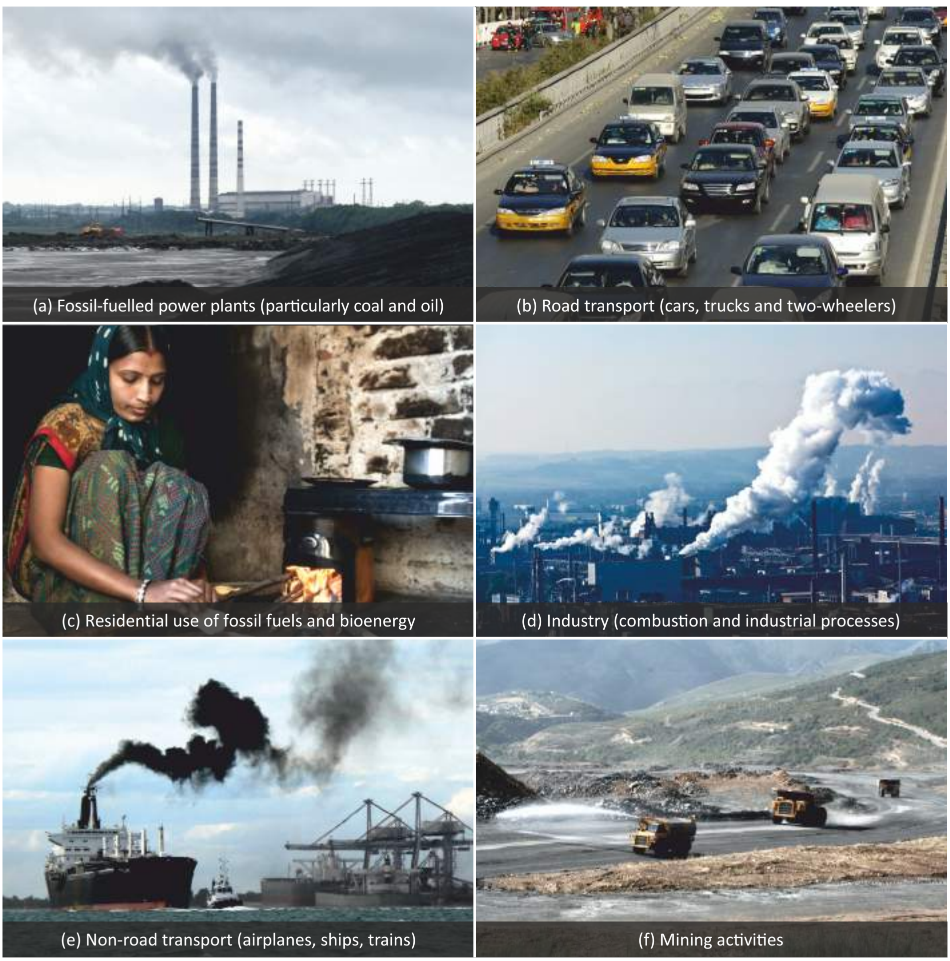
- **Particulate matter (PM)** is a mix of solid/liquid organic and inorganic substances that may be a primary or secondary pollutant. PM is linked to major detrimental health impacts. Size is an important factor in determining these impacts: – "coarse particles" are between 2.5 and 10 micrometres (µm) in diameter and "fine particles" are smaller than 2.5 µm. The adverse health impacts of $PM_{10}$ are less severe than those of the fine particles, however, there is a longer history of data on $PM_{10}$ and even today many cities lack the equipment to monitor outdoor concentrations of $PM_{2.5}$. Black carbon, a particular type of fine PM, is formed by the incomplete combustion of fossil fuels and bioenergy, and is a short-lived climate pollutant (SLCP).
- **Carbon monoxide (CO)** is a colourless, odourless, toxic gas that comes from the incomplete combustion of road transport fuels, natural gas, coal or wood.
- **Volatile organic compounds (VOCs)** are released from chemicals, solvents or fuels (as well as natural sources) as they evaporate or sublimate into the surrounding air; they are associated with a range of negative health effects. Methane ($CH_4$), the main component of natural gas (also a SLCP), is often considered separately from other VOCs as its characteristics differ.
- **Ammonia ($NH_3$)** is released in relation to agricultural and waste management activities; once in the atmosphere ammonia reacts with oxides of nitrogen and sulfur to form secondary particles.
- **Ground-level ozone ($O_3$)** is formed from $NO_X$ and VOCs in the presence of sunlight. At high concentrations, ozone is a pollutant and a SLCP.

Other pollutants include heavy metals such as lead, emitted from industry, power generation, waste incineration and (in some countries) from transport fuels, and mercury, mainly from coal combustion.

Air pollution is often understood as an urban issue and it is true that cities concentrate economic activity and demand for energy services, and, so, tend to experience the most harmful concentrations of air pollution. The precise mix of pollutants and the severity of the health impacts are different from Paris to Delhi, Los Angeles to Lagos, Beijing to Mexico City, but all have air quality that reduces life expectancy. Air pollution does not stop at the city gate: the sources are widespread, sometimes rural in nature and, although some pollutants disperse only locally, others travel large distances in the atmosphere and have regional and global impacts. Many of the world's poorest communities are heavily exposed to toxic fumes when cooking, or heating and lighting their homes.

The type and level of energy-related air pollution is often linked to a country's stage of economic development. At low-income levels, households tend to be heavily reliant on solid biomass (as in many developing African and Asian countries) the use of which usually leads to undesirable exposure to particulate matter, a leading cause of premature deaths. As economies industrialise, their use of fossil fuels in power generation and industry generally rises, as do resulting emissions of sulfur dioxide and other pollutants. Modern agricultural techniques, which include mechanisation, intensified farming and the use of chemical fertilisers and pesticides, can result in higher levels of air pollution, as well as having other environmental impacts. As incomes rise further, household air pollution may subside (if consumers switch to cleaner sources of energy), but demand is unleashed for more energy services, including electricity for appliances and oil for transport, potentially resulting in higher emissions of sulfur oxides, nitrogen oxides and other pollutants. Demographic changes that often occur in parallel with the earlier stages of economic development, such as a growing and more urbanised population, can also boost and concentrate energy-related air pollution.

**Figure 1.1 ▷ Examples of sources of energy-related air pollution**



(a) Fossil-fuelled power plants (particularly coal and oil)

(b) Road transport (cars, trucks and two-wheelers)

(c) Residential use of fossil fuels and bioenergy

(d) Industry (combustion and industrial processes)

(e) Non-road transport (airplanes, ships, trains)

(f) Mining activities

Photo credits: (a) © Bankwatch, *https://goo.gl/NYsznY*, CC BY-NC-SA 2.0; (b) and (d) © GraphicObsession; (c) © Global Alliance for Clean Cookstoves; (e) © Roberto Venturini, *https://goo.gl/FVGrfU*, CC BY 2.0.

**Box 1.2 ▷ Which sources and pollutants does this report cover?**

This report focuses specifically on the links between energy and air quality, which are complex and multi-faceted and therefore require the boundaries of enquiry to be carefully drawn. For the purposes of this report, it is important to note that:

- The focus is on primary air pollution resulting from human activity, with data, analysis and projections in the report excluding emissions from natural sources (which are often very variable, uncertain and beyond the influence of policy makers).
- Specifically, this report addresses the role of energy in air pollution. The scope covers energy production, transformation and use, i.e. the entire chain from extraction to final use.
- The analysis concentrates on anthropogenic emissions of $SO_2$, $NO_X$ and PM, which are predominantly derived from the energy sector and whose effects are among the most damaging.
- Actions taken to tackle these pollutants can also help reduce other emissions in some cases, but these co-benefits are not quantified here. The synergies and trade-offs for policies relating to the energy sector, which address air quality and climate change are explored (see Chapter 3), but climate change and greenhouse gases are not a major focus here. (They were the focus in *Energy and Climate Change: World Energy Outlook Special Report* [IEA, 2015]).
- While there is growing evidence of the health impacts from long-term exposure to ozone, specific modelling and analysis of ozone is beyond the scope of this study.
- Both combustion and non-combustion emissions are covered (referred to collectively as energy-related emissions):
- Combustion emissions are directly linked to fuel burning in boilers, transport and machinery engines, turbines, cookstoves, cement kilns, process heaters, etc.
- Non-combustion emissions consist of process emissions in industry and non-exhaust emissions in transport. Process emissions in industry relate to the formation of emitted compounds from non-combustion chemical syntheses or dust production, and stem from activities such as iron and steel, aluminium paper and brick production, mining and chemical and petrochemical production. Non-exhaust emissions are very significant in transport, relating to emissions from the abrasion and corrosion of vehicle parts (e.g. tyres, brakes) and road surfaces, and are (in many cases) still relevant for those vehicles that have no exhaust emissions.

As with any quantitative study, the analysis and projections in this special report rely on the quality of underlying data. Data on air pollution are generally improving, but are still patchy, with incomplete coverage of some countries and pollutants, or reliance on data that are several years old. For this study, a major effort has been undertaken to produce estimates of emissions in 2015 and to use them to underpin the energy projections of the IEA and the Greenhouse Gas and Air Pollution Interactions and Synergies (GAINS) model of the International Institute for Applied Systems Analysis (IIASA). This is a notable step forward, but it is important to highlight these estimates may vary from national estimates due to differences in methodology, and that there remains a need for significant further steps to improve the quality, coverage and frequency of air pollution data. That said, the remaining imperfections are not so severe as to undermine the analysis and conclusions of this report.

Governments, at all levels, are far from powerless to tackle this issue: proven policies and technologies are available to address energy-related air pollution. Many countries and parts of the energy sector have amassed, over several decades, considerable experience of how to respond to changing environmental challenges and have developed effective means of decoupling polluting emission levels from rising economic activity. While no jurisdiction can claim that the job is complete, the sort of air pollution disaster seen in London during the Great Smog of 1952 (when visibility was reduced to a few metres) has been relegated to history by environmental regulation and changes in the energy sector. Similarly, in the United States, there has been no return to the elevated pollution levels that characterised many of its cities in the years leading to the Clean Air Act of 1970 (with Los Angeles being the best example of dramatic change). Lower emission fuels, fuel switching, deploying various pollution control systems (for power generation, industry and transport), using more energy-efficient technologies, moving to combustion-free forms of energy supply, and new approaches to urban planning and waste management can all help to deliver benefits simultaneously to health, the quality of life, economic productivity and protection of vulnerable ecosystems. Importantly, retrospective analysis demonstrates that, typically, the benefits far outweigh the costs, offering reassurance that action on air quality need not hamper development. In many cases, policy interventions may simultaneously address air quality and climate change issues, though there can be cases where there are tensions and trade-offs that need to be considered (see Chapter 3).

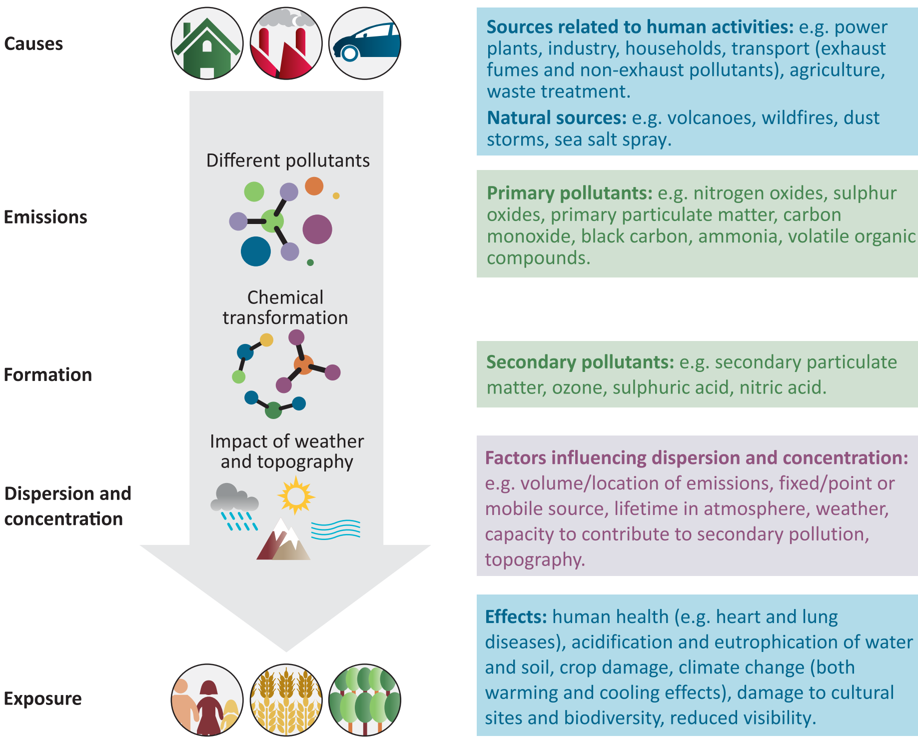
This chapter aims to provide a concise primer on energy and air quality, first outlining the main causes and effects of air pollution and then focusing on the specific role and responsibilities of the energy sector. It covers the different sources and types of energy-related air pollution, the degree to which the pollutants disperse in different settings and the extent to which their concentrations in the air results in harmful exposure and measurable impact and damage. This report focuses on three key air pollutants: sulfur dioxide, nitrogen oxides and particulate matter ($PM_{2.5}$ specifically) (Box 1.2). These are the most damaging of the air pollutants derived from energy activities and those for which the most reliable systematic data are available.

# Air pollution: causes, concentrations and effects

## *Causes*

Mapping a pathway for air pollution, from sources to impacts, can be a useful way to expose what is, in practice, a complex and multi-faceted issue (Figure 1.2). This process encompasses the initial source of the emissions, how the emissions disperse in the air, any transformation that takes place, the extent to which the population/environment is exposed to the pollutants and at what concentration levels and, ultimately, the consequences that flow from this exposure.

**Figure 1.2 ▷ Mapping air pollution from sources to impacts**

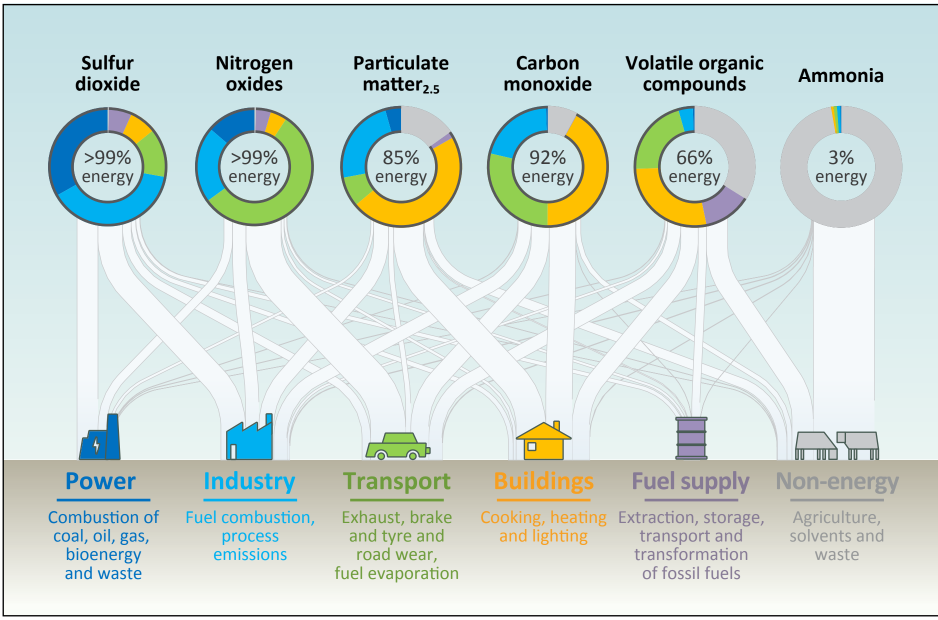



Source: IEA adapted from (EEA, 2016).

The energy sector is by far the largest source of air pollution emissions from human activity. They come primarily from the combustion of fossil fuels and bioenergy, but also from coal extraction and other forms of mining (oil sands, uranium) and industrial activities, the processing/washing of coal, transportation of coal and natural gas, oil refining and charcoal production, as well as non-exhaust emissions from the transport sector (mainly tyre and brake wear, and road abrasion).

Energy production and use not only accounts for most of the air pollution arising from human activity, it also accounts for a very high proportion of the human-related emissions of some key pollutants. This is true of both sulfur dioxide ($SO_2$) and nitrogen oxides ($NO_X$), emissions of which are almost entirely attributable to energy production and use, and of some 85% of primary PM (Figure 1.3). These three categories of pollutants – $SO_2$, $NO_X$ and primary PM – are the main focus of this report.

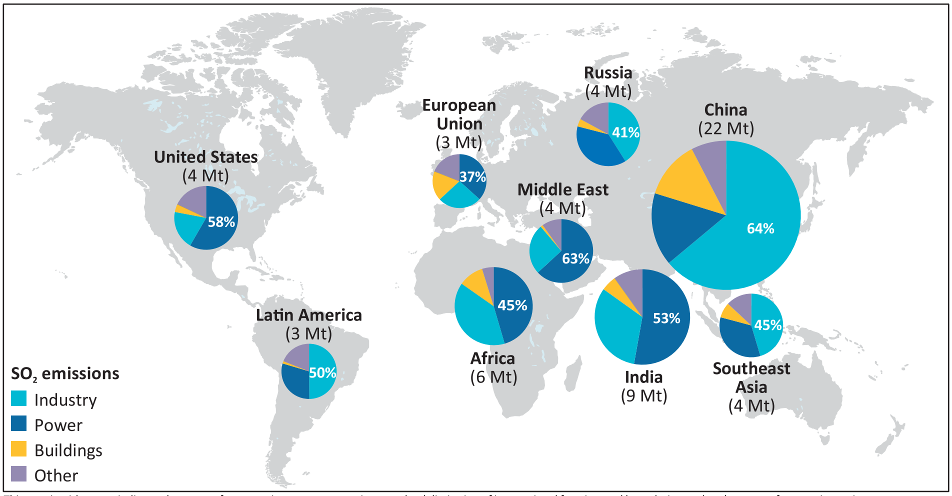
**Figure 1.3 ▷ Selected primary air pollutants and their sources, 2015**




Taking each of the main pollutants in turn, we estimate that, in 2015, the energy sector was responsible for over 80 million tonnes (Mt) of $SO_2$ emissions, with over 45% from industry and one-third from the power sector. Over one-quarter of total energy-related $SO_2$ 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 (Figure 1.4). 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.

At the world level, energy-related emissions of nitrogen oxides continue to increase. They stood at 107 Mt in 2015, with transport accounting for the largest share (over 50%), followed by industry (26%) and power (14%). Increases in $NO_X$ emissions in many developing countries have been rapid and these increases have 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. Transport is the largest source of such emissions 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.

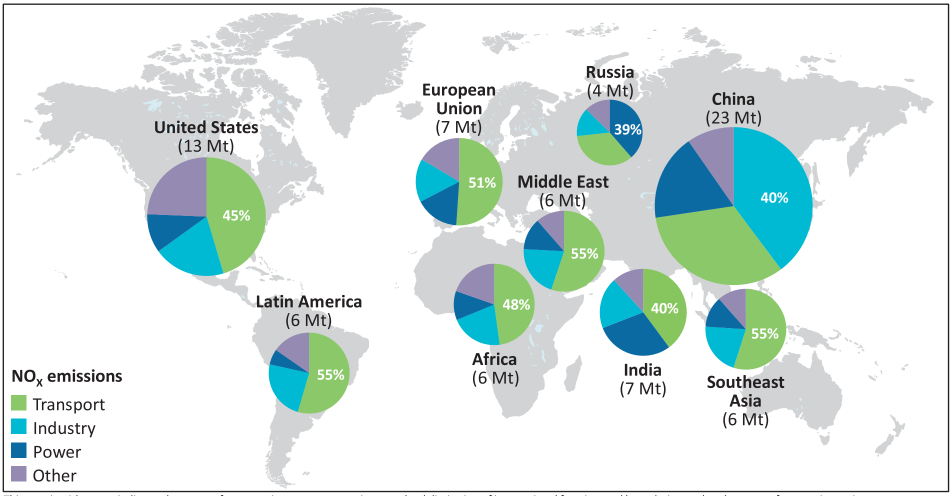
**Figure 1.4 ▷ Energy-related $SO_2$ emissions by region and sector, 2015**




This map is without prejudice to the status of or sovereignty over any territory, to the delimitation of international frontiers and boundaries, and to the name of any territory, city or area.

Source: IEA analysis based on IIASA data.

**Figure 1.5 ▷ Energy-related $NO_X$ emissions by region and sector, 2015**

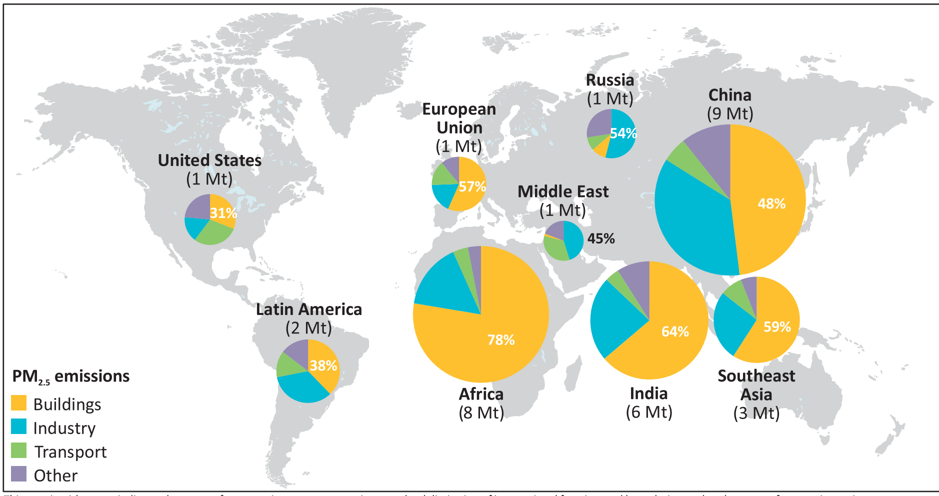



This map is without prejudice to the status of or sovereignty over any territory, to the delimitation of international frontiers and boundaries, and to the name of any territory, city or area.

Source: IEA analysis based on IIASA data.

More than half of global energy-related particulate matter emissions come from the residential sector. The regional picture is heavily skewed towards Africa and Asia (China and India, in particular), with 80% of the global total. PM 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 are heavily concentrated in developing countries and in one sector.

**Figure 1.6 ▷ Energy-related $PM_{2.5}$ emissions by region and sector, 2015**




This map is without prejudice to the status of or sovereignty over any territory, to the delimitation of international frontiers and boundaries, and to the name of any territory, city or area.

Source: IEA analysis based on IIASA data.

## *Concentrations*

The main determinants of the concentration of pollutants are the scale and composition of local economic activity, population size and density, the energy mix, the strength of local pollution regulation, and geographic and meteorological conditions that affect pollutant dispersion in the atmosphere.[2] Typically, pollutants have a lifetime of no more than a few days and high concentrations correlate with periods of high emissions. For example, transport-related emissions may peak in cities during rush-hour periods, household emissions during the cold seasons, power sector emissions at times of high electricity demand, industrial emissions during the working day and agricultural emissions at particular periods in the growing season. Climate and meteorological conditions (in particular, wind speed, the differences in temperature between atmospheric layers that trap pollutants at ground-level, and heat and sunlight, that contribute to ozone formation) play a major role in explaining the seasonal distribution of episodes of high pollutant concentrations. For instance, in the northern hemisphere, PM episodes happen mostly in winter, while ozone episodes happen in summer. Some persistent pollutants, e.g. toxic metals, get into the food chain and can affect us for years, decades or, in some cases, even centuries.

[2] A useful distinction can be made between pollution that is emitted in households (from cooking and heating with traditional biomass or lighting with kerosene) and outdoors (power plants, cars, airplanes). While the pollutants are often the same, and may move from indoors to outdoors and vice versa, the distinction can be important when analysing their impacts (as concentration levels and exposure may be higher indoors) and potential policy interventions.

The relationship between sources and concentrations of air pollution is far from straightforward, complicating the task of measurement and assessment. Primary pollutants can react in the atmosphere to form secondary PM and ozone. For instance, once released in the atmosphere, some of the $SO_2$ and some of the $NO_X$ are converted into secondary PM: respectively sulfates and nitrates aerosols. Then, through chemical reactions, condensation or agglomeration, combinations occur with ammonia, black carbon, organic carbon or other substances to form other types of secondary PM of various sizes and chemical composition. In addition, in the presence of heat and sunlight, nitrogen oxide can react with methane, other VOCs or carbon monoxide to form ozone.

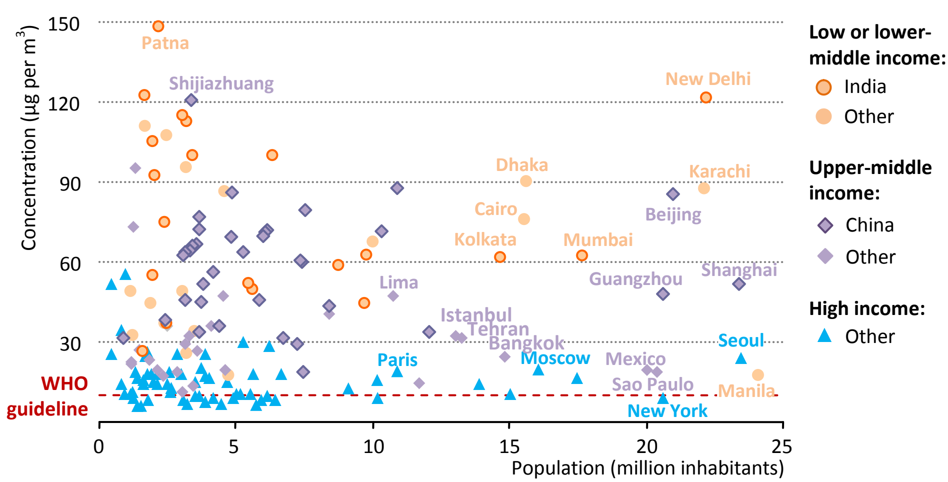
The impact of a pollution source depends strongly on the relation between the site, the stack height of the source (where appropriate) and the distribution of the affected population. Such variation with site and stack height is especially strong for primary pollutants, in particular PM. Most power plants and some industrial sources are outside cities and have tall stacks: their pollution is habitually diluted and dispersed before it reaches large population centres. Vehicles, by contrast, emit their pollution much more directly into the air that people breathe. For example, the impact of one kilogramme (kg) of $PM_{2.5}$ emitted by cars in a metropolis like Paris is two orders of magnitude greater than that of the same kg of $PM_{2.5}$ emitted from a tall stack in a rural zone. Variation with site and stack height is weaker in the case of ozone and much weaker in the case of sulfate and nitrate aerosols, because these pollutants are formed only gradually over tens (for ozone) to hundreds (for nitrates and sulfates) of kilometres from the source.

Primary pollutants are often characterised as "local" (though they can, in some instances, move over considerable distances) and secondary particles and ozone are often a transboundary phenomenon. The acidification of lakes across much of northern Europe in the 1970s was due in large part to transboundary emissions. Today, in a city like Paris, high PM episodes often reflect an increase in background concentrations originating from pollutant emissions in other parts of Europe. Global measurements taken at a number of remote sites, e.g. remote islands, with no local sources of pollutants, provide an increasing body of quantitative evidence on the amount of pollutants transported significant distances from where they were emitted, based on satellite and ground-based data. A substantial increase in ozone concentrations has been measured downwind of eastern Asia, while measurements at some locations on the western coasts of Europe and North America clearly show that transcontinental air flows can carry ozone concentrations that approach or exceed air quality standards or objectives (Convention on Long-range Transboundary Air Pollution, 2010).

Density of population and of energy use is a major factor, with many (but not all) types of energy-related activity giving rise to air pollution often being at its most intense in or around cities. More than 3.9 billion people – 54% of the global population – live in urban areas, accounting for around 80% of global economic activity. Cities often provide an efficient means to deliver access to energy services to a large population, but can also introduce challenges, such as road transport congestion and the concentrated emission of air pollutants in a heavily populated area. Dense road networks and high volumes of traffic, insufficient mass transportation capacity, building density and building height, topographical and meteorological dynamics can all be air pollution risk factors.

Targets for air quality vary in their coverage and stringency in different countries and regions, but WHO Air Quality Guidelines provide a valuable international reference point for threshold and health risks (Box 1.3). However, today populations around the world live with air quality that consistently fails to meet the annual mean concentration standards for PM set out by the WHO. According to the WHO Global Urban Ambient Air Pollution Database,[3] nearly 80% of the population living in those urban areas that monitor air quality are breathing air that does not comply with the WHO air quality guidelines (WHO, 2016a). Air pollution levels in many cities in high-income economies exceed the WHO guidelines. Around 90% of urban Europeans are exposed to levels of air pollutants exceeding WHO guidelines, but less than 10% of Europeans live in cities where air pollutant levels exceed the European Union's (EU) own (less stringent) air quality standards (European Environment Agency [EEA], 2015). The situation is even more acute in many urban areas of emerging economies, in particular in China and India (Figure 1.7), where concentrations may be many times higher than the WHO guidelines. Such levels are attributable to a combination of pollutants from a very wide variety of emission sources: industry, transportation, roads and construction work (dust), household biomass burning, power generation and open-air waste burning.

**Figure 1.7 ▷ Average annual outdoor $PM_{2.5}$ concentrations in selected urban areas**




Sources: WHO (2016) Global Urban Ambient Air Pollution Database; Demographia (2015) for population; country groups per income based on World Bank (2016).

[3] This database, published in 2016, includes ground-level particulate matter concentrations measured in 3 000 cities, *www.who.int/phe/health_topics/outdoorair/databases/cities/en/*.

**Box 1.3 ▷ How much is too much? WHO guidelines for air quality**

The World Health Organization has issued Air Quality Guidelines for a number of air pollutants, including $SO_2$, $NO_2$, PM and ozone (Table 1.1). The guidelines apply worldwide and are based on expert evaluation of the scientific evidence. In the case of $PM_{2.5}$, in addition to the air quality guideline of annual mean concentration of 10 μg/m$^3$, the WHO has introduced a series of interim targets that are less stringent but represent an attainable set of milestones on the pathway towards better air quality (Table 1.2). In this report, reference to "WHO guidelines" is to the ultimate recommended figures not the interim targets (unless otherwise specified).

**Table 1.1 ▷ WHO air quality guidelines for concentrations of PM, $NO_2$ and $SO_2$**

| | $PM_{2.5}$ | $PM_{10}$ | $NO_2$ | $SO_2$ |
|---|---|---|---|---|
| Annual mean | 10 μg/m$^3$ | 20 μg/m$^3$ | 40 μg/m$^3$ | - |
| 24-hour mean | 25 μg/m$^3$ | 50 μg/m$^3$ | - | 20 μg/m$^3$ |
| 1-hour mean | - | - | 200 μg/m$^3$ | - |
| 10-minute mean | - | - | - | 500 μg/m$^3$ |

Notes: Air quality measurements are typically reported in terms of daily or annual mean concentrations of particles per cubic metre of air volume, μg/m$^3$ = micrograms per cubic metre. The guideline values relate to defined time-periods, i.e. a $SO_2$ concentration of 500 μg/m$^3$ should not be exceeded over an average period of 10-minute duration.

Source: WHO, 2006.

The US Environmental Protection Agency (US EPA) defines maximum values of concentration for six pollutants, including a target of maximum 12 μg/m$^3$ on average for primary $PM_{2.5}$. The EU standard is currently 25 μg/m$^3$, with provision for attainment of the WHO guideline by 2030. China sets the maximum average PM concentration of 35 μg/m$^3$, with time allowed to get this level in some of the most industrialised areas.

**Table 1.2 ▷ WHO air quality guidelines and interim targets for PM**

| | $PM_{2.5}$ (μg/m$^3$) | $PM_{10}$ (μg/m$^3$) | Basis for the selected level |
|---|---|---|---|
| **Interim target-1 (IT-1)** | 35 | 70 | These levels are associated with about a 15% higher long-term mortality risk relative to the ultimate guidelines. |
| **Interim target-2 (IT-2)** | 25 | 50 | These levels lower the risk of premature mortality by approximately 6% (2–11%) relative to the IT-1 level, in addition to other health benefits. |
| **Interim target-3 (IT-3)** | 15 | 30 | These levels reduce the mortality risk by approximately 6% (2-11%) relative to the IT-2 level, in addition to other health benefits |
| **Air quality guideline** | 10 | 20 | Below this level, there is no evidence (95% probability) of increased cardiopulmonary and lung cancer mortality in response to long-term exposure to $PM_{2.5}$. |

Note: Annual mean concentration.

Source: WHO, 2006.

High concentrations of nitrogen dioxide affect cities in both high-income and lower/higher-middle-income economies. The very steep increase in $NO_2$ concentrations in some urban areas of China, India and the Middle East observed from satellites since the mid-1990s is attributable to the increasing number of vehicles and to the growth of power generation and industry (Hilboll, Richters and Burrows, 2013). During the same period, $NO_2$ concentrations tended to decrease in most of the cities of high-income economies, even though levels remained high. In 2013, annual $NO_2$ concentrations above the WHO guideline level were reported in almost all EU cities with a population larger than 500 000 and were observed to significantly exceed the target in cities such as Paris, London and Milan (EEA, 2015). In addition, and particularly for $NO_2$, there are significant variations in pollution levels within cities, with roads acting as pollution pathways[4] and airports, ports and industrial zones (or areas downwind of them) proving to be hotspots. Episodes of high ozone concentrations, which are linked to an increase in the emissions of precursors (such as $NO_X$, $O_3$, CO and VOCs) and are relatively frequent in high-income economies in the summer season, now largely affect emerging lower and upper-middle economies, with, due to long-range ozone transportation, regional and global consequence (for Korea, Japan and even the west coast of the United States).

Sulfur dioxide concentrations have strongly declined in the high-income economies due to efficient pollution controls. Hotspots remain, however, for instance in some areas of Central and Eastern Europe (EEA, 2015). Cities in emerging and developing countries, especially those with high industrial activity, can experience very high $SO_2$ concentrations. In coastal areas, and more particularly in ports, emissions from ships contribute to high $SO_2$ concentrations (Merk, 2014).

### *Effects*

Air pollution has many undesirable effects, the extent of which is determined by the levels of concentration of the different pollutants. There is a range of negative health impacts, adverse impacts on vegetation (leading to lower agricultural yields), acidification (leading to "acid rain") and eutrophication.[5] Some forms of air pollution also contribute to climate change. The characteristics of different pollutants define their particular health impacts: even relatively slight exposure may come with high health risks for vulnerable segments of the population.

[4] For example, while London is not cited as one of the world's most polluted cities, Oxford Street (a busy commercial street in central London) reported an annual mean $NO_2$ concentration of 134 $\mu g/m^3$ in 2013 (more than three-times the WHO guideline) and nearly 1 600 hours when it exceeded the 200 $\mu g/m^3$ WHO guideline for maximum hourly exposure, plus an outright maximum level of 489 $\mu g/m^3$.

[5] The process by which a body of water acquires a high level of nutrients promoting the growth of algae, which then results in the depletion of oxygen in the water, causing the death of fish and other organisms.

### *Health impacts*

Air pollution is the fourth-largest overall risk to health, after high blood pressure, dietary risks and smoking (WHO, 2014) (Box 1.4). It is an ongoing health crisis for which many of the causes and cures are to be found in the energy sector. Fine particulate matter ($PM_{2.5}$), even at low concentrations, is associated with a range of serious illnesses and has the most significant effect on human health, due to its propensity to penetrate deep into the lungs. Ozone, nitrogen dioxide and sulfur dioxide also have negative health impacts.

**Box 1.4 ▷ Health impacts of air pollution**

Damage to health can arise from both short-term (a few hours or days) and long-term (over months or years) exposure to air pollution. Particulate matter is linked to lung cancer, chronic obstructive pulmonary disease and heart diseases. The single biggest killer of children less than five-years old worldwide is pneumonia, with more than half of the almost one million premature deaths being caused by exposure to household air pollution (WHO, 2016c). Air pollution can also contribute to low birth weight, tuberculosis, cataracts and throat cancers. Ozone, nitrogen dioxide and sulfur dioxide are linked to asthma, bronchial disease, reduced lung function and lung disease.

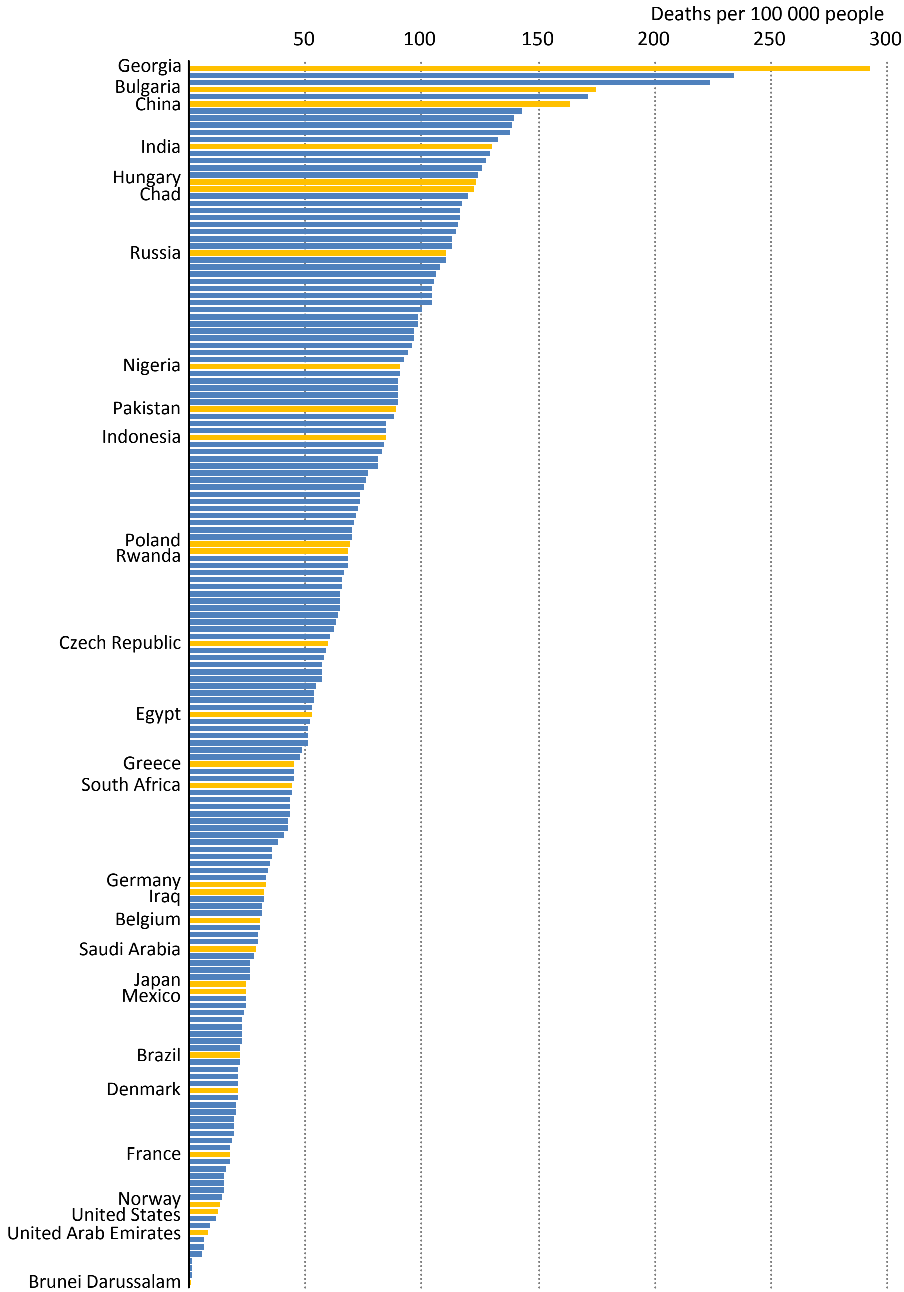
The nature and extent of the health impact of air pollution depends primarily on the level of concentration the length of exposure to the pollution a person has and their profile, with the very young and the elderly being most vulnerable.[6] The effects range from persistent mild personal discomfort to death. Various indicators are used to measure these impacts, but mortality is the over-riding concern. This report focuses on the mortality indicators only, using two of the most common:

- **Number of premature deaths**: this is the number of deaths that are attributable to a given risk factor (in this case, air pollution) and are considered to have been preventable if the risk had been eliminated. All deaths are considered equally, regardless of age.
- **Years-of-life-lost** (YLL): the years of potential life lost as a result of premature death (assessed relative to a given life expectancy). YLL therefore takes into account the age at death, giving more weight to deaths at a younger age and less weight to deaths at an older age.

In 2012, 6.5 million premature deaths were attributed to air pollution (both household and outdoor) (WHO, 2016b) – more than one-in-every-nine deaths worldwide. Even relatively low levels of air pollution pose risks to health and, because of the large number of people exposed, it causes significant morbidity and mortality in all countries. While all parts of the population are affected by air pollution, the burden of ill health consequences falls most

[6] A recent summary of the “cradle to grave” impacts of air pollution was published by the UK Royal College of Physicians and the Royal College of Paediatrics and Child Health (Royal College of Physicians, 2016).

**Figure 1.8 ▷ Mortality rate attributed to air pollution (household and outdoor) by country, 2012**



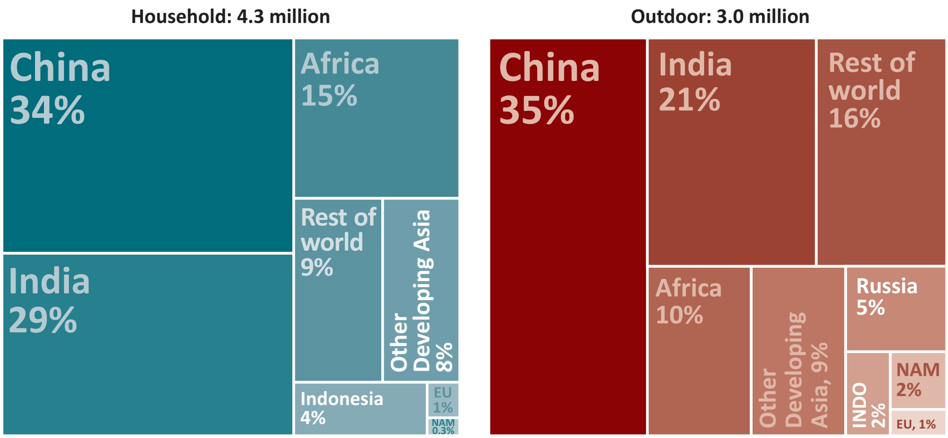

Note: Only a selection of countries are highlighted.

Sources: WHO (2016b) and IEA analysis.

heavily on the poorest segments of society. By age group, children (in particular under five-year olds) and the elderly are the most vulnerable. The countries with the largest number of premature deaths caused by air pollution are mostly in Asia, but also in Africa. However, when adjusted to take account of the size of a countries population (i.e. deaths per 100 000 people), the highest rates of mortality from air pollution can be seen to also span across other parts of the world, such as Eastern Europe (Figure 1.8). The global impact of air pollution has increased over time, although this hides large regional disparities. Premature deaths have declined in Europe, the United States and a number of others, while they have increased in many countries in Asia and Africa in particular.

Household air pollution was the cause of an estimated 4.3 million premature deaths in 2012,[7] heavily concentrated in low- and middle-income countries (WHO, 2016c). Around 80% of this total was in Asia, where around 1.9 billion people rely on the traditional use of solid bioenergy for cooking, and many rely on kerosene for lighting. By country, the largest numbers of premature deaths were in China (1.5 million) and India (1.25 million), followed by Indonesia (165 000), Nigeria (130 000), Pakistan (120 000), Bangladesh (85 000), Democratic Republic of Congo, Philippines, Viet Nam and Myanmar.

**Figure 1.9 ▷ Deaths attributable to household and outdoor air pollution, 2012**




Notes: EU = European Union; NAM = North America; INDO = Indonesia.

Sources: WHO (2016d, forthcoming) and IEA analysis.

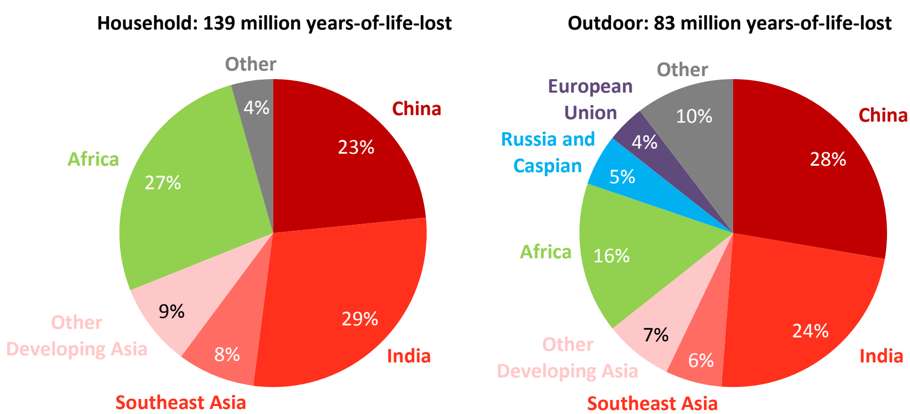
Outdoor air pollution from particulate matter was responsible for 3 million premature deaths in 2012 (WHO, 2016d, forthcoming), with around 200 000 additional deaths linked to ground-level ozone (Forouzanfar, 2015). China has by far the largest number of premature deaths from outdoor air pollution related to particulate matter (more than 1 million), followed by India (620 000). In both cases, particulate emissions from coal

[7] The line between indoor and outdoor air pollution is often blurred (household air pollution can quickly escape outside and vice versa), meaning that premature deaths from each type cannot be summed together to arrive at an aggregate figure.

combustion are a key underlying factor. In the European Union, more then 175 000 premature deaths were attributed to PM[8] and around 16 000 to ground-level ozone exposure (EEA, 2015). The next largest numbers of premature deaths are in Russia (140 000), Indonesia and Pakistan (both around 60 000), Ukraine and Nigeria (both around 50 000), Egypt and the United States (both around 40 000).

Analysis of the years-of-life-lost (YLL) indicates that citizens around the world suffer negative health impacts from air pollution to differing degrees and that many more people are affected than the numbers of premature deaths indicate. The impacts in Asia and Africa are among the most severe, particularly in the case of household air pollution, but with countries in Europe and elsewhere more affected in the case of outdoor air pollution (Figure 1.10). In absolute terms, China and India see the largest number of YLL due to air pollution but, when viewed on a population-adjusted basis, it becomes clear that the health impacts are spread more widely – with many of the most severe impacts in African countries. The relationship between air quality and health outcomes is not linear (particularly at high concentrations), but, by reducing air pollution levels, countries can reduce the burdens of disease from stroke, heart conditions, lung cancer, and both chronic and acute respiratory diseases.

**Figure 1.10 ▷ Total years-of-life-lost attributed to household and outdoor air pollution by region, 2012**




Sources: WHO (2016d, forthcoming) and IEA analysis.

### *Economic and other impacts*

Existing studies of the economic impacts of air pollution differ in many respects (e.g. geographic and sectoral coverage, methodology), but most conclude that the costs of inaction are very large and outweigh the cost of taking mitigating steps. The costs associated with the health impacts tend to dominate any overall economic assessment. For

[8] To note, the European Environment Agency has published estimates reporting over 400 000 premature deaths attributable to PM emissions.

example, impact analysis in the EU finds that the health impact accounts for all the external costs related to PM emissions, to 95% of the costs of $SO_2$ emissions and to 80% of the costs of $NO_X$ (Rabl, Spadaro, & Holland, 2014). As a result, there is a fairly close degree of consistency between those countries that bear the most significant health burden from air pollution and those that are judged to suffer the biggest economic impacts. However, there are complicating factors to this seemingly simple relationship: the main one relates to differences in the costs that are assessed, which may be in narrow financial terms or may also seek to account for social welfare costs, through the notion of "value of a statistical life" (VSL).[9] In both cases, national income levels are an influential variable and vary significantly from one country to another. As a result, the economic cost may appear low in a developing country that has relatively high health impacts and low per-capita income, while the reverse may be true for some developed countries. Using this approach, China is estimated to suffer the largest impact (high health impact, upper-middle income), followed by India (high health impact, lower-middle income), Russia (relatively low health impact, high-income), the United States, Indonesia, Japan, Germany and others (Figure 1.11).

There have been several national studies into the economic impacts of air pollution.[10] While often not comparable to one another, they confirm the high cost of air pollution across different countries and sectors, and the high benefits of policy action. In the European Union, the value of the health impacts was estimated at $440-1 250 billion in 2010 (EC, 2013). The cost of damage from air pollution, just from the largest industrial facilities, is estimated to have been $55-155 billion in 2012, with half of the total from just 1% of industrial plants (EEA, 2014). In the United States, where the cost of compliance with the 1990 Clean Air Act Amendments are expected to rise to around $65 billion per year by 2020, the economic value of the resulting improvements in health and environmental conditions are estimated at around $2 trillion in the same year (US EPA, 2011). Other studies value the adverse health impact in the United States from fossil-fuel supply and power generation activities alone at over $160 billion in 2011 (Jaramillo and Muller, 2016).

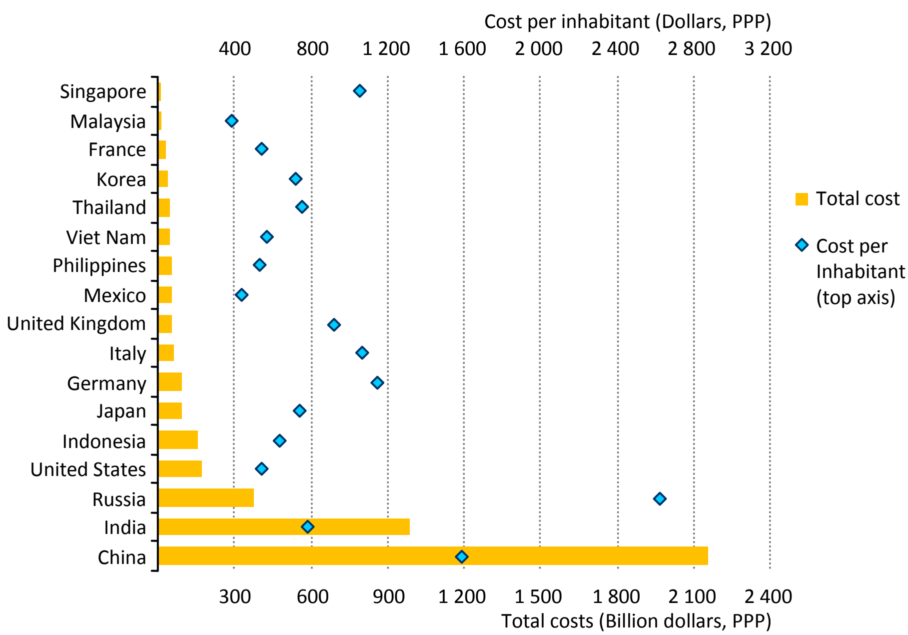
Across the OECD as a whole, the road transport sector has been estimated to account for around half of the total health-related economic cost of outdoor air pollution – road transport costing around $865 billion in 2010 (OECD, 2014a). In emerging economies, power generation and industry (with the prominence of coal) and buildings (with important reliance on coal and solid biomass) are the sectors which make the most significant

[9] A purely financial approach considers values of the health impacts as the losses due to lower production and higher health expenditure. In a social welfare approach, the valuation takes into account the importance ascribed by people to adverse health impacts. In the case of the cost of mortality, the valuation is obtained by multiplying the number of premature deaths with a "value of a statistical life" that reflects individual willingness to pay to reduce the risk of mortality. The VSL used tends to vary widely across different valuation studies, covering a range from $0.4-8.8 million. Based on an extensive compilation of regional studies, OECD (2012) proposed a VSL from $1.5-4.5 million for the OECD countries. Note that the VSL tends to increase with average income.

[10] Estimates of the economic impacts of air pollution in this section are presented in $2010 purchasing power parity terms and so may differ from those quoted in the referenced reports.

contribution to the health impacts and thus to the economic cost of air pollution. In China, estimates of the economic cost have increased over time (as average incomes have grown rapidly): they were assessed to be between around $85-280 billion in 2003 (World Bank, 2007). In India, an estimate of the cost of air pollution was around $160 billion in 2009 (World Bank, 2013). Studies for a range of other countries confirm the significant economic costs associated with air pollution: Nigeria about $80 billion in 2006 (Yaduma, Kortelainen and Wossink, 2013), Pakistan around $6 billion in 2005 (Sànchez-Triana, et al., 2014).

**Figure 1.11 ⊳ Estimated welfare cost of premature deaths due to household and outdoor air pollution, 2012**




Notes: Welfare cost = number of premature deaths times the value of a statistical life. The mortality numbers correspond to WHO (2016d, forthcoming). The VSLs were taken from (OECD, 2014a) for OECD countries, India, China and Southeast Asian countries (OECD, 2014b); and WHO and OECD (2015) for Russia. PPP = purchasing power parity.

There are also economic losses from crop losses attributable to air pollution. Ground-level ozone has a significant impact on global crop yields[11] and has been highlighted as an issue affecting global food security (Tai, Val Martin and Heald, 2014). Peak ozone concentrations have tended to decline in parallel with reductions in the decline in precursor emissions in North America and Europe (Ashmore, 2005), but the opposite trend is evident (and expected to continue) in many developing countries. Unsurprisingly, the most significant

[11] According to one study, 2.2-5.5% for maize, 3.9-15% for wheat and 8.5-14% for soybeans (Wilkinson et al, 2012).

additional losses arise in developing countries that have both large-scale crop production and relatively high pollution levels. It has been estimated that the annual cost of ozone pollution to agriculture in India has been around 3.5 million tonnes of foregone wheat production and 2.1 million tonnes of rice, sufficient to feed over 90 million people (Ghude, et al., 2014).

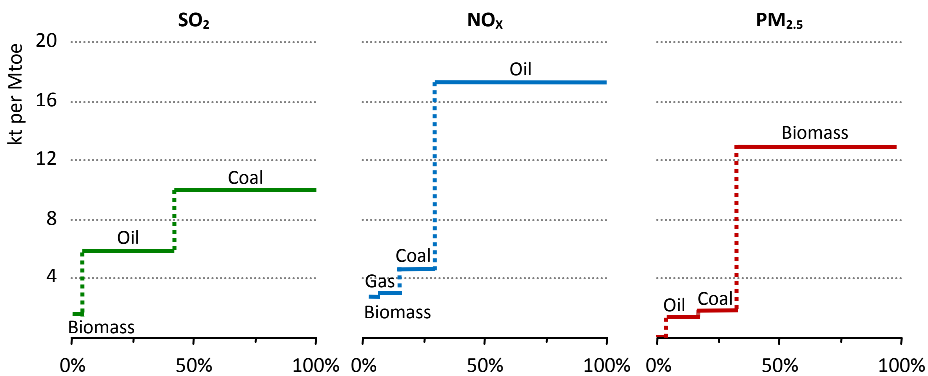
Beyond agriculture, ground-level ozone and other air pollutants can affect vegetation and animal life and influence longer term changes to the ecosystem. Together with ammonia, $NO_X$ and $SO_2$ are also the main precursors of acid rain, which affects soil and water (with adverse impact on vegetation and animal life) and can accelerate the deterioration of equipment and cultural heritage. Pollution episodes often reduce visibility, produce odours and discourage tourism. Certain air pollutants (mainly methane, black carbon and ozone) are also short-lived climate pollutants and so are directly relevant to climate change (see Chapter 3).

## The role of energy in air pollution

Fossil fuels continue to dominate the global energy mix. Despite the increased attention being given to low-carbon sources of energy, the overall share of oil, coal and natural gas in global energy consumption has been remarkably stable over the last 25 years: these fuels accounted for 81% of total energy use in 1989, exactly the same percentage as in 2014. Over this period, the share of oil has declined, from 37% to 31%, but that of natural gas rose (from 19% to 21%) and coal increased even more (from 25% to 28%). The role of bioenergy has remained steady, meeting around 10% of global energy needs.

The relationship between fuels, their use and the resulting emissions is not straightforward. Not all fuels emit all pollutants and different grades/qualities of fuel contain them in different quantities. These pollutants may be reduced or removed from these fuels at various stages prior to combustion (e.g. coal washing and oil refining), the nature of the combustion process itself can influence emissions levels (e.g. the temperature of combustion) and post-combustion technologies may be utilised to chemically alter or capture harmful emissions (e.g. catalytic converters). This means that there is no single level of emissions per unit of a specific fuel but, rather, a range of emission factors depending on such variables. Nonetheless, it is clear that specific fuels play a key role in relation to certain types of air pollution, both in terms of emissions per unit of fuel consumed and in terms of their share of total emissions (Figure 1.12). Coal use dominates sulfur dioxide emissions, emitting the highest level of $SO_2$ per unit (10 kilotonnes (kt) per million tonnes of oil equivalent (Mtoe) and accounting for more than half energy-related $SO_2$ emissions (followed by oil, some way behind). Depending on coal quality, power plant efficiency and control technology, average $SO_2$ emissions from coal power plants vary between less than 1 kt/Mtoe to above 30 kt/Mtoe. For nitrogen oxides, oil leads the way, accounting for more than half of total emissions (coal is also a notable contributor). Emission factors vary widely for each fuel among end-use sectors, depending on the technology choice: a gasoline car with a catalytic converter can emit 1.4 kt of $NO_X$ per Mtoe, but a diesel truck without filters can emit more than 50 kt of $NO_X$ per Mtoe. For PM, bioenergy dominates due to the effect of its use by households in traditional stoves, with average emissions per unit of 13 kt/Mtoe and accounting for the clear majority of total energy-related PM emissions. In all cases, natural gas results in much lower emissions, as there is an imperative – for safety reasons and to avoid corrosion to the pipeline transport system – to remove sulfur as soon as practicable after production.

**Figure 1.12 ⊳ Global average emissions factors and share of major pollutant emissions by fuel, 2015**




Notes: The most relevant fuels in terms of emission factors are represented; fuels not shown are considered negligible. Global average emission factors are calculated across all types of sectoral activity and all types of technology.

This section examines the role of energy in air pollution in more detail, looking initially at the issues associated with energy production, including the critical issue of fuel quality, and then by sector with power generation and the main end-use sectors (transport, industry and buildings). It illustrates how changing patterns of energy use and the application of pollution mitigation technologies are constantly re-shaping the links between energy use and the main air pollutants.

## *Fossil-fuel production*

Pollutant emissions occur along the whole chain of the fossil-fuel life cycle, from extraction to final use. In all cases, the production phase involves the on-site consumption of energy, mainly diesel or produced natural gas. In addition, there is sometimes non-productive combustion resulting in carbon dioxide ($CO_2$) emissions, e.g. the practice in parts of the oil sector to flare unmarketable volumes of associated gas, as well as, in some instances, the direct venting of natural gas to the atmosphere. There can also be fugitive emissions of methane from leaking valves, seals or pipelines, as well as emissions of other VOCs and gaseous pollutants from in and around production sites.

The effect of coal mining on local air quality is site specific, but the main pollutants emitted from mining activities are PM and coal seam gas (methane). Dust emissions – with dispersion beyond the immediate mine site – occur to a serious extent only as a result of surface mining (which accounts for some 30% of global coal production), because of blasting and earth moving. These emissions can be significant from mines in dry climates without dust suppression technologies. The most common form of dust suppression in mining is spraying water onto the relevant excavation areas and uncovered heaps of waste rock and coal. Locally significant dust emissions can also form in coal transport and storage; covered railcars, trucks and conveyor belts are an effective means of limiting this pollution and have been mandated in many coal mining areas.

Data on upstream sector pollutant emissions are scarce: methane (the primary component of natural gas) is the most researched subject but, even here, there is a wide range of estimates. The most recent estimates used by the IEA suggest that the energy sector as a whole, via activities linked to oil, gas, coal and bioenergy supply, may contribute around 100 Mt per year of anthropogenic methane emissions, around one-third of the total (IEA, 2015). Of this 100 Mt, the oil and gas sector accounts for around 55 Mt (with an upstream share of around 60%) and coal mining another 30 Mt. Of the remaining 15 Mt, the majority is estimated to come from the incomplete combustion of biomass in the end-use sectors (mainly in the residential sector).

### *Fuel quality*

Fuel quality is a very important determinant of the eventual impact on air quality. Coal, for example, contains various impurities and chemical components, such as minerals, metals, volatile matter and sulfur. During the combustion of coal, some of these components may be released into the air if the flue gas is not adequately treated. The minerals (most commonly known as ash) present in the coal largely determine the amount of PM in the flue gas, while the sulfur content is responsible for the amount of $SO_2$ formed in the combustion process. Metallic components, such as mercury, may also be present in coal and be released into the flue gas.

The chemical composition of coal depends on the conditions under which the coal was formed millions of years ago and is therefore very different by region. For instance, most coal in India has a high share of mineral matter (ranging between 30% and 50% for the bulk of the production) while Indonesian coal is known for its very low-sulfur content (ranging between 0.1% and 1%). In the United States, Illinois Basin coals have untypically high-sulfur content of up to 3%, while coal from the Powder River Basin in Wyoming has such low-sulfur content that many power plants using this coal comply with $SO_2$ emission limits without control technology.

Coal washing aims primarily to reduce the content of mineral matter in order to reduce transport costs and increase power plant efficiency. Often coal washing also reduces the sulfur content. Mineral particles, however, can be removed successfully only if they are not embedded in the combustible part of the coal (so-called free ash). Similarly, sulfur removal requires the sulfur to be inorganic (as opposed to organic sulfur, which is typically not washable). However, whether coal washing makes sense is primarily an economic question: often the pollutants can be removed post-combustion at a lower cost than through pre-combustion coal washing.

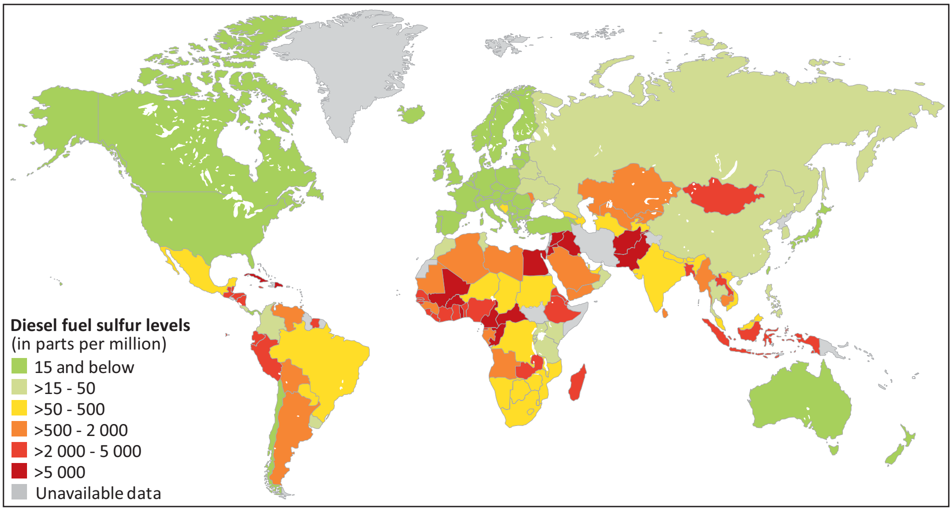
In the case of oil, only around 1% of oil is used in a crude state (mainly in power generation plants in the Middle East). Worldwide almost all oil is consumed in the form of oil products coming from refineries or fractionation plants (for natural gas liquids). The refining process itself is energy intensive, with crude oil heated to separate out the different fractions and then the atmospheric residues going through even more heat-intensive cracking or coking processes to yield lighter fuels. Energy use in the refining sector produces some 2 Mt of $SO_2$ and 1.2 Mt of $NO_X$ emissions annually. It is not a significant source for PM emissions on a global basis, but an especially large coker unit close to densely populated areas may have a substantial local impact.

Removing sulfur from oil products (via hydrogen- and energy-intensive processes such as cracking and coking) is a major part of the refining process, as governments typically regulate the sulfur content of fuels – usually starting with road transport fuels and going on to residential heating, industrial combustion (including power generation) and agriculture.[12] The naturally occurring sulfur in crude oil ranges between 0.2% and 4%, while specifications for gasoline and diesel for road transport can be as tight as 10 parts per million (ppm) (0.001%), such as in OECD and some developing countries, rising to above 500 ppm (0.05%) in some non-regulated markets in Asia and Africa (Figure 1.13). Fuel oils have the highest allowed sulfur content – up to 3.5% in fuels for marine shipping. Natural gas does not go through the same refining process as oil, but it is nevertheless treated in gas processing plants to remove sulfur and liquids. The naturally occurring sulfur in gas ranges from close to zero to 20-30% and even higher in some exceptional wells.

Consumption of oil has some unique features that define the challenges and the specifics of pollution control policies. Unlike coal and gas, which are mostly used in relatively large-volume stationary sectors (power generation, industry), oil is mostly used in mobile applications: transport accounts for over 55% of oil demand. Small-scale stationary use, such as fuel for buildings and agriculture, covers another 10% of oil demand. Thus, only a third of oil is used in large-scale stationary sources in industry and power generation, compared to almost 95% for coal and over 70% for natural gas.

[12] Sulfur specifications for fuels generally are imposed at the point of sale rather than as an obligation on refiners. Refiners can continue to produce fuels with higher sulfur content; however, they generally would have to find export markets. While in the United States, it is the refiners that have to comply with sulfur specifications, though there is a fuel emissions credit system whereby non-complying refiners can purchase credits from others that achieve more than the regulated quality standard.

**Figure 1.13** ▷ **Mandated sulfur levels in diesel transport fuel** (as of January 2016)




This map is without prejudice to the status of or sovereignty over any territory, to the delimitation of international frontiers and boundaries, and to the name of any territory, city or area.

Source: UNEP (2016).

## *Stationary sources*

### *Power generation*

Despite the rapid expansion in recent years of renewable sources of electricity, the great majority of the world's power generation continues to come from the combustion of fossil fuels, with coal-fired generation still providing the backbone of the global power system (around 40% of global electricity supply). Different types and qualities of fuel, types of power plant, whether they include pollution mitigation technologies, location and smoke stack (chimney) height can all have a big influence on power plant pollution levels and their impact. Most of the visible emissions coming from power plants are water vapour from the cooling tower and – if the plant is insufficiently controlled – particles and $SO_2$ from the smoke stack.

Power generation is a major source of worldwide sulfur dioxide emissions (nearly 27 Mt of $SO_2$ in 2015, one-third of the global total) and makes a small but still significant contribution to emissions of nitrogen oxides (14% of total $NO_X$) and particulate matter (5% of total $PM_{2.5}$). Coal is the chief fuel responsible for air pollution in the power sector, accounting for three-quarters of the sector's $SO_2$ emissions, 70% of its $NO_X$ emissions and over 90% of its $PM_{2.5}$ emissions. Consistent with its minor contribution (4%) to global electricity generation, oil-fired power generation accounts for 7% of the global emissions of $SO_2$. Much of the oil-fired generation comes from ageing power plants – particularly in the Middle East – with minimal pollution control technology installed. Burning oil to generate electricity also produces significant quantities of $NO_X$ and, in some cases, $PM_{2.5}$. In general, natural gas-fired plants emit fewer air pollutants than coal and oil-fired power plants. In 2015, gas-fired generation emitted close to 20% of $NO_X$ from power generation but barely any $SO_2$ or $PM_{2.5}$. Natural gas with sulfur content is typically treated, i.e. the sulfur is removed, before the gas is commercialised, explaining the low-sulfur emissions from gas-fired power generation. Biomass currently plays a negligible role in global power generation, accounting for around 2% of total output, and thus contributes comparatively little to air pollution. Yet, in relative terms (emissions per unit of output), biomass performs only slightly better than coal-fired plants for $NO_X$ emissions, moderately better for $PM_{2.5}$ emissions, but is much better in terms of $SO_2$ emissions.

Over the last decade, global $SO_2$ emissions, and to a lesser extent $NO_X$ and $PM_{2.5}$ emissions, have decoupled from the increase in coal-fired generation. From 2005 to 2015, coal-fired power generation grew 34%, while total power sector emissions of $SO_2$, $NO_X$ and $PM_{2.5}$ decreased by 55%, 34% and 32% respectively. This decoupling is principally due to the introduction of emission standards for coal-fired power plants, which led either to the use of coal with a lower sulfur content or to the installation of pollution control technologies. Regulation for $PM_{2.5}$, $SO_2$ and $NO_X$ emissions from coal-fired plants has been introduced in many countries. Governments in the United States, Europe and Japan have been regulating air pollution from coal plants since the 1970s, and since the turn of the century, many emerging economies have introduced regulations. Even though the emission standards have been introduced throughout the world, there are significant differences in their stringency from country to country. China, Korea, Japan, the United States and European Union currently have the most stringent emission standards in the world.

### *Industry*

In 2015, manufacturing industries and other transformation sectors, such as refining and mining, accounted for around half of global energy-related emissions of $SO_2$ (37 Mt $SO_2$) and some 30% of both $NO_X$ (28 Mt) and $PM_{2.5}$ (10 Mt). The $SO_2$ and $NO_X$ emissions were generated in roughly equal parts from combustion activities and as reacted or related compounds embedded in the raw materials, i.e. process-related emissions. Most $PM_{2.5}$ emissions were process-related.

The source fuels and the combustion operating conditions (including the implementation of abatement technologies) are crucial determinants of combustion-related pollutant emissions. Coal makes up 31% of current global industrial final energy use, and accounts for more than three-quarters of combustion-related $SO_2$ emissions in manufacturing industries. By contrast, $NO_X$ emissions in the sector were split between coal and oil combustion (38% and 35%, respectively) and $PM_{2.5}$ emissions were dominated by bioenergy and coal (44% and 37%, respectively).

Process-related pollutants come from a wide range of industrial sources, in differing amounts and concentrations. Worldwide the largest specific industrial emitters of process-related $SO_2$ are cement (13%), steel (9%) and refineries (9%), although the pulp and paper sub-sector has by far the largest specific emissions intensity (on a global basis 3.7 kt $SO_2$/Mt of paper[13] compared with other industries ranging from 0.6 kt $SO_2$/Mt of cement to 0.2 kt $SO_2$/Mt of crude steel). Process-related $NO_X$ emissions are mostly released in cement making (1.5 kt $NO_X$ / Mt of cement, accounting for over 50% of global process-related $NO_X$ emissions) followed by pulp and paper production (1.2 kt $NO_X$ /Mt of paper). Aluminium stands out as the largest emitter of $PM_{2.5}$ per unit of output (2.1 kt $PM_{2.5}$/Mt of aluminium), compared with other industrial activities that are below a 0.7 kt $PM_{2.5}$/Mt of product level globally. The largest portion of global process-related $PM_{2.5}$ emissions arise in the cement, and iron and steel sub-sectors (about 70% jointly).

From a regional perspective (considering both combustion and process emissions), China was the largest emitter of $SO_2$, $NO_X$, and $PM_{2.5}$ in 2015 in manufacturing industries, accounting for 44% of $SO_2$ emissions, almost 40% of $NO_X$ emissions and 35% of $PM_{2.5}$ emissions. China was followed by India for $SO_2$ (9%) and $PM_{2.5}$ (14%) emissions, and by the United States for $NO_X$ emissions (11%). The dominant role of China in industrial pollutant emissions is not surprising, considering its significant share of world manufacturing activities (China consumed 35% of global final industrial energy use in 2013). However, considered per unit of industrial output, in 2015 South Africa topped the ranking for combustion-related $SO_2$ emissions intensity (0.5 kt $SO_2$ per petajoule), followed by the Caspian region. Chile, followed by northern African countries, the Caspian region and the United States, had the highest combustion-related $NO_X$ emissions intensity (0.4 kt $NO_X$ per petajoule).

As with power generation and to a lesser extent transport, developed countries have reduced their $NO_X$ and $SO_2$ emissions from industry over many years, while emissions from developing countries have increased significantly. Over recent decades, $NO_X$ and $SO_2$ emissions from US industry have declined steeply, while $NO_X$ and $SO_2$ emissions from Chinese and Indian industry have increased strongly. Pollutant trends are heavily influenced by trends in industrial production in the different regions; but, in all cases – albeit to differing degrees – there is a decoupling of production and pollutant emissions. This reflects the impact both of energy-related developments (such as energy efficiency improvements) and the use of emission control technologies.

The decoupling of industrial production and air pollutants emissions growth has been achieved largely by regulation. The policies applied to industry are similar to those applied to power generation and mainly involve imposing standards, which require installations to adopt the best available technologies for pollution control. The United States and Europe introduced such standards in the 1970s and 1980s and developing countries are now progressively introducing air pollution standards as well (albeit less stringent than those in developed countries). However, in both developed and developing countries, air pollutants emission standards tend to apply only to large installations. Compared with the power

[13] Process-related $SO_2$ emissions in the pulp and paper sub-sector are mainly due to oxidation in the recovery furnace of sulfur compounds that are formed by reactions of raw materials with different process streams in the production of chemical pulp.

generation sector, which tends to be made up of large installations, the industrial sector is more heterogeneous, involving a wide range and installations of varying size. For instance, smaller plants are more common in non-energy intensive industries, such as machinery manufacturing or textiles, compared with larger industrial energy consumers, such as cement or iron and steel. To date, regulators have been reluctant to place limits on small installations, due to compliance costs. In general, the larger the installation, the lower the unit cost of air pollution control technology.[14]

### *Mitigation options for stationary sources*

The imposition of emissions standards for the main air pollutants incentivises the installation of state-of-the-art control equipment in new plants, investments in existing plants to retrofit control technologies, as well as, in some cases, the use of low-sulfur coal (Table 1.3). The initial emphasis in regulation in many countries was on reducing PM, followed by $SO_2$ (due to increasing concerns about the effects of acid rain) and then $NO_X$. The abatement techniques for air pollutants in power generation have a lot in common with those in industrial activities. They fall into two categories: primary combustion technologies or measures that prevent the generation of a particular type of emissions and end-of-pipe technologies that capture pollutants to avoid them being released into the environment.

Primary combustion technologies to reduce thermal $NO_X$ emissions include improved combustion techniques and the installation of low-$NO_X$ burners in process heaters and industrial heat and electricity generation plants. These burners operate by phasing air and fuel injection to achieve lower temperature flames, making use of the fact that there is an exponential (positive) relationship between combustion temperatures and thermal generation of $NO_X$. Another primary combustion technology is fluidised-bed combustion technology for solid fuels that reduces the emission of both $SO_2$ and $NO_X$. End-of-pipe technologies focus on the removal of $SO_2$, PM and $NO_X$ from flue gases before release to the atmosphere, by means of either physical separation or chemical reactions. This group of technologies includes: electrostatic precipitators (to separate PM from gaseous streams); flue-gas desulfurisation plants that use a sorbent (typically alkaline compounds such as limestone) to absorb and/or oxidise $SO_2$ into solid matter, which is then physically separated from the flue gases; and selective catalytic reduction systems (using ammonia) or selective non-catalytic reduction systems (using urea) that reduce the $NO_X$ in the flue gas to nitrogen and water (Figure 1.14 and Table 1.4).

[14] One approach to overcome this barrier and to improve the overall mitigation potential would be for regulators to target industrial clusters/parks as a whole, with the abatement technologies installed for the merged off-gases and flue gas streams from the industrial activities of the cluster as a whole.

**Table 1.3 ▷ Emission limits for existing and new power plants in selected countries/regions** (mg/m³)

| Region | Policy | $SO_2$ | | $NO_X$ | | PM | |
|---|---|---|---|---|---|---|---|
| | | Existing | New | Existing | New | Existing | New |
| China | Emission standard of air pollutants for thermal power plants | 200-400 | 100 | 200 | 100 | 30 | 30 |
| European Union | Industrial Emissions Directive | 200-400 | 150-400 | 200-450 | 150-400 | 20-30 | 10-20 |
| United States* | New Source Performance Standards | 160-640 | 160 | 117-640 | 117 | 23 | 23 |
| India | Environment (Protection) Amendment Rules, 2015 | 200-600 | 100 | 300-600 | 100 | 50-100 | 30 |
| Indonesia | MOE decree no. 21 2008 | 750 | 750 | 850 | 750 | 150 | 100 |
| Japan** | Air Pollution Control Law | - | - | 123-513 | 123-513 | 30-100 | 30-100 |
| Mexico*** | Mexican Official Standard NOM-085-ECOL-1994 (in PPMV for $SO_2$ and $NO_X$) | 550 -2 200 | 30 -2 200 | 110 -375 | 25 -375 | 60 -450 | 60 -450 |
| Philippines | National Emission Standards for Particulate Matter for Stationary Sources | 1 000 -1 500 | 200 -700 | 1 000 -1 500 | 500 -1 000 | 150 -200 | 150 -200 |
| South Africa | The Minimum Emissions Standards are published by the government | 3 500 | 500 | 1 100 | 750 | 100 | 50 |
| Korea | Special Measures for Metropolitan Air Quality Improvement | 286 | 229 | 308 | 164 | 40 | 20-30 |
| Thailand | Royal Thai Government Gazette | 700 -1 300 | 180 -360 | 400 | 200 | 80-320 | 80 |
| Vietnam | Industrial emission standards for dust and inorganic substances | 1 500 | 500 | 1 000 | 650 -1 000 | 400 | 200 |

Notes: "Existing" refers to the emission limit for currently operating power plants. "New" refers to the limit for planned or proposed plants. * US emission limits were converted from lb/MBtu to mg/m$^3$ assuming an F-factor of 1 800 standard cubic feet of $CO_2$ and a $CO_2$ content of 12% in the flue gas. ** Japan's Air Pollution Control Law (APCL) specifies emission limits for $SO_X$, $NO_X$ and PM that differ depending on the scale of facilities, technologies and regions. Prior to the construction of new plants in Japan, local authorities and power generation companies usually arrive at bilateral pollution prevention agreements more stringent than those mandated in the APCL. *** For Mexico, $SO_2$ and $NO_X$ are expressed in parts per million by volume (PPMV).

Sources: Nalbandian-Sudgen, (2006); IEA Clean Coal Centre (2015) and IEA analysis.

**Figure 1.14 ▷ Typical emissions control systems for power plants**

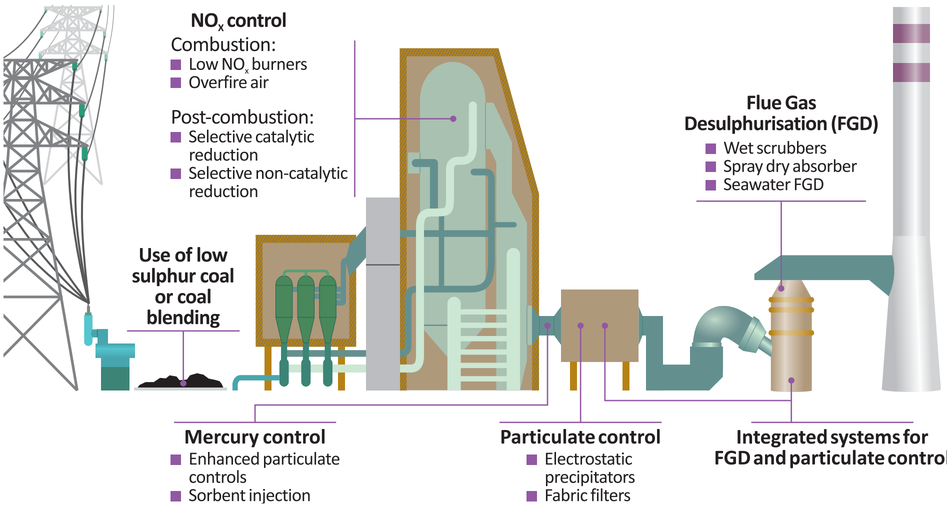



**Table 1.4 ▷ Selected mitigation technologies for air pollutants in power generation and industry**

| Pollutant | Mitigation technology | Type of technology | Abatement efficiency |
|---|---|---|---|
| $SO_2$ | Wet flue-gas desulfurisation | End-of-pipe | 70-98%* |
| | Spray-drier absorption | End-of-pipe | 50-70% |
| $NO_X$ | Low and ultralow-$NO_X$ burners | Integral to combustion process | 20-30% |
| | Selective catalytic reduction | End-of-pipe | 90% |
| | Selective non-catalytic reduction | End-of-pipe | <50% |
| $PM_{2.5}$ | Fabric filtration | End-of-pipe | >99% |
| | Electrostatic precipitators | End-of-pipe | >99% |

*Abatement efficiency based on coals with 0.3-4.8% sulfur content.

Sources: Nalbandian-Sudgen, H.; IEA Clean Coal Centre (2006) and IEA analysis.

Primary combustion technologies and measures tend to be preferred over end-of-pipe technologies because of their lower installation cost. However, achieving mandated reductions in air pollutant emissions often requires the implementation of post-treatment mitigation technologies, especially for certain pollutants, such as $PM_{2.5}$. An alternative to control technologies is the use of low-sulfur coal to fuel power plants. The sulfur content of coal can vary significantly between different deposits. In some cases, blending various coal types can achieve compliance at a lower cost than a retrofit with flue-gas desulfurisation equipment. In the industrial sectors, each industrial activity has specific constraints in terms of the mitigation measures that can be implemented. For instance, the significant dependency of current iron and steel making on coal for coke making opens up the possibility of moving to less metallurgical coal types, with a lower sulfur content, but limits the possibility of moving to less $SO_2$-intensive fuel, such as natural gas.[15]

## *Transport*

The transport sector remains a major source of air pollutants, despite the many policy and technology advances achieved. Transport is responsible for around half of all energy-related nitrogen oxide emissions (56 Mt in 2015) and is an important source of primary particulate matter (accounting for around 10% of total energy-related primary $PM_{2.5}$ emissions). Road transport is by far the largest source of the sector's $NO_X$ and primary $PM_{2.5}$ emissions (58% and 73% of the total), while navigation accounts for the largest share of $SO_2$ emissions. Road vehicles are driven intensively in populated regions, which tends to concentrate emissions in urban areas, plus their exhaust pipes are close to the ground and therefore to the inhabitants leading individual exposure to vehicle-generated pollutants to be higher, on average, than exposure to other sources. These emissions can broadly be categorised as:

- **Exhaust emissions:** Produced during combustion, the amount of each pollutant emitted is highly dependent on the type of fuel used and, even more, on the engine and after-treatment technology. Diesel engines, for example, are more fuel-efficient than gasoline engines, but can emit higher levels of $NO_X$ and PM, depending on the emission control technologies applied.[16] Although PM emissions are greatly reduced by means of particulate filters (also available as retrofits for trucks) in newer diesel vehicles, to a level comparable to gasoline, there is still a trade-off to be struck between policies on fuel economy and those tackling air pollution.
- **Abrasion emissions:** Produced by the wearing and corrosion of vehicle components, road materials and safety barriers. Significant levels of PM may be produced by the wearing down of a vehicle's tyres, brakes and clutch, as well as from road surface wear and corrosion of the vehicle.
- **Evaporative emissions:** Results from fuel evaporating and becoming a vapour that may vent from the vehicle's fuel tank and injection system (e.g. seals and tubes). Evaporative emissions are much higher from gasoline-fuelled vehicles and result in emissions of VOCs, which can, in certain settings (e.g. North American cities), make up a substantial fraction of VOC emissions. Systems have been designed to reduce evaporative emissions in newer vehicles.[17]

[15] Coke is used as a reducing agent of iron ore for the production of pig iron in blast furnaces.

[16] The proportion of harmful $NO_2$ in the $NO_X$ emissions of a diesel vehicle is far higher than the proportion emitted by a gasoline vehicle, which can be attributed in part to emission control technologies (such as catalysed particle traps) which reduce $NO_X$ emissions of non-$NO_2$ chemical species more effectively than $NO_2$ itself.

[17] These emissions are not included in our estimates and projections.

Oil accounts for more than 90% of transport energy demand (in final energy terms), with different oil products serving different modes of transportation, with differing implications for emissions. Over time, the share of diesel vehicles in some national light-duty vehicle fleets has grown. This phenomenon, which is referred to as dieselisation, is most pronounced in the countries of the European Union and European Free Trade Association and in India. In European countries, policies that make diesel cars cheaper to purchase and operate than gasoline cars, including lower vehicle purchase and fuel tax rates, have contributed to this development.

Road transport is the largest consumer of oil, but gasoline (22 million barrels per day [mb/d]) and diesel (16 mb/d) are, to an extent, distinct in terms of the forms of transport that they fuel – diesel use is dominant in heavy-duty vehicles such as trucks. Both have shares in the light-duty fleet, but with significant variations across regions; gasoline dominates passenger car demand in the United States, while in Europe, more than half of cars are diesel. Beyond road transport, the aviation sector relies on kerosene, while the maritime sector relies primarily on heavy fuel oil (72%) and secondarily on diesel (25%). Intercity rail relies on diesel in many countries, at least in part (though many intercity rail networks have electrified and continue to do so). Collectively, the oil used by these non-road modes amounts to 22% of the road transport total.

### *Road transport*

Due to their large engine size, high rates of use and overwhelming reliance on diesel fuel, heavy-duty vehicles (HDVs) account for a disproportionate share of emissions – far greater than their share in the global vehicle stock (7% when excluding two- and three-wheelers) or activity (25%, measured as vehicle-kilometres). Worldwide, in 2015 HDVs accounted for over 40% of $NO_X$ emissions from the transport sector and more than 50% of $PM_{2.5}$ emissions. However, since light-duty vehicles (LDVs) are driven primarily in populated regions, the health impacts of their use is augmented by the proximity of their emissions to people, which results in higher levels of exposure. Even so, in urban areas, HDVs emit more pollutants per kilometre driven, and hence have a disproportionate impact in urban areas, despite the fact that LDVs are generally more numerous in urban settings. Non-exhaust emissions (including tyre and break abrasion, as well as road wear) are estimated to account for 13% of all primary $PM_{2.5}$ emitted by road transport.

A combination of regulatory measures and broader fiscal and air quality policies have been generally effective in abating the growth of vehicular emissions, despite increasing vehicle fleets, with the important exception of $NO_X$. Standards limiting the maximum permissible tailpipe and evaporative emissions from each vehicle type (per unit of distance, time or final energy consumption) and specifying fuel quality (mandating the phase-out of lead and staged reductions in the maximum sulfur content in automotive fuels) have reduced the emissions of road vehicle fleets in all countries and cities where they have been adopted and enforced. Indeed, as the technologies controlling tailpipe emissions become more advanced, they enforce the provision of higher quality fuels (e.g. unleaded and low-sulfur gasoline and diesel) to ensure that they operate effectively and are sufficiently durable. In addition, in addressing vehicular emissions global leaders, such as California, have implemented mandatory annual inspection and certification of all operating vehicles contributing to ensuring that the emissions control devices of high-emitting vehicles are repaired, or replaced, or that the vehicles are taken off the road.

Air quality standards, together with measures implemented at the local level to manage transport use (such as better transport planning and public transport incentives), have helped to limit exhaust emissions from road transport in cities and urban agglomerations (Table 1.5). Worldwide, road transport activity grew by one-quarter over the past decade, but $NO_X$ and PM emissions grew by 5% and fell by 6%, respectively. However, the failure of the EU regulations (called Euro standards) effectively to reduce $NO_X$ emissions from LDVs in real-world driving has deferred full realisation of potential improvements, notably in Europe (Figure 1.15).

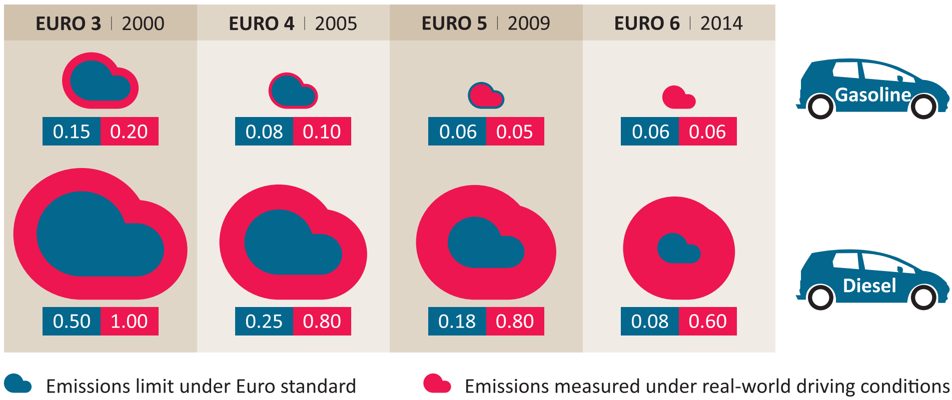
**Table 1.5 ▷ Emissions and fuel sulfur standards in selected regions**

| Region | Emission standards | | | | | | Fuel sulfur standards | |
|---|---|---|---|---|---|---|---|---|
| | Light-duty vehicles | | | Heavy-duty vehicles | | | | |
| | Global vehicle sales in 2014 (%) | Passenger-kms activity (%) | National standard | Global vehicle sales in 2014 (%) | Tonne-kms activity (%) | National standard | Diesel ppm (year) | Gasoline ppm (year) |
| United States | 19.0% | 15.9% | Tier 3 (2017) | 11.8% | 10.9% | US 2010 | 10 (2017) | 10 (2017) |
| Canada | 2.4% | 1.5% | Tier 3 (2017) | 1.5% | 1.2% | Phase 2 | 15 | 10 (2017) |
| European Union | 21.0% | 14.7% | Euro 6 | 9.4% | 9.3% | Euro VI | 10 | 10 |
| Japan | 7.1% | 2.8% | PNLTES | 2.9% | 1.4% | PNLT | 10 | 10 |
| Korea | 1.8% | 1.4% | CARB NMOG / Euro 6 (diesel) | 1.5% | 1.0% | Euro VI | 10 | 10 |
| Australia | 1.4% | 1.0% | Euro 6 (2018) | 0.5% | 0.5% | Euro V | 10 | 50 |
| Turkey | 1.2% | 1.4% | Euro 5 | 1.5% | 1.8% | Euro VI | 10 | 10 |
| China | 23.9% | 15.2% | China 5 (2018) | 48.5% | 19.8% | China IV (2014), China V (diesel, 2017) | 10 (2017) | 10 (2017) |
| Russia | 3.4% | 3.6% | Euro 5 | 1.9% | 1.7% | Euro V | 10 | 10 |
| Brazil | 5.5% | 4.1% | L-6 | 2.8% | 6.4% | P-7 | 50 | 500 |
| Argentina | 0.8% | 0.8% | Euro 5 | 0.3% | 0.9% | Euro V (2018) | 150 | 10 |
| India | 8.8% | 4.3% | Bharat IV (2017) | 3.9% | 11.4% | Bharat IV (2017) | 50 (2017) | 50 (2017) |
| Mexico | 2.0% | 2.7% | Between Euro 3-4 | 0.9% | 2.9% | Euro IV | 500 | 80 |
| Indonesia | 1.4% | 1.0% | Euro 2 | 2.5% | 1.5% | Euro II | 500 | 3 500 |
| South Africa | 0.8% | 1.7% | Euro 2 | 0.6% | 1.0% | Euro II | 500 | 500 |
| Saudi Arabia | 0.7% | 1.0% | Euro 2 | 0.5% | 5.3% | Euro II | 10 | N/A |

| Standards: | *Stricter than Euro 6/VI* | *EURO 6/VI Equivalent* | *EURO 5/V Equivalent* | *EURO 4/IV Equivalent* | *EURO 3/III Equivalent* | *EURO 2/II Equivalent* |
|---|---|---|---|---|---|---|

Sources: IEA's Mobility Model (MoMo); ICCT (2015) with IEA updates.

**Figure 1.15 ▹ Comparison of $NO_X$ emissions standards for passenger vehicles of different Euro classes** (grammes per kilometre driven)




Note: Real-world driving measurements indicate that $NO_X$ emissions from Euro 6 petrol vehicles are slightly higher than those from earlier Euro 5 vehicles (Graz University of Technology, 2013).

Source: EEA (2016).

The first emission standards for road vehicles were introduced in the United States in the 1960s in response to elevated air pollution levels in California. Regulatory programmes have since been developed throughout the United States as well as in Europe and Japan, with many countries directly following or adapting one of these standards (most commonly the EU standards) for tailpipe emissions and low-sulfur fuel requirements for local purposes. The current European standard for passenger cars – Euro 6 – can significantly reduce average lifetime $PM_{2.5}$ and $NO_X$ emissions of diesel cars. LDV emissions standards in the United States and Japan are even more stringent than Euro 6.

Personal passenger transport is provided primarily by LDVs and two- and three-wheelers (motorcycles). For LDVs, the control technologies needed to comply with the most stringent standards for low-sulfur fuel and tailpipe emissions are widely available (ICCT, 2015a). The cost of control technologies depends on whether the vehicle is fuelled by gasoline or diesel and on the stringency of the relevant emission standard. $NO_X$ and $PM_{2.5}$ control technologies for LDVs using gasoline engines are based on air-fuel control and catalytic treatment, including three-way catalysts. With the advent of gasoline direct injection and other advanced combustion technologies for spark-ignition engines, new after-treatment technologies are being developed to address PM emissions. A 2012 study estimated the costs of complying with Euro 6 in the range of $361-416 for a four-cylinder petrol engine (ICCT, 2012). In diesel vehicles, selective catalytic reduction (SCR), a lean $NO_X$ trap (LNT) and exhaust gas recirculation (EGR) are the principal technology options, and either SCR or (less often) LNT are typically used in conjunction with EGR to reduce $NO_X$ emissions. The costs of SCR range $418-494, the costs of LNT range $320-509 and EGR costs range $142-160, depending on engine size (ICCT, 2015b).

Emissions of $PM_{2.5}$ can be mitigated using particle filtration systems that are specific to engine type – hence diesel particulate filters (DPF) and gasoline particulate filters differ in design, principles of operation and costs. Even though the technologies are readily available and the costs are not prohibitively expensive, there are significant regional differences in the schedules for implementing emission and fuel standards that are more stringent. Motorcycles make use of similar control technologies as gasoline cars, including oxidation catalysts, electronic fuel injection and secondary air injection. The most effective way to reduce PM emissions from motorcycles in a short-time frame would be to ban sales of two-stroke engines (which have dramatically higher PM emissions than four-stroke engines), and to implement scrappage programmes (including replacement incentives, if needed) to take currently operating two-stroke motorcycles off the roads.

For HDVs, emissions control technologies are the same as those for diesel cars, but given the differences in vehicle weight, operations, use cycles and on-road lifetime, as well as in emission standards, the costs and configurations of the technologies differ substantially. To comply with the leading global standards, diesel trucks generally need both SCR and DPF, as well as in-cylinder emission controls (including fuel and air injection systems and EGR). Current HDV standards in the United States (US 2010) and Europe (Euro VI) reduce $NO_X$ and $PM_{2.5}$ emissions of compliant vehicles by around 95% from the basic standards (US $NO_X$ 1994 and Euro II) that relied upon 500 ppm sulfur diesel, developed in the early 1990s (ICCT, 2016). The costs of developing and integrating the emissions control technologies needed to comply with tighter emissions standards range from $426 for compliance with Euro III and $50 for compliance with US 1998, to nearly $7 000 to comply with current standards (Euro VI and US 2010), but this equates to less than 5% of the purchase price of a truck on the US market (ICCT, 2016).

### *Navigation*

Maritime transport is of the utmost importance for international trade, transporting more than 80% of internationally traded goods.[18] It traditionally tends to use the cheapest available fuels. There was a switch from coal to oil at the beginning of the last century and now ships are almost exclusively fuelled by oil products. International maritime bunkers are estimated to account for around 7% of transport oil demand, some 3.7 mb/d and generate around 90% of transport sector $SO_2$ emissions (9 Mt). The sulfur content of maritime bunker fuel oil can be as high as 3.5%, while the oil products used in road transport can contain as little as 10 ppm.

A significant part of the fuel burn happens hundreds of miles offshore, but this does not diminish the problem faced by coastal residents living near shipping lanes or ports. Moreover, secondary pollutants originating from ship effluents can travel several hundred kilometres in the atmosphere, potentially contributing to air quality problems on land. Ship emissions in areas through which major shipping lanes pass tend to be the largest source of

[18] *www.imo.org*.

$SO_X$ and $NO_X$ emissions in the area (Dalsoren, et al., 2009). In port cities that usually are big urban conglomerations, emissions from navigation account for even more significant shares of local pollution. Apart from fuel burned in approaching and leaving the port facilities, vessels may spend days waiting at anchor just a few miles offshore, or at berth, to load or offload goods, while continuing burning oil for power. In Hong Kong, before action was taken to tackle the pollution, the contribution from maritime activities to sulfur emissions was 44%, while for $NO_X$ it was 33%.[19] In Los Angeles/Long Beach the share prior to taking mitigating action was about 45% (Merk, 2014), while, in Vancouver, British Columbia, marine vessels were the biggest source of $SO_2$ emissions (and of diesel PM) prior to mitigating action.[20] Although comprehensive data are not available, Asian ports and areas adjacent to them are likely to be the most affected, as over 40% of the time spent in ports by the world's shipping fleets occurs in Asia, followed by Europe at 31% (Dalsoren, et al., 2009). Many ports are starting to be more active in maritime pollution mitigation. Some either require or incentivise so-called "cold ironing", whereby vessels at berth plug in to onshore power supply in order not to run on-board diesel generators. This concerns only an estimated 1-2% of bunker consumption globally, but it is an emissions reduction effect where it matters most, i.e. at ports, very close to shore. Naturally, this creates its own challenges in terms of managing port infrastructure and power supply, but it shows that mitigation of emissions from navigation requires a more holistic approach than just a simple cap and control mechanism.

The International Maritime Organisation (IMO), an agency of the United Nations, is responsible for, among other things, the prevention of marine pollution by ocean-going vessels, including air pollutant emissions. It introduced the first global sulfur cap for marine fuels, at 4.5%, in 1997 which in 2012 was tightened to the current level of 3.5%. In addition, the IMO designated emission control areas (ECA) in several coastal zones with even stricter sulfur emission specifications, designated as SECAs: the Baltic Sea came into effect in 2006 and the North Sea SECA in 2007, followed by North American and Caribbean ECAs in 2012 and 2013 respectively. In January 2015, the sulfur cap in these ECAs was reduced from 1.5% to 0.1%. It is now estimated that the average sulfur content of fuels burned at sea is closer to 2.5% (IMO, 2016). In Asia, there have been a number of local government or port authority initiatives. Hong Kong was the first in the Asia region to pioneer with research, monitoring and raising awareness of the air pollution raising from maritime pollution, with measures designed to first, encourage voluntary fuel switching, and, in 2015, to require all vessels to use only 0.5% sulfur content fuels while at berth in its port. Its counterpart in China's Pearl River Delta, Shenzhen port, also introduced a list of measures, including subsidies to encourage switching to lower sulfur fuel while in port. In December 2015, China's government introduced a timeline for the functioning of three ECAs within Chinese waters: Zhujiang River Delta (Pearl River Delta), Yangtze River Delta and Bohai Sea. With progressive steps that will first apply to main ports and later to all the ports, and, by 2019,

[19] *www.epd.gov.hk/epd/english/environmentinhk/air/data/emission_inve.html*

[20] *www.bc.lung.ca/sites/default/files/media/State%20of%20the%20Air%20Report%202015_1.pdf*

all the waters in the designated areas, the sulfur emissions cap is set at 0.5%. After 2019, the government will discuss introducing a 0.1% cap on fuels consumed in these areas, which will bring it closer to the IMO-mandated European and American ECAs.

## *Buildings*[21]

Energy use in buildings is responsible for 55% of all fine particulate matter ($PM_{2.5}$) emissions from human activity (19.3 Mt in 2015), as well as 5% of all nitrogen oxide emissions (5.0 Mt in 2015) and 7% of sulfur dioxide emissions (6.0 Mt in 2015). Behind these aggregate numbers, though, lies a wide range of regional circumstances and challenges. The main challenge in developing countries, particularly in many parts of sub-Saharan Africa, India and lower-income Asian countries, is access to modern energy technologies. For the 1.2 billion people without electricity, oil/kerosene lamps are widely used for lighting, including by 80 million households in India. For the more than 2.7 billion without modern cooking fuels or advanced biomass stoves, traditional open fires using solid biomass (wood, charcoal, agricultural waste and animal dung) are the main choice for cooking. Incomplete combustion of this solid biomass accounted for 90% of all $PM_{2.5}$ emissions in households in 2015. The fact that the resulting emissions occur in an enclosed space and often with poor ventilation results in major health impacts: indoor smoke can contain small particles at levels 100-times higher than the acceptable level, due to inappropriate technologies and lack of ventilation.

The solutions are to replace kerosene lighting with electricity (Box 1.5) and to provide access to clean cooking facilities. Some progress is being made on these fronts, particularly in relation to providing access to electricity: yet, as tracking reports for the UN SE4All process make clear, overall progress towards the target of ensuring universal access to modern energy services falls substantially short of what is required to attain this objective by the target date of 2030. In particular, efforts to improve access to clean cooking are largely offset by population growth, meaning no reduction is foreseen in the number of people – typically women and children – exposed to smoky and unsafe living conditions. Cleaner cookstoves are a very cost-effective way of tackling household air pollution, compared with the cost of control technologies needed in other parts of the energy system to tackle outdoor air pollution. There are already a high number of options available although performance (pollutant emissions, efficiencies) and cost vary widely.[22]

In emerging and developed countries, the patterns of household energy use and the associated air pollution challenges are quite different. Alongside the expansion of the residential natural gas distribution network in China, there has also been strong continued use of coal for domestic heating purposes – a phenomenon also observed in South Africa.

[21] The buildings sector includes energy used in residential (households), commercial and institutional buildings. It includes space heating and cooling, water heating, lighting, appliances and cooking equipment.

[22] Global Alliance for Clean Cookstoves has established guidelines for stove performance (International Workshop Agreements (IWA) Tiers of Performance) that enable comparison between the available cookstoves in their catalogue (*www.cleancookstoves.org*).

The switch away from biomass has been particularly strong in growing urban areas. As a result, while global $SO_2$ emissions from the buildings sector peaked in the 1980s and have declined more than 35% since then, the fall in the use of coal for domestic cooking and heating has not occurred in all markets. In OECD markets, the main fuels used in the buildings sector are electricity and natural gas. However, in some developed countries, notably the EU, there has also been increased use of bioenergy for heating. There has been an associated increase in PM emissions, due to the lack (until very recently) of standards in the European Union and the United States to control the level of PM emitted from wood-burning stoves.

**Box 1.5 ▹ The dark side of lighting**

Kerosene lamps are used not only by many of the 1.2 billion people estimated to be without electricity, but also are a regular source for many more that are considered to be ”under-electrified”, i.e. with frequent interruptions to supply. Yet kerosene lamps present multiple risks: they are dangerous, polluting and unhealthy. They emit very fine particulates that can cause a range of respiratory problems and illnesses; they are a fire hazard; and they provide a poor quality of light, compromising visual health (UNICEF, 2015). Moreover, UNICEF has reported that the primary cause of child poisoning in developing countries is the accidental ingestion of kerosene as the fuel is often stored in soda bottles and mistaken as such.

Phasing out kerosene lamps via the provision of electricity or solar lamps, along with efforts to improve access to clean cooking, is vital to reduce household air pollution and improve welfare. Reducing emissions of black carbon, a particularly damaging component of PM, is the priority. Recent research suggests that around 8% of the kerosene used in a simple lamp is converted into pure black carbon (more than 20-times the level of previous estimates), compared to only half of 1% of the emissions from burning wood (Lam, 2012). The benefits of cutting these emissions would extend well beyond public health, as black carbon is also a short-lived climate pollutant, with a very high global warming potential. The estimated 270 kt of black carbon emitted from kerosene lamps is equivalent to around 240 Mt of $CO_2$.

# Outlook for air pollution

## Towards blue skies?

### Highlights

- The IEA has undertaken a first-of-a-kind assessment of the impact of energy and air pollution policies on air pollutant emissions through 2040. This *World Energy Outlook Special Report* finds that despite a global decline in emissions, existing and planned energy sector policies are not sufficient to improve air quality: in our central scenario, premature deaths attributable to outdoor air pollution increase to 4.5 million in 2040 (from around 3 million today), while premature deaths due to household air pollution fall to 2.9 million (from 3.5 million today).

- The global results mask strong regional differences, which stem from the energy mix and the rigour of energy and air quality policies. In our central scenario, emissions continue to fall in industrialised countries, while in China, recent signs of decline are consolidated. Emissions generally rise in India, Southeast Asia and Africa, as expected growth in energy demand dwarfs policy efforts related to air quality. Poor air quality continues to affect the poorest most adversely: by 2040, 1.8 billion people still have no access to clean cooking devices (from 2.7 billion today), exposing mostly women and children to harmful household air pollution. The policies with the most impact on reducing emissions include those that increase access to modern energy services in developing countries, improve energy efficiency, promote fuel diversification and control air pollutant emissions.

- The outlook for air quality is a policy choice to be made: new energy and air quality policies can deliver cleaner air. This is why the IEA proposes the Clean Air Scenario that builds on proven and pragmatic energy and air quality policies and uses only existing technologies. Their implementation provides citizens with cleaner air and better health. In the Clean Air Scenario, premature deaths from outdoor air pollution fall to 2.8 million in 2040 and from household air pollution to 1.3 million. The benefits are largest in developing countries: the share of India's population exposed to $PM_{2.5}$ concentrations above the least stringent WHO target falls to 18% in 2040 (from 62% today), while in China, it shrinks to 23% (from 56% today) and to almost zero in Indonesia and South Africa.

- Achieving the benefits of the Clean Air Scenario depends upon implementation of a range of policies: access to clean cooking for all is essential to reduce the use of inefficient biomass cookstoves and associated $PM_{2.5}$ emissions. Emissions standards – strictly enforced – in road transport are central to reducing $NO_X$ emissions, in particular in cities. $SO_2$ emissions are brought down by controlling emissions and switching fuels in the power sector, and increasing energy efficiency in the industry sector. The additional investment needs are not insurmountable: cumulative investment in the Clean Air Scenario is 7% (or $4.8 trillion) higher than in the New Policies Scenario. The value of the resultant benefits is typically many times higher.

## Introduction: framing the scenarios

What impact will existing and planned air quality policies have on air pollutant emissions from future energy production and use? Will announced and intended policy efforts prove to be significantly sufficient to improve air quality, or will stronger action be needed? What is the role of policies specifically addressing air pollution, and what is the broader contribution of the energy sector transformation already taking place under the impetus of COP21 and other forces? Building on the analysis in Chapter 1 of the interaction between energy and air quality, this chapter examines future prospects based on various assumptions and assesses the costs of substantially eliminating energy-related air pollutants and the value of the benefits in terms of human health. This analysis, presented as *Energy and Air Pollution: World Energy Outlook Special Report,* has involved a first-of-a-kind assessment of the outlook for energy-related air pollutant emissions by country and region to 2040. The objective is to provide a clear and transparent picture of where we are heading and guidance on possible areas for future improvement. The conclusions rely on four major areas of research and analysis:

- A detailed country-by-country review of energy-related policies that affect the outlook for air pollution, both policies in place and those under discussion. The whole of the energy value chain is covered, from policies that affect energy production and transformation to those that affect energy consumption in the end-use sectors.[1]
- An assessment of the impact that these policies might have on improving – or impairing – air quality in the medium- and long-term trends for energy-related air pollution. This assessment is based on an updated *World Energy Outlook* (*WEO)* New Policies Scenario and was made possible thanks to a coupling of modelling and analytical efforts between the *World Energy Outlook* team and the International Institute for Applied Systems Analysis (IIASA) (Box 2.1).
- The introduction of a major new scenario, the Clean Air Scenario, incorporating a pragmatic suite of additional policies that can deliver a significant reduction in air pollution. The choice of additional measures in the Clean Air Scenario is tailored to each region, based on experience with the implementation of policies and technologies elsewhere.
- A quantification of the implications of each scenario for human health, the largest economic cost of air pollution. This was achieved by looking at the projected concentrations of energy-related particulate matter in ambient air, the number of premature deaths associated with those levels of pollution, both today and in the future, as a result of household and outdoor air pollution, and the effects on average life expectancy (see Chapter 1, Box 1.3).

[1] The review was conducted using the energy and climate policy databases of the IEA's *World Energy Outlook,* supplemented by sources that look specifically at air pollution measures, notably, *www.transportpolicy.net/* and *www.unep.org/Transport/Airquality/* and national government sources.

**Box 2.1 ▷ Analysing future air pollution trends for this *Special Report* – a coupling of IEA's World Energy Model with IIASA's GAINS model**

The main tool of analysis of the International Energy Agency's *World Energy Outlook* series is the World Energy Model (WEM)[2], 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 (such as vehicle-kilometres driven in transport, or the evolution of demand for steel or aluminium 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. Among the key outputs of the model are projections of energy-related greenhouse-gas emissions, such as carbon dioxide ($CO_2$), methane ($CH_4$) and nitrous oxide ($N_2O$). However the model does not, in isolation, generate projections for energy-related air pollution.

For this *WEO Special Report*, WEM was therefore coupled with the Greenhouse Gas and Air Pollution Interactions and Synergies (GAINS)[3] model of the IIASA. GAINS is a widely recognised model which estimates historic emissions of air pollutants by country, using international energy and industrial statistics, emission inventories and data supplied by countries. It uses this assessment of historic emissions to assess the future path of pollutant emissions by country in five-year intervals through to 2050 for different scenarios and policy packages. The GAINS model also calculates the effects of these levels of emissions on ambient air quality, and the subsequent impacts on human health and ecosystems.

GAINS and WEM have been coupled in the past in order to assess the impact of energy policy on air pollution. For this *Special Report*, the level of integration of the two models has been significantly deepened in order for GAINS to closely reproduce WEM's historical data and future projections of sectoral activity, as well as the resulting future energy demand. This enables this *WEO Special Report* to assess in detail the impact of existing and planned energy and air quality policies on the *Outlook* for air pollutants and their impacts, as well as to develop alternative scenarios in an attempt to derive key insights into policy and technology trade-offs for policy makers.

## *Policies to tackle energy-related air pollution*

The levels of pollutants that reach the atmosphere and the way that they affect human health depend on a wide variety of factors and policies. The various policies, in so far as they concern the energy sector, can be classified in different ways, but – for the purposes of this analysis – they are divided into two main groups:

[2] See *www.worldenergyoutlook.org/weomodel/* for details.

[3] See *www.iiasa.ac.at/web/home/research/modelsData/GAINS/GAINS.en.html* for details.

- ***Policies that avoid pollutant emissions,*** either because energy services are provided more efficiently or because they are provided in a way that does not involve the combustion of fuels. Examples include:
  - *Efficiency policies* including, in the buildings, industry and transport sectors, minimum energy performance standards for lighting, fans, air conditioners, industrial boilers, electric motors, cars, trucks and so on.[4] Policies that deliver process improvements or materials savings in industry have a similar impact. In developing countries, this category includes policies to promote the use of more efficient biomass cookstoves to reduce household air pollution.
  - *Policies promoting renewable sources of energy*, such as feed-in tariffs or technology-specific auctions that promote the deployment of wind or solar power. This category also includes energy access policies based on renewables, such as programmes to provide solar cookstoves or solar lighting.
  - *Improvements to transport networks and urban planning* that lead to less reliance on individual vehicles, whether through better provision of public transport, measures that allow for more journeys to be taken on foot or by bicycle, or those that shift freight transport off the roads and onto rail or waterborne transport.
- ***Policies that reduce the impact of the combustion of fuels and energy-related processes***, either through mandatory standards limiting pollutant concentrations in the flue gas (so encouraging the uptake of emissions control technologies) or through measures that otherwise dilute their impact once emitted or encourage a switch to combustion of a less-polluting fuel.[5] Examples include:
  - *Industrial and power sector emissions standards* that limit the pollution that an individual source or plant can emit during combustion or the energy-consuming process, or mandate a control technology that must be used. Examples of this type of regulation include specific emissions limits for power plants or specific industrial facilities, e.g. the European Union's Large Combustion Plant Directive (2001) and the Industrial Emissions Directive (2010).[6]
  - *Regulations on stack height or improved ventilation* (for household air pollutants), that dilutes the concentrations of pollutants reaching people's lungs.

[4] Some effects on air pollution of increasing energy efficiency are indirect. For example, more efficient refrigerators or televisions do not assist in reducing household air pollution in the buildings sector, but lower overall electricity demand decreases air pollution from the power sector. For road vehicles, lowering fuel consumption per kilometre driven does not necessarily reduce $NO_X$ emissions, but it can reduce the cost of compliance with emissions standards.

[5] Measures can also be imposed to limit emissions from non-energy activity, for instance dust from construction work or restrictions on waste burning in the residential and agricultural sectors.

[6] In Japan, the Air Pollution Control Law sets emissions limits, but it has been a conventional practice for power companies and industries to enact pollution prevention agreements with local authorities with more stringent standards. To date, more than 20 000 such agreements have been enacted.

- *Vehicle emission standards*, such as the US Tier 1, 2 and 3 emissions limits for different categories of vehicles.
- *Regulations on fuel quality*, such as limits on the sulfur content of transport fuels (down to 10 parts per million [ppm] in most OECD countries) or measures to promote coal-washing.
- *Fuel switching to a less-polluting fuel*, notably switching from coal-to-gas in power generation or industry, from heavy fuel oil to liquefied natural gas (LNG) in maritime transport, or from solid biomass to liquefied petroleum gas (LPG) for cooking in developing countries.
- *Regulations targeting specific fuels or activities*, such as the bans in many Chinese cities on buildings use of low-grade coal, or the increasing number of "low emissions zones" in urban areas that restrict access to traffic failing to meet strict emissions norms.
- *Monitoring and retrofit programmes for existing equipment / vehicles:* measures include programmes for regular inspection and maintenance, and programmes to encourage the retrofit of emissions control systems.



Although the overlap is not complete, policies and measures that lead to an avoidance of air pollution emissions tend to be associated with the broader transformation of the energy sector into one that is more efficient and less reliant on fossil fuels: over the longer term, the simplest way to tackle air pollution is not to produce the pollutants in the first place. Policies and measures that lead to a reduction in emissions, or reduce the impact of emissions, are often introduced specifically for the purposes of tackling air pollution.

Efforts by public policy makers to avoid or reduce pollutant emissions are widespread and have proven effective in many countries. Their effectiveness can be enhanced if fuel pricing policy is used to provide an economic incentive to change behaviour and avoid or reduce air pollution to the required level or even below, where the investment calculations or operational decisions of individual consumer are sufficiently affected.[7] The transport sector offers a useful example: avoiding pollution through improving transport networks and urban planning can be usefully supported through pricing policy that affects consumer choices, as even an improved public transport is effective in addressing air pollution only to the extent that it is actually used by the consumer.

[7] Although policy making places strong emphasis on direct regulatory measures to avoid or reduce emissions today, economic incentives have played an important role in reducing air pollution. A prominent example is the US Acid Rain Program, established under the Clean Air Act, which requires major emission reductions of $SO_2$ and $NO_X$ from the power sector, the primary precursors of acid rain. The $SO_2$ programme sets a permanent cap on the total amount of $SO_2$ that may be emitted by power plants. The program was phased in, with the final 2010 $SO_2$ cap set at 8.95 million tonnes, around half of 1980 power sector emissions. The US experience has inspired the introduction of air pollutant emission trading schemes in Ontario (Canada) and in the Seoul (Korea) metropolitan area. Other examples of economic incentives include emissions taxes: Sweden has had a tax on $NO_X$ emissions since the early 1990s and Japan introduced a tax on $SO_2$ emissions in the 1970s.

Typical examples of such pricing policies include:

- Reform of fossil-fuel consumption subsidies, such as recent energy pricing reforms in India, Indonesia and parts of the Middle East.
- Fuel taxes and road pricing, which are components of the fuel price regime in many countries, although diesel – which emits much more particulate matter (PM) and nitrogen oxides ($NO_X$) than gasoline – is still less heavily taxed in many countries (OECD, 2015).
- Congestion charges, such as the London Congestion Charge Zone that requires a payment to enter a defined geographical area (and that offers discounts for ultra-low emissions vehicles).

All these policies can be effective both as an element of urban transport policy, and to improve the economic case for switching to more efficient or lower-emitting vehicles.

## *Scenario definitions*

This analysis is conducted on the basis of two scenarios: the New Policies Scenario, which assumes the continuation of existing and planned policies, and the Clean Air Scenario, in which the implementation of additional measures achieves a significant reduction in air pollutant emissions.

### *New Policies Scenario*

The New Policies Scenario assesses the outlook for energy-related air pollution by considering, country-by-country and sector-by-sector, all relevant policies and measures that are already adopted today, or have been announced as intended policies, even when the implementing measures have yet to be fully defined. For those that have been announced, the extent and timing of their implementation is assessed according to the prevailing institutional, political and economic circumstances.

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 (Spotlight). 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). Importantly, this category also includes energy-related targets expressed through the Intended Nationally Determined Contributions, submitted by national governments as pledges in the run-up to the United Nations Framework Convention on Climate Change Conference of the Parties (COP) 21 and adopted as part of the Paris Agreement. Part B of this report includes more detail on the policies included in the New Policies Scenario in the featured countries and regions, and more detail on their impact on long-term pollutant emissions trends.

S P O T L I G H T

## What is the link between economic development and air quality?

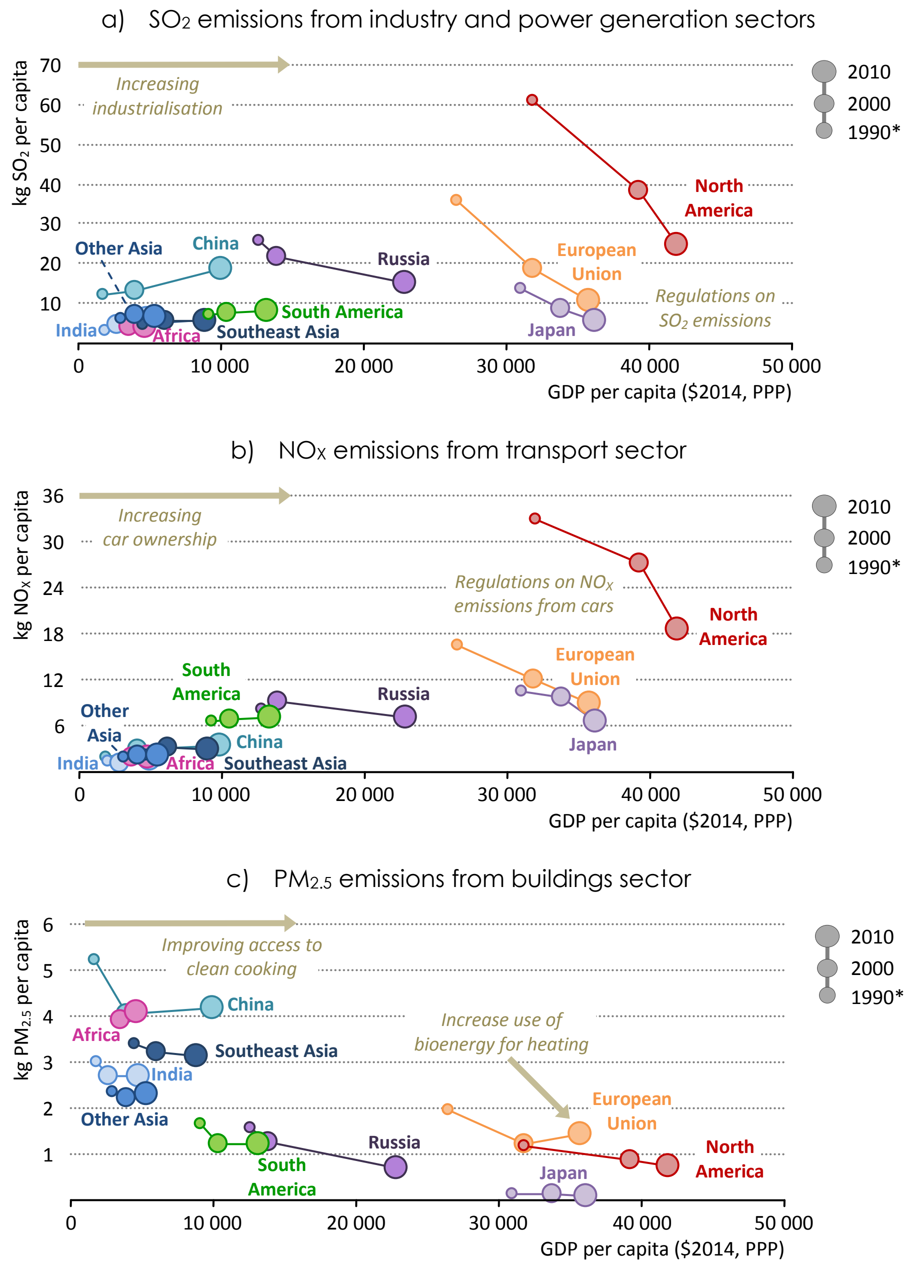
The different phases of economic development within a country define the nature of the level of access to different energy services and, by consequence, can be a strong determinant of the level of emissions of various pollutants. In very general terms, low-income countries tend to use solid biomass for cooking, giving rise to a higher incidence of PM emissions. Middle-income countries, in which the energy system often has to keep pace with rapid economic growth and industrialisation, can see rising sulfur dioxide ($SO_2$) emissions. And as incomes rise further, so countries can witness strong growth in $NO_X$ emissions due to transport growth (primarily the increase in the fleet of vehicles).

The way in which this plays out in individual cases is highly contingent on national circumstances. While some general observations hold true for the relationship between incomes and air quality trends from 1990 to 2010 (Figure 2.1), there are variations between the pollutants and among different countries and regions. Structural differences between economies and their energy mixes can explain a large part of these variations. In addition, the presence (or absence) of policies devoted to air quality control is significant in determining the relationship between incomes and pollutant emissions.

In the case of $SO_2$ and $NO_X$, an encouraging trend is that all the emerging and developing countries appear to be on a lower pathway for emissions per capita than the very high levels reached in previous decades in North America and Europe. Another observation concerns the apparent inflexion point, once countries reach middle-income levels, at which the trend of rising emissions per capita goes into reverse, suggesting that rising incomes boost both the policy priority attached to air quality and the availability of capital to invest in control technologies. Stronger regulatory actions in North America, the European Union (EU) and Japan has led to large falls in $SO_2$ and $NO_X$ emissions per capita since 1990. In the case of $PM_{2.5}$[8], there generally is a strong correlation between rising average incomes and reductions in emissions, underpinned by improved access to clean cooking facilities. There are, though, two important caveats relating to the period 2000-2010. In China, the use of coal as a substitute for solid biomass in the buildings sector arrested a downward trend in $PM_{2.5}$ emissions. In the EU, increased use of bioenergy for heating has contributed to a fall in $CO_2$ emissions, but also to growth in per-capita exposure to $PM_{2.5}$.

[8] Size is an important factor in determining the health impacts of PM: "coarse particles" are between 2.5 and 10 micrometres (μm) in diameter and "fine particles" are smaller than 2.5 μm.

**Figure 2.1 ▷ Air pollutant emissions by type from key sectors**




* For Russia, 1995 data have been taken into account as first series point.

Notes: kg = kilogrammes. Calculated based on gross domestic product expressed in year-2014 dollars in purchasing power parity (PPP) terms.

Source: Crippa, et al., (2016).

### *Clean Air Scenario*

Existing and planned policies, in many countries, are not sufficient to reduce significantly the impacts of air pollution, compared with today. Pollutant emissions may still rise as energy demand (or population) grows, with the result that the impact on human health and the environment worsens as economies develop. In some countries, despite considerable policy efforts, there are other complex interactions in play: even where air pollutant emissions go down on the basis of existing and planned policies, the impact on human health can be worse as a result of increasing urbanisation (which can increase the extent of human exposure to pollution) or some other change in demographics (which can increase the share of the population that is vulnerable to severe air pollution).

That is why this *WEO Special Report* develops an alternative scenario, the Clean Air Scenario, which shows what might be achieved through stronger policy action, delivering a significant reduction in pollutant emissions and the consequent impacts on human health. Implementation of the various policy measures in the Clean Air Scenario does not deliver a pollutant-free atmosphere, but it does offer a pragmatic agenda for change, all the more so since the improved outcomes do not depend on any technological breakthroughs or radical innovations on the policy side.[9] As in the New Policies Scenario, the Clean Air Scenario assumes cost and efficiency improvements in existing technologies, e.g. continued cost reductions in battery technology and the wider deployment of renewables, but the scenario essentially relies on the implementation of approaches that are known and proven already today.[10]

Following the typology outlined in the previous section, the policies included in the Clean Air Scenario are categorised in two ways (Table 2.1): those that *avoid* pollutant emissions altogether, and those that *reduce* emissions or otherwise mitigate their impact. They are complemented by economic incentives to support their implementation. Countries approach these policy goals from a wide range of starting points. In all cases, the policy package in the Clean Air Scenario scales up the level of ambition, but countries with well-developed regulatory frameworks may ultimately be in a position to go farther and faster. For others, full implementation of these policies requires a concerted effort over an extended period of time. That is why, within a common framework, the timelines for implementation in different countries and regions vary, governed by the general consideration that the further that today's regulation is from the required benchmark, the longer the period required for adjustment in the Clean Air Scenario.

[9] Measures in the Clean Air Scenario include increasing energy efficiency, reducing the use of the least-efficient coal-fired power plants and banning their construction, increasing investment in renewable energy technologies and phasing out fossil fuel subsidies, many of which have also been proposed as part of the IEA's Bridge Strategy for raising climate ambition to 2030 (IEA, 2015), a set of policy measures endorsed by IEA Energy Ministers. The links between air quality and climate change policies are discussed in Chapter 3.

[10] The rate of technology learning for some renewable technologies in the Clean Air Scenario is faster than in the New Policies Scenario, as progress is facilitated by higher levels of projected deployment.

**Table 2.1 ▷ Policy pillars to avoid or remove air pollutant emissions in the Clean Air Scenario**

| Avoid | Reduce |
|---|---|
| **Strong push for industrial and power sector efficiency:**<br>For industry, the introduction or strengthening of existing minimum energy performance standards (MEPs) for electric motor-driven systems.<br>In the power sector, reduced use of inefficient coal-fired power plants (typically subcritical) and a ban on new inefficient coal-fired power plants. | **Stringent emissions limits for new and existing combustion plants.**<br>For plants above 50 $MW_{th}$ using solid fuels, emissions limits are set at 30 $mg/m^3$ for PM and 200 $mg/m^3$ for $NO_X$ and $SO_2$. Existing plants need to be retrofitted within 10 years.<br>Emission limits for smaller plants (below 50$MW_{th}$) depending on size, fuel and combustion process.[11]<br>Industrial processes required to be fitted with the best available techniques in order to obtain operating permits.[12] |
| **Strong efficiency policies for appliances and buildings:**<br>Introduction or strengthening of existing MEPs for appliances, lighting, heating and cooling.<br>Introduction of mandatory energy conservation building codes. | **Stringent controls for biomass boilers in residential buildings:**<br>Emissions limits for biomass boilers set at 40-60 $mg/m^3$ for PM and 200 $mg/m^3$ for $NO_X$.[13] |
| **Higher fuel-efficiency standards:**<br>Adoption or strengthening of fuel-economy standards for road vehicles, including for both light- and heavy-duty vehicles. | **Higher vehicle emissions standards:**<br>For light-duty diesel vehicles: limits as low as 0.1 g/km for $NO_X$ and 0.01 g/km for PM.<br>For heavy-duty diesel vehicles and machinery: limits of 3.5 g/km for $NO_X$ and 0.03 g/km for PM.<br>For all vehicles, full on-road compliance by 2025.<br>A ban on light-duty gasoline vehicles without three-way catalysts and tight evaporative controls, and a phase-out of two-stroke engines for two-and three-wheelers. |
| **Increased support to non-thermal renewable power generation:**<br>Increased investment in renewable energy technologies in the power sector. | **Fuel switching to lower emissions fuels**:<br>Increased coal-to-gas switching and use of low-sulfur fuels in maritime transport. |
| **Better public transport, urban planning and support to alternative transport fuels:**<br>Promotion of public transport, a switch to electric two- and three-wheelers, electric commercial vehicles and natural gas buses. | **Improved fuel quality:**<br>Maximum sulfur content of oil products capped at 1% for heavy fuel oil, 0.1% for gasoil and 10 ppm for gasoline and diesel. |
| **Access to electricity / clean cooking facilities:**<br>Enhanced provision of electricity and clean cooking access based on renewable technologies. | **Access to electricity / clean cooking facilities:**<br>Enhanced provision of improved cookstoves and modern fuels for cooking. |
| **Support avoid and/or reduce via a change in economic incentives** | |
| **Phase-out fossil-fuel consumption subsidies**<br>Pricing reforms that remove the incentives for wasteful consumption of fossil fuels. | |

Notes: $MW_{th}$ =megawatts thermal; $mg/m^3$ = micrograms per cubic metre; g/km = grammes per kilometre; ppm = parts per million.

[11] The Medium Combustion Plants Directive of the European Union and the revised US Clean Air Standards from 2015 provided the guidelines for achievable emission limit values in these cases.

[12] The BAT Reference Documents of the Industrial Emissions Directive of the European Union and the New Source Performance Standards in the United States are important sources for best available techniques.

[13] The EU's EcoDesign Directive provides a guide for implementation.

The assumed stricter emissions limits and controls are introduced in a staggered manner over the period to 2025, depending on conditions in the country in question. From the moment when more stringent emissions limits apply, existing large combustion plants have an extra ten years to be retrofitted to the higher standards. In the same way, higher vehicle emissions standards for road vehicles are introduced in most countries by 2020, and everywhere by 2025, with an additional five years in each case to achieve full on-road compliance. With regard to the efficiency measures, the timing of the introduction of new MEPs is dependent on country circumstances, but in all cases is implemented to support a phase-out of the least-efficient categories of equipment and appliances by 2030. Higher fuel-efficiency standards are eventually reached in all countries for new light- and heavy-duty vehicles, such that the average fuel consumption for these new vehicles is up to 50% more efficient by 2030 compared with today. The stipulated maximum sulfur content of oil products is achieved in all countries by 2025.



Full universal access to electricity and to clean cooking facilities is achieved by 2040, whereas today more than 2.7 billion people still rely on the traditional use of biomass for cooking and 1.2 billion have no access to electricity. These circumstances are also the biggest cause of premature deaths related to household air pollution. The target date of 2040 adopted here means that the Clean Air Scenario allows an extra ten years for full attainment of these objectives, compared with the 2030 date specified in the UN Sustainable Development Goal number 7. This reflects the latest assessment of the global tracking framework report, which concludes that the current rate of progress falls substantially short of what is required to meet the UN objectives by 2030 (IEA and World Bank, 2015). The level of achievement in the Clean Air Scenario is, nonetheless, much higher than that projected in the New Policies Scenario.

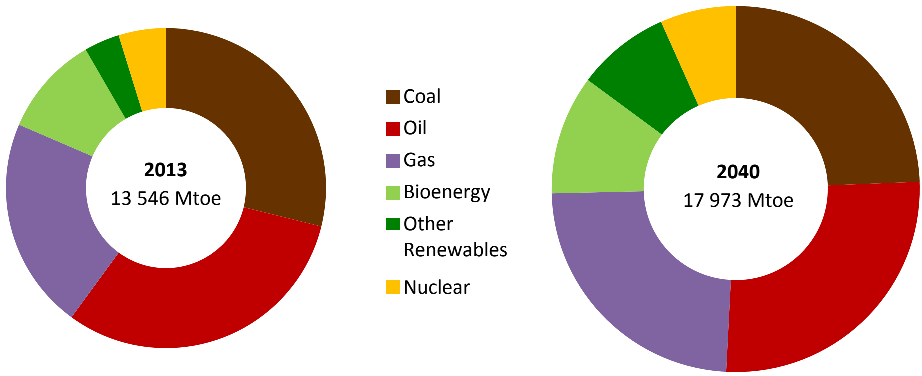
## Outlook for energy-related air pollution in the New Policies Scenario

Governments, counties, municipalities – all are taking measures to address energy-related air pollution. Their actions are multiple and varied, ranging from short-term to long-term measures, from energy sector to air quality policies, and from adopting best technological practice to urban planning and other measures that profoundly influence human behaviour. The degree to which such policies are adopted in the New Policies Scenario differs by country, depending on the status of development of individual countries and the structure of the energy mix.[14] It is all of these measures combined that guide the *Outlook* for energy-related air pollution in the New Policies Scenario.

In the New Policies Scenario, global primary energy demand increases by one-third to 2040 (Figure 2.2), driven by population growth (up by around one-quarter over today's level) and income growth (the economy in 2040 is two-and-a-half times larger than today). As a result,

[14] Detailed country and regional analyses of air quality and energy policy frameworks and their impact on the *Outlook* for energy-related pollution and air quality are presented in selected profiles in Part B. The profiles also discuss in detail the respective results of the Clean Air Scenario.

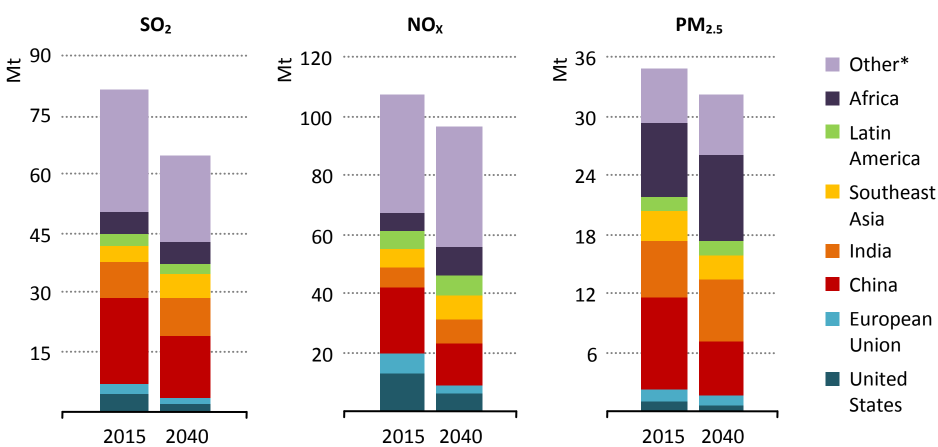
**Figure 2.2 ▷ World primary energy demand in the New Policies Scenario**




Note: Mtoe = million tonnes of oil equivalent.

energy intensity (i.e. the amount of energy used per unit of gross domestic product) declines by 2.4% per year, about 1.5 times faster than over the past 25 years. Taking into account the energy-related components of the climate pledges made at COP21, the main contribution to satisfying total global energy demand growth (at 35% of the total) comes from energy sources that do not emit any air pollutants during normal operations, including nuclear, hydropower, wind and solar energy. Natural gas is the second-largest contributor, at 31% of total demand growth, while the remainder is split in almost equal parts between coal, oil and biomass (including biofuels), the principal contributors to the emission of combustion-related air pollutants from the energy sector.

**Figure 2.3 ▷ Air pollutant emissions from the energy sector by region in the New Policies Scenario**




* Includes international bunkers. Note: Mt = million tonnes.

Sources: IEA; IIASA.

Although global energy demand continues to grow, energy-related air pollutant emissions (including process-related emissions) decline in many countries to 2040 (Figure 2.3). Global $SO_2$ emissions decline by 20% in 2040 relative to 2015, $NO_X$ emissions by 10% and $PM_{2.5}$ emissions by 7%. Although this reflects positively on current policy efforts generally, the trends differ substantially by region and state of economic development. No single country or region, considered individually in the analysis, eliminates energy-related air pollution emissions to the full extent.



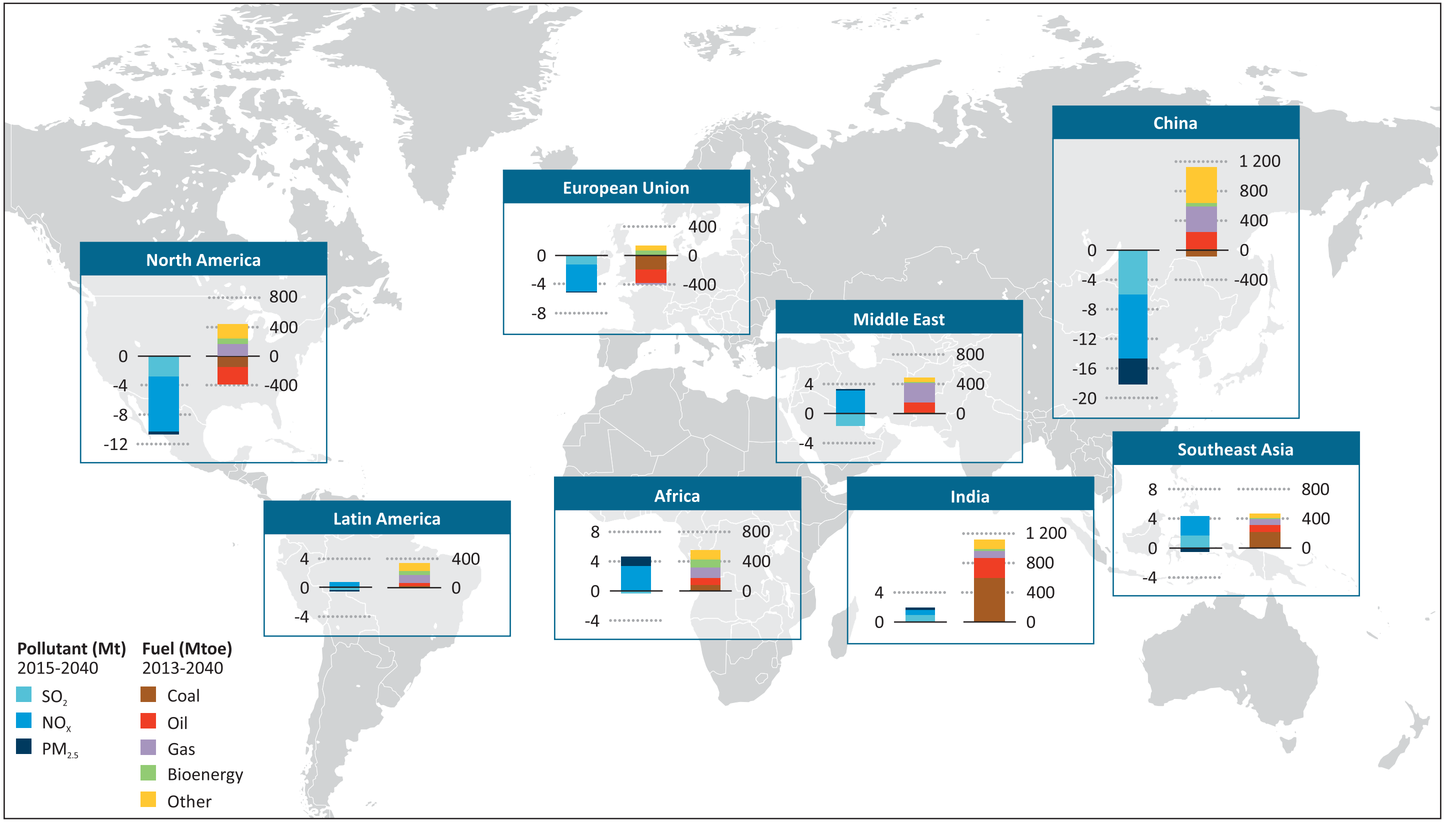
### *Air pollutant trends by region*

Emissions of most major pollutants are already in decline in many industrialised countries, and this trend continues in the New Policies Scenario as total energy demand falls (reflecting increasing energy efficiency), the use of low-carbon alternatives increases and more stringent combustion control regulations take effect (Figure 2.4). In the *United States*, existing and planned energy policies reduce the use of coal by more than one-third to 2040 and that of oil by one-quarter, while low-carbon energy sources (including biomass) grow rapidly and expand their share in the energy mix by ten percentage points to 27% in 2040. Combined with air pollution policies, this brings down emissions of all major pollutants: $SO_2$ and $NO_X$ emissions drop by more than 50% to 2040, led by the power and transport sectors respectively. $PM_{2.5}$ emissions fall by 35%. Similarly, in the *European Union*, efforts to decarbonise the power sector under the EU's energy and climate package drive an almost 50% drop in $SO_2$ emissions by 2040, while efforts to improve compliance with existing transport regulations drive a 55% decline in $NO_X$ emissions. $PM_{2.5}$ emissions fall by less than 20%, as a decline in transport emissions is partially offset by a rise in emissions from biomass use in the residential and power sectors. In *Japan*, energy sector regulations to reduce air pollution are already prevalent and efforts to increase energy efficiency across all sectors continue in the New Policies Scenario.[15] As a result, $SO_2$ and $PM_{2.5}$ emissions each fall by one-third by 2040, while $NO_X$ emissions decline by 45%.

In *China*, recent signs of pollutant decline are confirmed in the long term: energy demand growth slows considerably, the fuel mix becomes increasingly diversified and recent efforts to significantly strengthen air quality regulation are reflected in energy capital stock. As a result, emissions of all pollutants decline in the New Policies Scenario by 2040: $SO_2$ emissions fall by almost 30%, and $NO_X$ and $PM_{2.5}$ emissions by around 40%, relative to today. Despite such progress the problem of air pollution is not resolved in China, as urban sources become relatively more dominant, exposing larger parts of an ageing population to harmful pollution.

[15] For example, Japan has recently set new efficiency standards for fossil fuel-fired power plants, including coal-fired power plants. The new standard mandates heat efficiency of at least 42% for all new coal-fired power, a level equivalent to ultra-supercritical plants or the best technology available.

**Figure 2.4 ▷ Change in air pollutant emissions and energy demand by region in the New Policies Scenario**




This map is without prejudice to the status of or sovereignty over any territory, to the delimitation of international frontiers and boundaries, and to the name of any territory, city or area.

Pollutant emissions are generally expected to rise in India, Southeast Asia and Africa on the basis of the policies of the New Policies Scenario. This is partly, but not entirely, due to policy shortfalls. *India*, for example, is taking important steps to address air pollution (which will curb emissions growth in the medium term) and has ambitious targets to increase the use of renewable energies in the power sector and increase the use of electric mobility. But as its economy develops and industrialisation and urbanisation increase, people increasingly demand access to mobility and other energy services. The associated rise in energy demand swamps policy interventions designed to tackle air pollution. In India, $NO_X$ emissions increase by 10% over current levels by 2040, largely driven by the industry sector (mostly cement) and despite a decline in transport-related emissions from new emissions regulation. $SO_2$ emissions are 11% above today's level, despite expected new regulation in the power sector. $PM_{2.5}$ emissions increase by 7%, despite a strong reduction in the buildings sector, where more people do obtain access to cleaner energy services. As a result, per-capita $PM_{2.5}$ emissions in India do fall through 2040, but they are still about 2.5 times the level of Korea today. In *Southeast Asia*, energy demand grows at a rapid pace in the New Policies Scenario, at 2.2% per year, a rate well above the global average. Much of the growth is supported by coal and oil in the New Policies Scenario, at around 45% and 20%, respectively. The rigour of regulation to mitigate air pollutant emissions varies strongly in the region, allowing $SO_2$ and $NO_X$ emissions to grow significantly through 2040: $PM_{2.5}$ emissions decline modestly, mainly because of efforts to improve access to improved cooking alternatives.

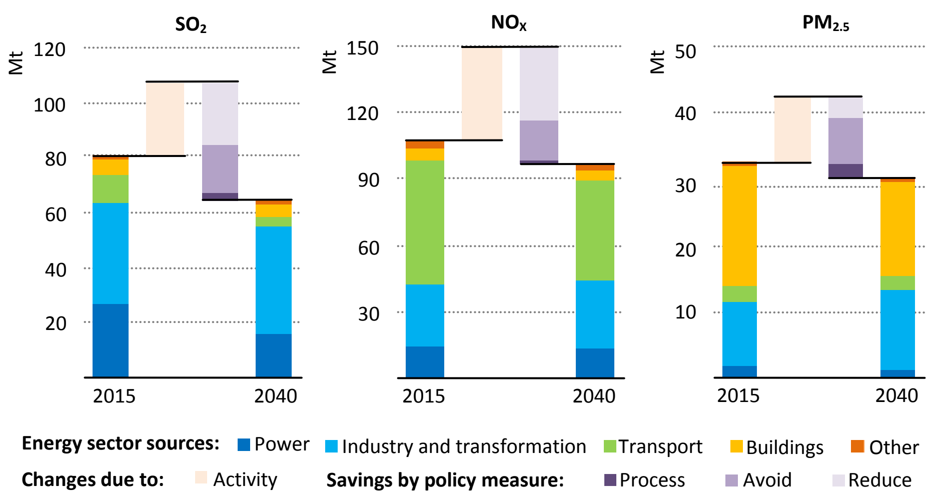
Emissions trends diverge in *Latin America* in the New Policies Scenario: $SO_2$ and $PM_{2.5}$ emissions fall by almost 10%, while $NO_X$ emissions rise by nearly 15% to 2040. The decline in $SO_2$ emissions stems largely from a more than 50% fall in the use of oil for power generation. The decline in power sector emissions is partially offset by an increase in emissions from the industry sector in Brazil, where emissions grow by around 60%, driven by the iron and steel sector. The decline in $PM_{2.5}$ emissions is triggered largely by the reduced traditional use of biomass for cooking, as the number of people relying on inefficient biomass cookstoves drops by around 20% through 2040. $NO_X$ emissions from transport fall in Latin America in the New Policies Scenario, but a near 50% increase in emissions from the industry and transformation sector (in particular cement) lifts the overall total.

*Africa* continues to struggle with air quality in the New Policies Scenario. While power sector regulation in South Africa helps to bring down $SO_2$ emissions in the medium term and the share of renewables (excluding biomass) and nuclear in the African power sector doubles by 2040, the gradual rise of energy demand brings up emissions again after 2030, in particular from the power and iron and steel sectors. Under existing and planned policies, many countries in Africa are set to follow the trend of other developing countries (and that of industrialised countries in the past): while per-capita income in sub-Saharan Africa (except South Africa) in 2040 is comparable with that of India today, existing and planned energy and air quality policies imply that per-capita emissions of $PM_{2.5}$ will also be at a similar level to that of India today. This problem will disproportionally disadvantage the poorest of the population on the continent: per-capita emissions of $PM_{2.5}$ associated with the use of inefficient cookstoves remain highest in Sub-Saharan Africa (except South Africa).

### *Air pollutant trends by sector*

The global decline in emissions stems jointly from policies to transform the energy sector and to reduce air pollutant emissions. Policy measures to avoid emissions contribute 40% of the global decline of $SO_2$ emissions by 2040, 35% for $NO_X$ emissions and almost 60% for $PM_{2.5}$ (Figure 2.5). Measures to reduce emissions contribute 53% of the decline in $SO_2$ emissions, 61% of $NO_X$ emissions and 26% of $PM_{2.5}$ emissions, while a drop in process-related emissions is responsible for 7% of the $SO_2$ savings, 3% for $NO_X$ and 17% for $PM_{2.5}$.

**Figure 2.5 ▷ Global air pollutant emissions from the energy sector and savings by policy type in the New Policies Scenario**




Sources: IEA; IIASA.

Air pollutant emission trends also vary significantly by sector. The entire energy sector emitted 81 million tonnes (Mt) $SO_2$ emissions in 2015, mostly in the industry and transformation (46%) and power sectors (33%). Three-quarters of $SO_2$ emissions were associated with the combustion of fuels, while the remainder were from energy processes in the industry and transformation sectors. About 60% of combustion-related $SO_2$ emissions were from the use of coal, mostly in the power and industry sectors; almost 40% from the use of oil and the remainder from the use of biomass. In the New Policies Scenario, policy efforts to avoid and reduce $SO_2$ emissions successfully bring down their level to 64 Mt in 2040, 20% below today's level. The decline is led by the power sector, where emissions from coal and oil combustion fall by 47% and 55% respectively, despite a growth of electricity generation by almost 70% relative to today. In the transport sector, $SO_2$ emissions fall by two-thirds through to the mid-2020s, largely due to regulations limiting the sulfur content (including in international navigation). As of the mid-2020s, however, the strong rise in demand for mobility offsets further declines and transport-related $SO_2$ emissions begin to rise modestly. Even so, by 2040, despite a more than doubling of the global car fleet and a significant rise in road and maritime freight activity, $SO_2$ emissions from transport are around 60% below current levels. In the industry and transformation sectors, global policy efforts are not sufficient to achieve similar reductions: $SO_2$ emissions from combustion activities remain broadly at today's level, despite a growth in industrial activity, as emissions from combustion activities are regulated in many countries. But process-related emissions in the industry sector continue to rise, mostly in the paper and iron and steel sectors. As a result, the share of process-related emissions in total energy-related $SO_2$ emissions rises to 35% by 2040, up from 25% today.

2

Global $NO_X$ emissions were almost 110 Mt in 2015; the main contributions coming from the transport sector (52% of global $NO_X$ emissions), industry and transformation (26%) and the power (14%) sector. $NO_X$ emissions in the energy sector are mostly a result of combustion activities, with oil combustion contributing around 60% of the global total, followed by coal (15%), natural gas (9%) and bioenergy (4%). The remainder are process-related emissions in the industry and transformation sectors. In the New Policies Scenario, $NO_X$ emissions fall by 10% to 97 Mt in 2040, despite rising energy demand. Trends by sector vary: $NO_X$ emissions in the transport sector fall by one-fifth to 2040, the decline being particularly fast until 2030, at 1.3% per year on average, and led by reductions in industrialised countries and China (which contributes more than one-quarter of the global decline). Transport-related $NO_X$ emissions continue to decline in the 2030s, but the pace of decline is more modest, at 0.4% per year, as strong growth in mobility and road freight demand in many developing countries partially offset emissions reductions in other countries. Although $NO_X$ emissions decline in the power and residential sectors in the New Policies Scenario, they increase by 11% in the industry and transformation sector. Emissions from the industry and transformation sectors from process-related activities account for 65% of the rise in $NO_X$ emissions, while an increase of $NO_X$ emissions from the combustion of natural gas and biomass contributes the remainder.

$PM_{2.5}$ emissions in 2015 were around 35 Mt. More than half of $PM_{2.5}$ emissions arise from the residential sector today, of which 90% derive from the combustion of biomass in households. Almost all biomass-related emissions in the residential sector occur in developing countries and are closely linked to the burning of fuelwood and charcoal in inefficient cookstoves: more than 2.7 billion people rely on such traditional use of biomass, with significant impacts on human health. Emissions from the use of biomass in the residential sector are significant also in developed countries, where biomass is used mostly for space heating purposes: in the EU, this use accounts for more than 40% of total $PM_{2.5}$ emissions, while the figure is around 30% in the United States. Another 30% of global $PM_{2.5}$ emissions arise from the industry sector, of which around 80% are process-related emissions and the remainder arise from the combustion of biomass, coal and oil. The transport sector contributes less than 10% to global $PM_{2.5}$ emissions, with almost 90% coming from the combustion of oil and much of the remainder from non-exhaust emissions related to the driving of vehicles.

**Box 2.2 ⊳ Relevance and impact of a global cap on maritime sulfur**

Shipping fuels contribute significantly to global $SO_2$ emissions (Chapter 1). The International Maritime Organization (IMO) has plans to introduce a global cap of 0.5% on $SO_2$ emissions and tighten $NO_X$ emission standards in emission control areas (ECA) in coastal zones. The IMO and all the other initiatives to control shipping emissions do not specify nor mandate the type or the quality of the fuel used, but only the emissions content of the flue gas. This leaves it up to the ship-owners to decide whether they will procure 0.5% sulfur oil fuels (essentially diesel, as most fuel oil produced has higher sulfur content), switch to practically zero-sulfur LNG bunkers, or install scrubbers to treat the engine effluents in order to remove the acid gases arising from the combustion of high sulfur fuels.

Compliance is difficult to predict in the shipping sector with its many individual players. Today's oversupply of diesel, thanks to rapid expansion of refining capacity and upgrading units in the Middle East, Russia and China, has suppressed the price differential between diesel and crude oil and led some ship-owners to judge that a switch to diesel for marine bunkers is the most obvious solution. However, in the longer term, diesel is expected to experience the largest demand growth among all oil products, primarily from the road freight sector in Asia. Choosing diesel to comply with emissions standards could, therefore, lock-in a solution that relies on price differentials which are very likely to increase in the future.

Desulfurising fuel oil at the refinery is another possibility. However, hydro-treating equipment requires investment that may be beyond the reach for many refiners. Desulfurisation is also an energy-intensive process, and, at a time when energy intensity in many industries is not only subject to more and more regulation, but plays an important role in regional competitiveness, it is relatively unlikely that refiners will opt for that. Refiners that process ultra-low sulfur crude oils (under 0.3%) will be able to produce 0.5% sulfur fuel oils without additional effort, but this type of crude oil makes up less than 20% of global supply.

An alternative to refinery-produced low-sulfur fuels is the use of scrubbers on ships – tailpipe treatment of the emissions. Retrofitting scrubbers might cost several million dollars, but at the same time, some owners believe that scrubbers might eventually be a cost-effective way to comply also with the expected tighter $NO_X$ and PM regulations. Switching to LNG bunkers would solve almost all of the challenges associated with current and expected emissions regulations, but it would be a massive investment undertaking for both the ship-owners and ship-builders and it would take more than a decade to make an appreciable dent in the market share of oil products.

For the last few years, the shipping industry and the affiliated organisations have been debating both the timing of the IMO's 0.5% global sulfur cap and the compliance methods. While planned for introduction in 2020, IMO may yet decide to delay implementation until 2025. In the New Policies Scenario, we assume implementation of the cap by 2025. As a result, $SO_2$ emissions then decline dramatically, reaching 2.5 Mt in

2040 from 8.2 Mt today. The use of LNG as a bunker fuel rises, reaching 10% of total energy demand from the sector by 2040. This brings down $SO_2$ emissions and avoids just under 2 Mt of $NO_X$ emissions, relative to today, which fall to 16 Mt in 2040.

To illustrate the benefit of earlier adoption of the global sulfur cap of 0.5%, the Clean Air Scenario assumes a phase-in by 2020. The share of LNG as a bunker fuel grows to 18% by 2040, helping to avoid an extra 1 Mt of $NO_X$. The share of diesel grows to one-third in the Clean Air Scenario (up from around one-fifth today), assuming ECA-type regulations along all economically significant coastlines in the world. The $SO_2$ emissions reduction is more rapid than in the New Policies Scenario, reaching 2.8 Mt in 2020 and 2.1 Mt in 2040 (compared with 5.5 Mt in 2020 in the New Policies Scenario). The initial reduction to 2020, though, relies heavily upon diesel use in bunkers, pushing up prices. This eventually brings back fuel oil, either desulfurised, or through the use of on-board scrubbers.



In the New Policies Scenario, global $PM_{2.5}$ emissions fall by 7% to 32 Mt in 2040. The global decline is largely a result of measures in the residential sector, where emissions fall by more than 20%. The number of people without access to clean cookstoves falls to 1.8 billion in 2040, bringing down $PM_{2.5}$ emissions related to the burning of fuelwood and charcoal in inefficient cookstoves. $PM_{2.5}$ emissions from the use of biomass for heating fall in the United States, but continue to increase modestly in the EU, despite regulatory efforts, as the increased use of biomass in the residential sector remains an important part of Europe's decarbonisation strategy. $PM_{2.5}$ emissions from the power sector decline by 30% to 2040, driven by a strong decline in emissions related to the combustion of coal, as a result of regulatory efforts to control emissions and power sector decarbonisation policies. However, emissions from the use of bioenergy and natural gas in the power sector increase with rising electricity generation. In the transport sector, $PM_{2.5}$ emissions fall by 15% to 2040. An increase of non-exhaust emissions by nearly 70% from rising demand for mobility and road freight holds back further decline. Among the main emitters of $PM_{2.5}$ emissions today, the industry and transformation sectors are the only ones that see a substantial rise in emissions through to 2040: emissions increase by around one-quarter and offset two-thirds of the decline in the residential sector. The increase in emissions is largely attributable to process emissions in the iron and steel production and occurs mainly in India on the back of strong economic growth.

## Towards cleaner air: energy-related air pollution in the Clean Air Scenario

In the New Policies Scenario, air pollution is set to worsen in many countries over the period to 2040. Even in those countries where air quality improves significantly, average life expectancy will still be reduced as a result of energy-related air pollution. Reducing such figures further is challenging: full safeguarding from energy-related emissions is only possible with zero emissions. But proven means to reduce energy-related emissions to a level comparable with the ultimate World Health Organization (WHO) guidelines (see Chapter 1, Box 1.3) are available. The Clean Air Scenario, developed here, does not require new technologies, but only the general adoption of policies to avoid and remove emissions that have already been successfully adopted by many countries. It is still possible to fuel an economy that is around 2.5 times larger than today.

**Table 2.2 ▷ World primary energy demand in the Clean Air Scenario**

| | Clean Air Scenario (Mtoe) | | | | | | CAAGR** |
|---|---|---|---|---|---|---|---|
| | 2013 | 2020 | 2025 | 2030 | 2035 | 2040 | 2013-2040 |
| Coal | 3 909 | 3 849 | 3 656 | 3 456 | 3 329 | 3 253 | -0.7% |
| Oil | 4 225 | 4 386 | 4 323 | 4 227 | 4 136 | 4 086 | -0.1% |
| Gas | 2 902 | 3 165 | 3 406 | 3 616 | 3 778 | 3 926 | 1.1% |
| Nuclear | 646 | 830 | 920 | 1 033 | 1 113 | 1 180 | 2.3% |
| Hydro | 326 | 384 | 431 | 479 | 525 | 566 | 2.1% |
| Bioenergy* | 1 376 | 1 421 | 1 389 | 1 399 | 1 436 | 1 498 | 0.3% |
| Other renewables | 161 | 321 | 478 | 677 | 907 | 1 153 | 7.6% |
| **Total** | **13 546** | **14 356** | **14 604** | **14 887** | **15 223** | **15 663** | **0.5%** |

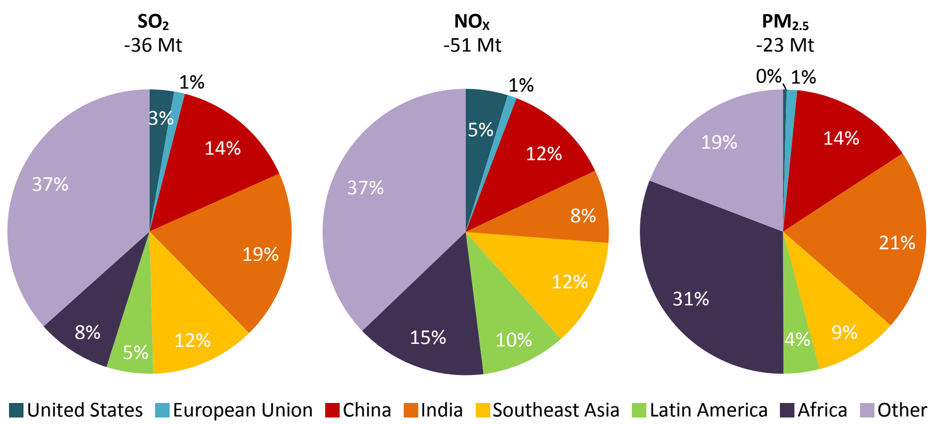
* Includes the traditional use of solid biomass and modern use of bioenergy. ** Compound average annual growth rate.

In the Clean Air Scenario, energy demand grows at 0.5% per year on average through 2040, a considerably slower pace than in the New Policies Scenario as stronger efforts to improve energy efficiency reduce energy intensity by 2.9% per year on average (compared with 2.4% in the New Policies Scenario). Coal demand peaks before 2020 and falls by one-quarter below the level of the New Policies Scenario in 2040, in large part as a result of phasing out of inefficient coal-fired power plants (Table 2.2). Oil demand peaks around 2020 and falls to just below 90 million barrels per day (mb/d) in 2040, around 15% below the level of the New Policies Scenario. The majority of the decline occurs in the transport sector, as passenger and freight vehicles become more efficient and efforts are taken in urban areas to reduce traffic movements or shift from individual to mass transport modes, such as buses or railways. Natural gas is the only fossil-fuel for which demand keeps rising in the Clean Air Scenario, although total demand in 2040, at almost 4 800 billion cubic metres (bcm), is still 8% lower than in the New Policies Scenario, reflecting lower overall energy demand. Relative to the New Policies Scenario, natural gas demand drops in the power sector (as a result of lower electricity demand) as well as in the industry and residential sectors. This decline is partly offset by increasing use of natural gas in the transport sector, in particular in urban buses, which increases the share of natural gas in the energy mix in 2040 to 25%, one percentage point above the level in the New Policies Scenario. The use of biomass in the Clean Air Scenario is 20% lower than in the New Policies Scenario in 2040 due to the increased use of efficient cookstoves and other alternatives in developing countries. Most people in urban areas gain access to such facilities by 2030, and by 2040, the use of fuelwood and charcoal for cooking with traditional cookstoves is also essentially phased out in rural areas. The level of nuclear energy in the Clean Air Scenario is similar to that in the New Policies Scenario, but the increased use of renewable energies in the power sector, in particular solar and wind, brings up the share of renewables (except biomass) in the energy mix by three percentage points in 2040.



The efficiency improvements, and the quicker transition away from fossil fuels and towards renewables goes hand-in-hand with action to secure universal access by 2040 not only to modern cooking fuels, but also to electricity, whereas in the New Policies Scenario 550 million people are still without electricity by 2040. Overall, around 60% of the electricity supplied to those gaining access over the projection period is sourced from renewables (hydropower and solar, followed by wind).

**Figure 2.6 ▷ Air pollutant emissions savings by region in the Clean Air Scenario relative to the New Policies Scenario, 2040**




Sources: IEA; IIASA.

In the Clean Air Scenario, the reduced energy demand and its more diversified supply, relative to the New Policies Scenario, together with direct policies to reduce air pollution from the energy sector, deliver a decline in air pollutant emissions in all countries and regions (Figure 2.6). In 2040, global $SO_2$ and $NO_X$ emissions are each more than 50% lower than in the New Policies Scenario, while $PM_{2.5}$ emissions fall by almost three-quarters. Emissions savings in 2040 in the Clean Air Scenario are largest in developing countries, either due to the anticipated strong growth in energy demand, or to a lack of stringent existing regulation, or both: around 70% of all $SO_2$ emissions savings in the Clean Air Scenario, relative to the New Policies Scenario, are secured in developing countries (of which almost three-quarters are in Asia alone), almost 80% of all $NO_X$ emissions savings (of which 19% are in Africa, 16% in China, 16% in Southeast Asia and 12% in Latin America) and 90% of all $PM_{2.5}$ emissions savings (of which 35% are in Africa, 23% in India and 16% in China).

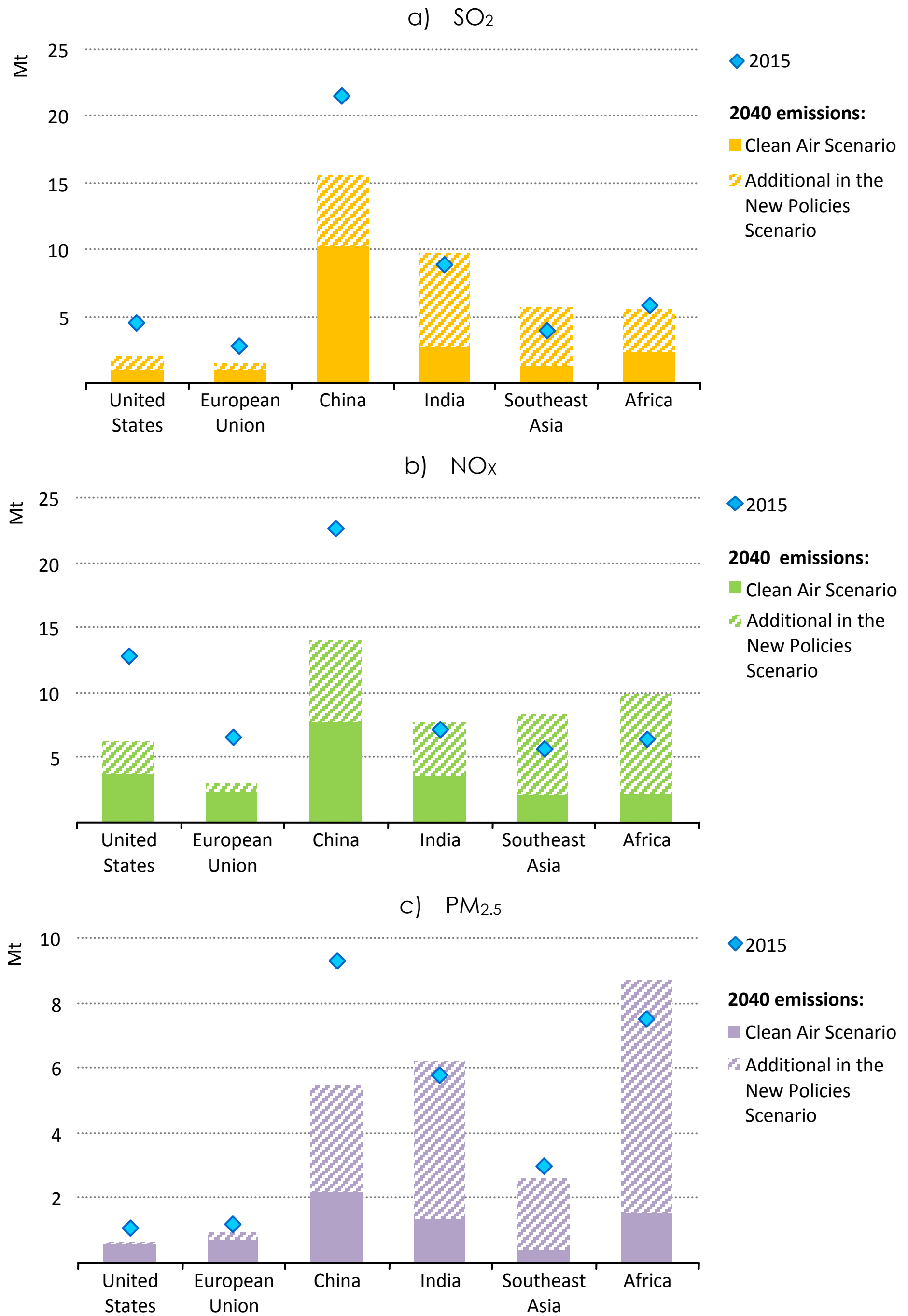
## *Air pollutant trends by region*

Air pollution is reduced in every country in the Clean Air Scenario, although the extent to which each of the proposed measures delivers additional emissions reductions, relative to the New Policies Scenario, depends on the extent to which such policy efforts are already in place (Figure 2.7). In North America, the largest additional pollutant reductions are achieved in the United States and Mexico. Emissions standards are already widespread in the *United States,* and the additional savings of the Clean Air Scenario are largely achieved through tightening existing regulations. About half of the additional $SO_2$ emissions savings are achieved in the power generation sector through increasing investment in renewable energy, switching from coal-to-gas and increasing post-combustion controls. In *Mexico* regulatory standards to reduce pollution of $NO_X$ and $PM_{2.5}$ are tightened in the industry and transformation sectors, which deliver significant emissions reductions. $NO_x$ emissions from heavy-duty vehicles are also reduced. In the *European Union*, $SO_2$ emissions are cut mostly through reducing emissions from industrial processes (in particular in the refinery, iron and steel and cement industries), while the largest additional cuts in $NO_X$ emissions in the EU are made in the transport sector. In transport, measures to avoid emissions through reducing traffic in urban areas and shifting movements to other modes (such as rail and buses), increasing the uptake of electric commercial vehicles and natural gas buses and increasing energy efficiency contribute twice as much to total transport savings as further tightening emissions standards. $PM_{2.5}$ emissions savings are largest in the residential sector and are mostly achieved through emissions standards for biomass-fired boilers.

Relative to the New Policies Scenario, a high proportion of the pollution savings in the Clean Air Scenario are achieved in Asia; but this does not reflect lack of current effort in the big Asian countries, China and India. On the contrary, both countries are making efforts in addressing air pollution (with results reflected in the New Policies Scenario). But the sheer scale of their energy demand provides the largest quantitative scope for additional savings.

Illustrating this, in *China*, the largest consumer of energy both today and in 2040, the reduction of $SO_2$ and $PM_{2.5}$ emissions in the Clean Air Scenario is each around 15% of the global total in 2040, relative to the New Policies Scenario, while that of $NO_X$ is 12%. $SO_2$ emissions are cut by one-third mainly in the industry and transformation sectors (especially process emissions in refining, cement, and pulp and paper) and the power generation sector. $NO_X$ emissions are reduced by around 45% in 2040, about half of the savings being achieved in the transport sector, mostly through tightening emissions regulations for road freight vehicles and inland navigation. $PM_{2.5}$ emissions are cut by 60% in 2040, relative to the New Policies Scenario, with the largest part of the savings being made in the residential sector (through eliminating reliance on inefficient traditional cookstoves) and the industry and transformation sectors (such as in iron and steel and chemicals production). The return is quick: in the Clean Air Scenario, 85% of the reduction in $PM_{2.5}$ emissions is achieved within the next ten years, allowing China to achieve its domestic air quality target much quicker than in the New Policies Scenario.

**Figure 2.7 ▷ Air pollutant emissions savings by type and selected regions in the Clean Air Scenario relative to the New Policies Scenario**




Sources: IEA; IIASA.

*India* stands to benefit significantly from the proposed additional policy efforts in the Clean Air Scenario. $SO_2$ and $PM_{2.5}$ emissions savings are each around 20% of the global total and $NO_X$ savings are just below 10%, relative to the New Policies Scenario. With its strong rise in energy demand, India's energy demand in 2040 approaches that of the United States in the New Policies Scenario. But energy demand growth is significantly reduced through energy efficiency measures in the Clean Air Scenario: by 2040, total energy demand is more than 15% lower than in the New Policies Scenario. $SO_2$ emissions are cut by more than 70% in 2040 in the Clean Air Scenario, relative to the New Policies Scenario, and $NO_X$ emissions by more than 50%. Most of these savings are achieved in the industry and transformation sectors (in particular through regulating emissions in the iron and steel, and cement industries). Transport sector regulation is tightened to reduce $NO_X$ emissions, in particular through increasing air pollution standards for heavy-duty vehicles (including trucks and buses), but the sources of more than three-quarters of the decline in $PM_{2.5}$ emissions in 2040 are the industry, transformation and residential sectors. Regulating process emissions in iron and steel is central to the savings in the industry sector, while achieving universal access to clean cookstoves (and other alternatives for cooking) is the reason for the decline in residential emissions. In India, similar to China, the results from these measures are quickly obtained: almost 70% of the decline in $PM_{2.5}$ emissions is achieved over the next ten years in the Clean Air Scenario.

In *Southeast Asia*, emissions reductions for each pollutant in the Clean Air Scenario are around 10% of the global total, relative to the New Policies Scenario. $SO_2$ emissions fall by three-quarters in 2040. Half of the savings are achieved in the power sector, through the imposition of standards and the switch from inefficient coal-fired power plants to renewables, while a large part of the remaining savings is achieved through regulating process emissions in the industry and transformation sectors. $NO_X$ emissions also fall by around three-quarters in 2040 relative to the New Policies Scenario. More than half of the savings come from the transport sector, where emissions standards for road freight and passenger vehicles, and efforts to promote modal shift and fuel switching in urban areas prove particularly effective. $PM_{2.5}$ emissions fall by 85% in 2040, relative to the New Policies Scenario, mostly because an additional 225 million people gain access to improved cookstoves in the Clean Air Scenario by 2040. As in China and India, the emissions reductions are achieved quickly: more than 80% of the additional $PM_{2.5}$ savings are achieved by 2025.

Brazil contributes around 40% to the reduction of each pollutant in *Latin America* in the Clean Air Scenario, relative to the New Policies Scenario. For all pollutants, the industry and transformation sectors are important, but for $NO_X$, the transport sector (in particular freight vehicle regulation) is the main contributor to the reduction in the Clean Air Scenario, because of the sector's strong reliance on oil and biofuels.

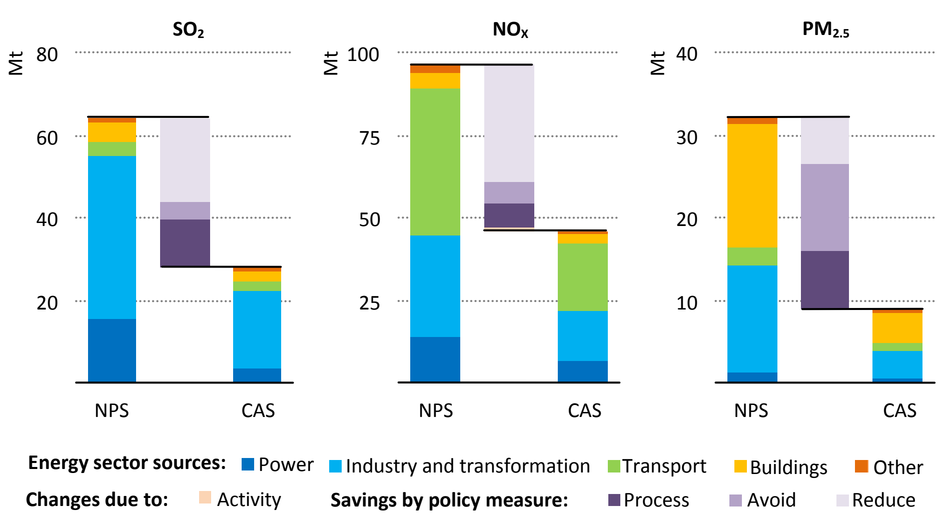
Emissions savings in *Africa* are large in the Clean Air Scenario, in particular of $PM_{2.5}$. An additional 650 million people gain access to clean cooking devices by 2040 relative to the New Policies Scenario, and an additional 500 million people gain access to electricity. As a result, $PM_{2.5}$ emissions from the residential sector fall by more than 80% in 2040 relative to the New Policies Scenario. This represents almost 50% of the global reduction in $PM_{2.5}$ emissions from the residential sector and almost one-quarter of the global reduction in $PM_{2.5}$ emissions in the Clean Air Scenario. The savings put $PM_{2.5}$ emissions per capita in Africa in 2040 on a par with Japan, a country where per-capita income is seven times higher than in Africa by that time, with significant health benefits. $SO_2$ emissions fall by almost 60% in 2040 in the Clean Air Scenario relative to the New Policies Scenario, mostly driven by measures to reduce emissions from coal-fired power generation. $NO_X$ emissions fall by more than three-quarters in the Clean Air Scenario compared with the New Policies Scenario. About half of the savings are achieved by road transport regulation, particularly of heavy-duty vehicles.



### *Air pollutant trends by sector*

Policies to avoid emissions (such as through energy sector transformation) and to reduce emissions (such as through mandating emissions controls) contribute to the emissions savings in the Clean Energy Scenario. Most of the decline of $SO_2$ emissions, relative to the New Policies Scenario, rests on measures to cut emissions from fuel combustion through measures that avoid (13%) or reduce emissions (56%); the remainder come from process-related emissions savings in the industry and transformation sectors (Figure 2.8). Half the combustion-related savings occur in the power sector and are in large part achieved by emissions control strategies (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 emissions from coal combustion (through imposing tighter pollution standards in the iron and steel industry) and oil combustion (particularly in the chemicals industry).

**Figure 2.8 ▷ Air pollutant emissions savings by policy measure in the Clean Air Scenario relative to the New Policies Scenario, 2040**




Note: NPS = New Policies Scenario; CAS = Clean Air Scenario. Sources: IEA; IIASA.

**SPOTLIGHT**

## Does the Clean Air Scenario achieve the UN Sustainable Development Goal on Energy?

The United Nations Sustainable Development Goal on Energy (SDG7) aims to ensure access to affordable, reliable, sustainable and modern energy for all. The underlying targets are:

- **Target 7.1:** Ensure universal access to affordable, reliable and modern energy services by 2030.
- **Target 7.2:** Increase substantially the share of renewable energy in the global energy mix by 2030.
- **Target 7.3:** Double the global rate of improvement in energy efficiency by 2030.

Do the results in the Clean Air Scenario achieve the SDG7 targets?

The Clean Air Scenario adopts, as an assumption, the achievement of universal access to modern energy services by 2040 and so, by extension, it does not achieve target 7.1. However, it does achieve a rapid acceleration in access to modern energy, providing access to electricity to half a billion more people by 2030 than in the New Policies Scenario. By that date, universal access to electricity is achieved in India, Indonesia and all other parts of Southeast Asia, Latin America and South Africa. Of those remaining without electricity access in 2030, over 90% are located in sub-Saharan Africa. More than one billion additional people than otherwise projected have adopted more modern means of cooking by 2030. China, Brazil and South Africa have made a full transition by 2030 and other countries, such as Indonesia, make significant additional progress towards that objective.

The Clean Air Scenario delivers the substantial increase in renewables specified in target 7.2, with the share of renewables in total final consumption (excluding the traditional use of biomass)[16] exceeding 17% in 2030 (from under 10% in 2010 and 11% in 2015). The UN Secretary-General's Sustainable Energy for All initiative (launched in 2011) is closely aligned to SDG7, but has a more stringent goal relating to renewables – to double the share of renewables in the energy mix by 2030 – and the Clean Air Scenario falls slightly short of this by 2030 (though achieving the goal by 2035). The Clean Air Scenario exceeds the level required for target 7.3. At 2.9% per year on average, energy efficiency improvements over the period to 2030 are more than double those of the base period (1.3% per year).

[16] It is generally accepted that there is a tension between goals 7.1 and 7.2 when it comes to the traditional use of biomass in households, i.e. transitioning away from biomass for cooking could, if not replaced by another form of renewable energy, see the share of renewables in the energy mix decline. For this reason, traditional biomass is often excluded from the renewables calculation to give a clearer sense of the pace of transformation in all other aspects of the energy system. It is also excluded for the purposes of this calculation as the intention of the Clean Air Scenario is to discourage biomass use in polluting stoves.

Compared with the energy path projected in the New Policies Scenario, the alternative path set out in the Clean Air Scenario is unquestionably to be preferred in moving the world towards the targets underpinning SDG7. As indicated, overall, the Clean Air Scenario meets two of the three targets and puts the world well on the way to meeting the third, reflecting the range of very positive co-benefits which accompany achievement of its core objective of reducing energy-related air pollution.



Around 85% of the additional $NO_X$ emissions savings in 2040 in the Clean Air Scenario are from policies that avoid (14%) or reduce (72%) emissions from the combustion of fuels; the remainder come from improvements in industrial processes. About half of the combustion-related emissions savings are in the transport sector and result mainly from more stringent pollutant emissions standards, which are particularly effective in reducing $NO_X$ emissions from road freight vehicles, contributing almost 60% of all transport-related $NO_X$ emissions savings in the Clean Air Scenario. For passenger cars, measures to avoid or reduce urban traffic contribute around 5% of all transport-related $NO_X$ emissions savings in the Clean Air Scenario relative to the New Policies Scenario, while energy efficiency policy plays a cost-effective, complementary role.

$PM_{2.5}$ emissions stem from a variety of sources. Their further reduction in the Clean Air Scenario rests (at the global level) mainly on measures to avoid emissions in the residential sector: almost half of the $PM_{2.5}$ additional savings in the Clean Air Scenario stem from this sector, mostly in developing countries through measures to increase the uptake of clean cookstoves or other low-emitting alternatives. Given the nature and extent of human exposure to emissions in the residential sector, the health benefits of this measure are particularly large. One-third of the $PM_{2.5}$ emissions savings in the Clean Air Scenario are achieved by reducing emissions from industrial processes, in particular in the iron and steel, and cement sectors. Most of these savings (80% of global total) occur in developing countries, given their strong economic growth and the corresponding rise of energy demand. Another 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).

## Health benefits and costs of improving air quality

There are known, proven ways substantially to reduce energy-related air pollution. But what are costs and how can the value of the benefits be quantified? It is rarely, (if ever) a cost-free process to impose increasingly stringent environmental standards on the energy sector to reduce air pollutant emissions, or measures to transform the energy sector to avoid emissions. On the other hand, assessments across different regions and sectors consistently reveal the benefits to society are worth many times more than the additional energy sector costs. One EU assessment finds that the benefits of new policies could reduce negative health impacts by more than half and bring overall economic benefits that outweigh the costs by more than twenty-to-one (EC, 2016). An evaluation of the 1990 amendments to the US Clean Air Act finds that, by 2020 alone, they are expected to prevent more than 230 000 premature deaths, 17 million days off work due to illness and over five million days of absences from school – its central estimate puts the value of the overall benefits as more than thirty-times higher than the costs (US EPA, 2011). China's latest action plan is also expected to yield economic benefits that exceed the estimated $277 billion investment cost (China Daily, 2013).

If the economic case is so strong, why is more action not forthcoming? One reason is that the burden of mitigation costs is likely to be immediate and relatively concentrated (falling on utilities, vehicle manufacturers etc.), while the benefits can occur over long time horizons and be spread across society (the health impacts, for example). The benefits, also, are not always easy to measure in monetary terms (e.g. what value do you place on quiet contemplation of a landscape unsullied by atmospheric pollution), or may not be fully valued by society (time spent collecting wood, deforestation), may be submerged by the policy quest for other pressing objectives or may, simply, be unrecognised by the general public. Moreover, there may be a lack of capacity to set, monitor and enforce air quality standards. Such challenges are not uncommon, but they can be overcome.

### *Health benefits of cleaner air*

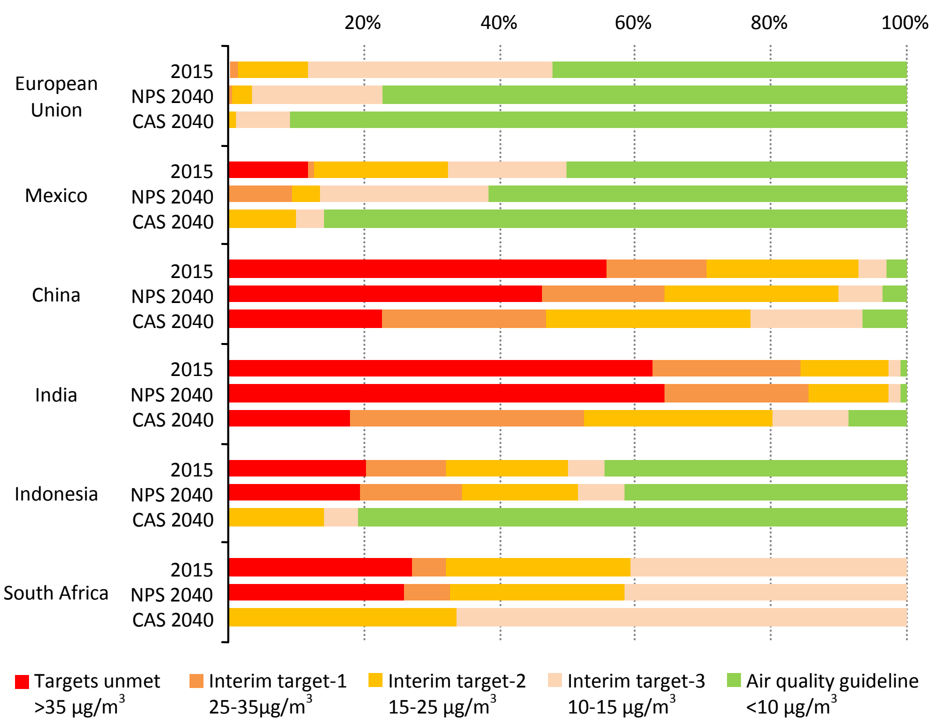
The main benefit of cleaner air lies in its contribution to human health. This benefit is the focus of this *WEO Special Report*, although Chapter 3 also discusses some of the additional benefits associated with the Clean Air Scenario. For the assessment of health impacts in this report, the IEA, together with IIASA, has made a unique effort to quantify the impact of air pollution trends related to energy production and use on human health. The analysis is applied across the two core scenarios of this report: the New Policies Scenario and the Clean Air Scenario (Box 2.3). It focuses particularly on $PM_{2.5}$ and measures its impact by scenario through three main indicators:

- The level of human exposure to different levels of $PM_{2.5}$ concentrations, matching this against the WHO guideline of 10 micrometres per cubic metre ($\mu g/m^3$) and the WHO interim targets (with interim target-1 at 35 $\mu g/m^3$ being the least stringent – (see Chapter 1, Box 1.4), used as indicators of the effectiveness of policy in improving air quality.
- The number of premature deaths (defined as deaths attributed or attributable to energy-related air pollution) as an indicator of the health benefits of cleaner air.
- The change in average life expectancy, measured by reference to years-of-life-lost (YLL) by each person, due to air pollution, i.e. the years or months of potential life lost owing to premature death, as another indicator for the health benefits of cleaner air.

The core finding is staggering. In the New Policies Scenario (i.e. when considering all existing and planned energy and air quality policies), large parts of the population, in many developing countries and beyond will live with a level of air quality that does not comply with the WHO guideline for average annual $PM_{2.5}$ concentrations in 2040. 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 (Figure 2.9). For example in India in the New Policies Scenario, despite the current policy attention to the issue, 64% of the population in 2040 live at a concentration level above the WHO target-1 (two percentage points above today's level), and only 1% at a level that is compatible with the ultimate WHO guideline.

In China, the national average air quality target for $PM_{2.5}$ of 35 $\mu g/m^3$ (comparable with WHO interim target-1) is reached during the 2030s in the New Policies Scenario. However, 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.

**Figure 2.9 ▹ Shares of population exposed to different $PM_{2.5}$ concentrations in selected regions by WHO interim targets and guideline by scenario**




Note: NPS = New Policies Scenario; CAS = Clean Air Scenario.

Source: IIASA.

**Box 2.3 ▷ Methodology for the assessment of health impacts**

The levels of air pollutant emissions, control costs and health impacts associated with air pollutant emissions by scenario in this report have been estimated using the GAINS model (Amann et al., 2011) of IIASA.[17] For Europe, GAINS estimates premature mortality and loss of life expectancy from ambient and household exposure to $PM_{2.5}$ following the methodology recommended by the WHO Europe (Health risks of air pollution in Europe [HRAPIE] project, Heroux et al., 2015), consistent with recent assessments undertaken for the EU air quality policy. For regions outside Europe (China, India, Indonesia, Korea, Brazil, Mexico and South Africa), the methodology follows the Global Burden of Disease (2010/2013) studies and includes the effects of household air pollution from household solid fuel use.

*Exposure to ambient air pollution (AAP):* GAINS computes the impact of exposure to ambient $PM_{2.5}$ on the projected future population after first calculating the impact of primary PM, $SO_2$, $NO_X$, ammonia ($NH_3$) and volatile organic compounds (VOCs) emissions in each country (states/provinces in India and China) on ambient $PM_{2.5}$ concentrations.[18] 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.[19] The resulting $PM_{2.5}$ concentration levels are used to estimate population exposure.[20]

*Exposure to household air pollution:* The health impact of household air pollution is calculated for users of solid fuels for cooking in China, India, Indonesia, Brazil, Mexico and South Africa. A typical exposure of 300 µg/m$^3$ is assumed for traditional stoves and 70 µg/m$^3$ for clean stoves, based on the wide range of observed concentrations (Balakrishnan et al. 2013; Larsen 2014). The model is calibrated to the numbers of solid fuel users using traditional and clean cook stoves as estimated by the IEA.

[17] The regions covered by IIASA modelling correspond to almost 70% of global premature deaths due to outdoor and almost 85% due to household air pollution in 2012, as assessed by WHO (2016). For other regions, premature deaths (PMDs) from outdoor air pollution in 2040 were calculated using the growth of PMDs per unit of PM emissions from OECD (2016) to total PM emissions growth (excluding the residential sector) in the New Policies Scenario, calibrated to WHO figures for 2012. PMDs in the Clean Air Scenario were calculated as the ratio between the rate of change in total PM emissions (excluding residential) relative to the New Policies Scenario and the rate of change in PMDs from regions modelled by IIASA (weighted by total deaths in 2015).

PMDs from household air pollution for regions not covered by IIASA modelling were assessed for each scenario as an exponential relation between the population relying on solid biomass (distinguishing traditional stoves and improved cookstoves) and coal for cooking, calibrated using IIASA estimates for other regions.

[18] The analysis uses transfer coefficients derived from sensitivity simulations with a full atmospheric chemistry transport model (the EMEP model) on a 0.5°×0.5° grid (Simpson et al. 2012).

[19] An 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 100×100m resolution from the Worldpop project (*www.worldpop.org.uk*).

[20] Projections of future population density are drawn from the UN World Urbanization Project (*www.esa.un.org/unpd/wup/*).

*Health impact calculation:* The assessment is conducted for all relevant diseases[21] (ischaemic heart disease, chronic obstructive pulmonary disease, stroke, lung cancer, acute lower respiratory infections) and separately for children below 10 and adults over 30 years of age. Country-specific baseline mortality rates for various age groups are derived from UN data (UN-ESA, 2011), correcting for the fraction of deaths attributable to ambient air pollution, household air pollution and smoking.[22] The approach takes into account the effect of the ageing of population, which increases the number of people vulnerable to air pollution-related diseases over time. For historical years, this approach can reveal different results than those published by WHO (2016), cited in Chapter 1; but the resulting central estimates are well within the uncertainty ranges of different studies (e.g., WHO, 2012; IHME, 2016).[23]

2

In Indonesia, the level of exposure to $PM_{2.5}$ concentrations remains broadly similar to today: 19% of the population still live above the WHO interim target-1 (compared with 20% today), while the share of the population that lives in areas meeting the ultimate WHO guideline drops by three percentage points, to 42%. Likewise, in South Africa, 26% of the population remains exposed to a $PM_{2.5}$ concentration above the WHO interim target-1 (from 27% today), and the ultimate WHO guideline remains out of reach across the country. In contrast, policy efforts of the EU are expected to bear more fruit: by 2040 in the New Policies Scenario, more than three-quarters 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 (25 $\mu g/m^3$).

The implementation of additional policies to avoid and reduce air pollutant emissions in the Clean Air Scenario brings about significant improvements for air quality. India sees the share of the population exposed to average annual concentrations of $PM_{2.5}$ above the WHO interim target-1 fall to 18% in 2040. China reaches its national air quality target of 35 $\mu g/m^3$ (equivalent to the WHO interim target-1) already during the 2020s and the share of the population living above it shrinks to 23% in 2040. In Indonesia, the Clean Air Scenario implies that the entire population could live at concentrations of $PM_{2.5}$ that are compatible at least with the WHO target-2 by 2040 (15-25 $\mu g/m^3$); more than 80% 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 outlook for air pollution and air quality has direct implications for human health. The principal standard measures of this impact are the number of premature death cases

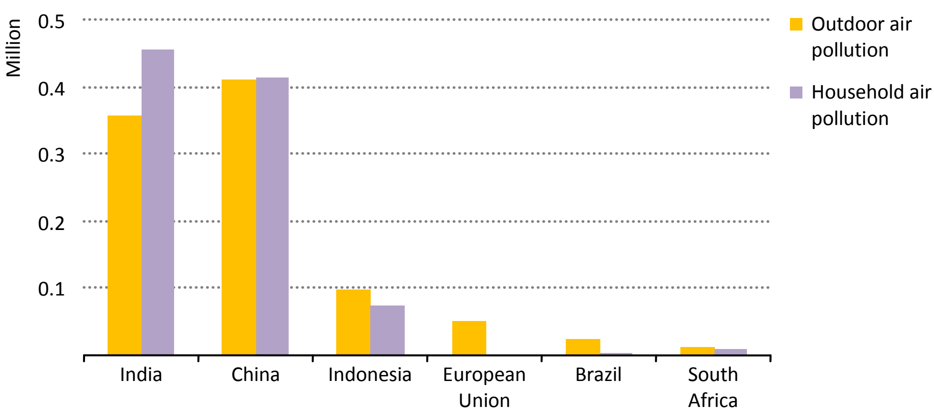
[21] The assessment uses the integrated exposure response (IER) functions developed by Burnett et al. (2014).

[22] The fractions of deaths attributable to these effects are provided by the Global Burden of Disease Database for 2010 (*www.vizhub.healthdata.org*).

[23] For this study, the analysis of uncertainties employs a Monte Carlo approach for the key parameters of the disease-specific IER functions (R. Burnett, personal communication), including the counterfactual concentrations.

attributable to air pollution and the average decrease of life expectancy per person (see Chapter 1). An estimated 3 million premature death cases were attributable to outdoor air pollution globally in 2015, while almost 3.5 million were attributable to household air pollution. Under the conditions of the New Policies Scenario, this number is set to increase: we estimate that 4.5 million premature deaths remain attributable to outdoor air pollution in 2040, and 2.9 million to household air pollution. But policy makers have the tools at hand to transform these figures. In the Clean Air Scenario, premature deaths from outdoor air pollution are cut to 2.8 million in 2040 and those attributable to household air pollution to 1.3 million (Figure 2.10).

**Figure 2.10 ▷ Premature deaths avoided in selected regions in the Clean Air Scenario relative to the New Policies Scenario, 2040**




Source: IIASA.

Quantifying the current number of premature deaths attributable to air pollution and projecting the future entails considerable uncertainty.[24] But there are several important discernible emerging trends. In the New Policies Scenario, the impact of outdoor air pollution on human health becomes more severe in developing countries in the period to 2040, as demand for energy services rises and existing policy efforts to address air pollution are insufficient to moderate air pollution (Table 2.3). In some countries, such as China, the expected demographic trends intensify the need for action: with an ageing population, the number of those most vulnerable to the effects of air pollution on human health rises. The scale and location of the rewards from supplementary action are also formidable: the largest health benefits from the policies of the Clean Air Scenario, stemming from the avoidance or reduction of pollutant emissions from the power, industry and transport sectors, in particular, unfold in developing countries.

[24] All premature death cases reported in the text (including in other chapters) refer to the mean value of a range of possible outcomes, selected to illustrate succinctly the effect of future energy trends on human health.

**Table 2.3 ▷ Premature death cases attributable to outdoor air pollution by selected region and scenario**

| | | European Union | Mexico | China | India | Indonesia | Brazil | South Africa |
|---|---|---|---|---|---|---|---|---|
| **2015** | Mean | 339 600 | 12 500 | 1 049 600 | 590 400 | 71 100 | 22 000 | 14 800 |
| | Upper range | 458 400 | 17 000 | 1 489 200 | 880 600 | 98 900 | 30 200 | 20 300 |
| | Lower range | 220 700 | 8 300 | 523 500 | 359 000 | 36 800 | 14 000 | 8 200 |
| **2040 NPS** | Mean | 226 300 | 15 500 | 1 495 300 | 915 600 | 117 800 | 36 100 | 16 900 |
| | Upper range | 305 500 | 21 900 | 2 122 700 | 1 374 900 | 163 700 | 50 200 | 23 700 |
| | Lower range | 147 100 | 10 300 | 772 400 | 548 600 | 60 000 | 23 200 | 9 000 |
| **2040 CAS** | Mean | 177 200 | 5 700 | 1 085 600 | 559 100 | 19 100 | 13 300 | 4 000 |
| | Upper range | 239 200 | 9 800 | 1 515 100 | 760 200 | 26 600 | 19 800 | 5 600 |
| | Lower range | 115 100 | 3 300 | 618 100 | 362 800 | 12 400 | 8 300 | 2 600 |

Note: NPS = New Policies Scenario; CAS = Clean Air Scenario. Source: IIASA.

Existing and planned policies make progress in addressing household air pollution in households, which is a pressing problem, in particular, in many parts of Asia and Africa (Table 2.4). In the New Policies Scenario, efforts to reduce reliance on fuelwood and charcoal for cooking, through providing access to more efficient cookstoves and other alternatives (such as LPG), and to provide electricity access for those currently deprived, bring down the number of premature deaths associated with household air pollution in many countries. But much more needs to be done. By 2040 in the New Policies Scenario, there are still 1.8 billion people who rely on the traditional use of biomass for cooking (from 2.7 billion today) and 550 million people have no access to electricity (from around 1.2 billion today). As a consequence, there are still 2.9 million people worldwide who die prematurely from household air pollution in 2040 in the New Policies Scenario.

**Table 2.4 ▷ Premature death cases attributable to household air pollution by selected region and scenario**

| | | Mexico | China | India | Indonesia | Brazil | Sub-Saharan Africa |
|---|---|---|---|---|---|---|---|
| **2015** | Mean | 12 500 | 1 160 700 | 1 021 500 | 142 300 | 15 100 | 471 700 |
| | Upper range | 18 100 | 1 548 000 | 1 460 400 | 193 900 | 21 600 | 654 200 |
| | Lower range | 8 200 | 706 700 | 692 500 | 79 200 | 9 000 | 269 700 |
| **2040 NPS** | Mean | 12 200 | 969 200 | 811 300 | 119 300 | 3 900 | 362 200 |
| | Upper range | 17 700 | 1 292 500 | 1 159 900 | 162 600 | 5 500 | 502 300 |
| | Lower range | 8 000 | 590 100 | 550 000 | 66 400 | 2 300 | 207 100 |
| **2040 CAS** | Mean | 7 700 | 556 300 | 356 900 | 44 900 | 840 | 141 900 |
| | Upper range | 12 200 | 818 800 | 567 100 | 66 900 | 1 300 | 214 100 |
| | Lower range | 4 200 | 256 000 | 202 900 | 18 700 | 400 | 61 900 |

Note: NPS = New Policies Scenario; CAS = Clean Air Scenario. Source: IIASA.

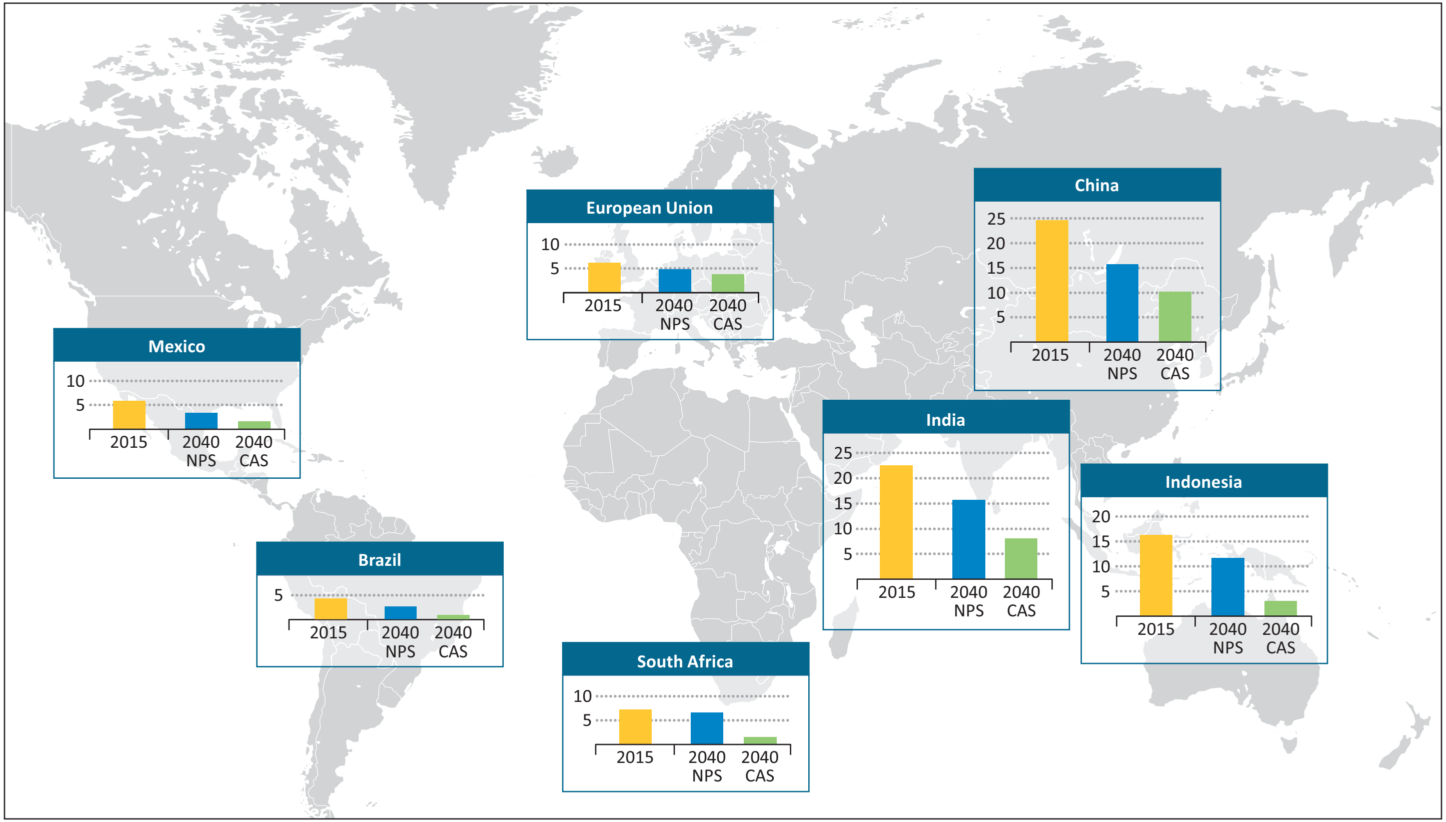
The result in the Clean Air Scenario is a situation much improved, though not fully resolved. Universal access is achieved by 2040 at the latest in all countries, but there remain cases of premature death attributable to household air pollution (Box 2.4). The underlying reasons vary but, typically, they involve very challenging economic, socio-cultural and infrastructure factors. In such cases, additional interventions, particularly in the near term, may profitably be directed towards reducing, rather than eliminating, household air pollution, through, for example, the deployment of improved biomass cookstoves, the installation of ventilation and the use of other new stoves using better fuels (such as LPG) as a supplement, rather than full replacement for traditional forms of cooking.

**Box 2.4 ▻ Emissions cuts and health benefits: linked, but not straightforward**

Millions of premature deaths are avoided in the Clean Air Scenario, but the reductions in percentage terms are not as large as the reductions in emissions. Why? One important reason is the ageing of population, which will enlarge the older population which is more vulnerable to air pollution. This trend is exacerbated by the increasing urbanisation (which concentrates pollution and population into more confined areas) and further enhanced by the general population growth in developing countries. Another important reason is that the health impact assessment assumes a non-linear relationship between changes in pollution concentrations to which people are exposed and the resulting health impacts, with declining impacts at higher concentrations. In addition, the energy sector is not the only source of particulate matter and emissions from other sectors – and from natural sources – may be occurring.

Looking at the health impacts across the population, it is possible to calculate the average loss of life expectancy attributable to air pollution, i.e. the years or months of potential life lost owing to premature death attributable to air pollution. This indicator confirms the above findings. While the situation generally improves in many countries in the New Policies Scenario, there remains much scope for improvement. The loss of average life expectancy in 2040 in the European Union as a result of air pollution falls to five months (from six months today). In China and India, the loss of life expectancy drops to 16 months (from 25 and 23 months today, respectively), while it declines to 12 months in Indonesia (from 16 months today) and remains relatively stable at 7 months in South Africa. By contrast, the loss of life expectancy per person associated with energy-related air pollution decreases sharply across all regions in the Clean Air Scenario (Figure 2.11).

**Figure 2.11** ▷ **Average loss of life expectancy in months per person in selected countries by scenario**



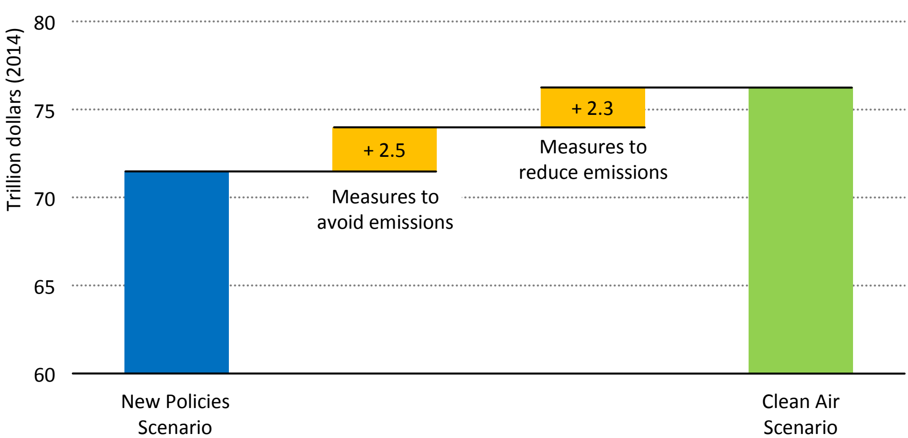

This map is without prejudice to the status of or sovereignty over any territory, to the delimitation of international frontiers and boundaries, and to the name of any territory, city or area.

Note: NPS = New Policies Scenario; CAS = Clean Air Scenario. Source: IIASA.

### *Cost of air pollution mitigation*

Investment specifically to reduce the environmental impact of energy supply and use is by no means new and existing energy sector investments already include provision to reduce air pollution or its impacts. The scale can vary from the major shift to renewable energy and the more efficient use of energy to the generally more modest investment required to supply homes with modern stoves and ventilation. Cumulative investment from 2016 to 2040 in energy supply, efficiency and pollution mitigation in the Clean Air Scenario is 7% higher than in the New Policies Scenario, at $76 trillion, rather than $71 trillion, (Figure 2.12). Slightly more than half ($2.5 trillion) of the investment is required to finance measures to avoid emissions (in large part, measures that change the nature of energy supply and demand). The majority of the additional investment in the Clean Air Scenario is required for boosting energy efficiency and the use of renewables, although the total figure is partly moderated by lower investment in fossil energy supply, due to lower demand. Overall, power sector investment increases only slightly, despite higher renewables investment, as efficiency efforts dampen growth in electricity demand. Achieving universal access to clean cooking in developing countries – the most effective measure to reduce household air pollution – comes at a very modest additional investment cost: it amounts to around 1% of the additional investment required in the Clean Air Scenario, relative to the New Policies Scenario.

**Figure 2.12 ▷ Cumulative energy sector investment including pollution control by scenario, 2016-2040**




Sources: IEA; IIASA.

Measures to reduce air pollutant emissions (such as through post-combustion control technologies) make up less than 10% of the cumulative energy sector investment over the *Outlook* period in the New Policies Scenario; raising this investment by around 40% (or $2.3 trillion) is required to reap the health benefits of the Clean Air Scenario. Two-thirds of this additional investment in post-combustion control measures is required in the transport sector (mostly in road transport) and almost one-fifth in the buildings sector. Investment in post-combustion control technologies in the power sector in the Clean Air Scenario increases only marginally, due to lower electricity demand (from energy efficiency) and higher use of renewables, cutting the investment needs for coal-fired power plants.



Around two-thirds of the additional investment in the Clean Air Scenario is required in developing countries, in particular in China (21%), Africa (16%), India (10%) and Southeast Asia (10%). Among the industrialised countries, the United States (15%) and the European Union (13%) require most of the investment. Each country has different investment needs: the investment focus in most industrialised countries in the Clean Air Scenario is on additional measures to avoid air pollution through energy sector transformation. In such countries, such measures absorb at least 70% of the additional investment in the Clean Air Scenario relative to the New Policies Scenario. By contrast, the investment focus in developing countries is on increasing measures to reduce emissions through post-combustion control and reducing process-emissions, which absorb around 55% of the additional investment in the Clean Air Scenario relative to the New Policies Scenario. Developing Asia, for example, requires around two-thirds of the global investment in post-combustion control technologies for stationary sources in the power and industry sectors in the Clean Air Scenario. In some cases, strategic additional investment in measures to avoid emissions through energy sector transformation reduces the investment need in pollution control in the Clean Air Scenario relative to the New Policies Scenario.

# Energy action for cleaner air

## Take a breath, and now take action

### Highlights

- The Clean Air Scenario shows how the application of proven policies and technologies can bring about a sustained reduction in pollutant emissions. To achieve the targeted objectives in practice, the energy sector needs to take strong action, co-ordinated effectively with others, to deliver a comprehensive overall package of air quality measures. This report identifies three key areas for action:

  1. Setting an ambitious long-term air quality goal, defined with reference to appropriate benchmarks, such as those of the WHO, to which multiple parts and tiers of government and other stakeholders can subscribe, and against which the variety of pollution mitigation options can be assessed.
  2. Putting in place a clean air strategy for the energy sector: this should draw on the range of measures included in the Clean Air Scenario, adapted in various combinations to different national and regional settings, that:
     - **Avoid** pollutant emissions, either by providing the energy service more efficiently or by providing it in a way that does not involve combustion of fossil fuels or bioenergy.
     - **Innovate** to reduce pollution abatement costs.
     - **Reduce** emissions, via the application of pollution control technologies, fuel switching or regulation of fuel quality.
  3. Ensuring effective monitoring, enforcement, evaluation and communication: keeping a strategy on course requires reliable data, a clear institutional framework defining responsibilities, a continuous focus on compliance and on policy improvement, where necessary, and timely and transparent public information.

- Air pollution policy cannot be viewed in isolation; it is closely linked not only to energy but also to other policy areas such as public health, climate change, transport, trade and agriculture. Integrated policymaking is essential to take into account the potential impacts of action in one area on another.

- Policy efforts to improve air quality, address climate change and achieve universal energy access are complementary, but need to be designed in a way that maximises the co-benefits. For example, an exclusive focus on direct emissions controls, rather than the package of measures proposed in the Clean Air Scenario, could result in increased commitments to high-carbon energy infrastructure, such as coal-fired power plants. As it stands, the Clean Air Scenario provides not only for a major reduction in pollutant emissions but also for an early peak in energy-related $CO_2$ emissions, a central provision of the COP21 Agreement.

## Three steps to cleaner air

Air pollution is a problem that will persist until governments decide to take it in hand; and the focal point for much of their action has to be the energy sector. As shown in the Clean Air Scenario, proven technologies and policies are available that achieve and sustain economic prosperity without a concurrent rise in energy-related air pollution, but judicious selection of policies and regulatory frameworks is required to accomplish the necessary energy transformation.

How is this transformation to come about? What are the options, trade-offs and pitfalls that policy makers face in practice? With growing public awareness and concern and a wide range of actions available to reduce emissions, the need and desire to act quickly should nonetheless be tempered by the need to define a path that is efficient for the long term and does not compromise other policy goals. There may be a choice between control technologies that reduce emissions (i.e. those that reduce pollutants after they have formed, such as scrubbers on smokestacks and catalytic converters on vehicle exhaust systems) and structural shifts that avoid the emissions occurring in the first place (energy efficiency measures, fuel switching or shifting to non-combustion technologies, such as wind and solar). Many actions on energy-related air pollution can bring desirable co-benefits for other energy objectives; but there may also be times when decision makers have to be aware of potential drawbacks. The aim of this chapter is to explore these issues, relying on elements of our analysis, as well as individual country examples.

The optimum policy path is one in which the energy sector takes urgent, strong action, co-ordinated effectively with others, to deliver a comprehensive overall package. As a means to support the energy sector in this goal, this *World Energy Outlook Special Report* considers three key areas for action:

- Setting an ambitious long-term air quality goal.
- Putting in place a clean air strategy for the energy sector.
- Ensuring effective monitoring, enforcement, evaluation and communication.

### *1. Setting an ambitious long-term air quality goal*

**The energy sector should have an ambitious long-term air quality goal, defined with reference to appropriate benchmarks, such as those of the World Health Organization and with buy-in from the public and relevant parts and levels of government. A clear expression of the desired destination for policy can translate into targets across various parts of the energy sector and guide investment in air quality improvements.**

Air pollution can be reduced, but has to be tackled from a variety of angles and by a variety of actors, so there is great value in establishing an overarching goal for air quality, to which all can subscribe, and against which the variety of pollution mitigation options can be assessed. This can be particularly important in countries undergoing rapid economic and social change, to ensure that short-term actions in fast-growing sectors are consistent with longer term objectives. An announced goal, accompanied by transparent availability of pollution data, can also provide a vital mechanism to win wider public awareness and acceptance, helping to keep air quality prominent on the policy agenda.

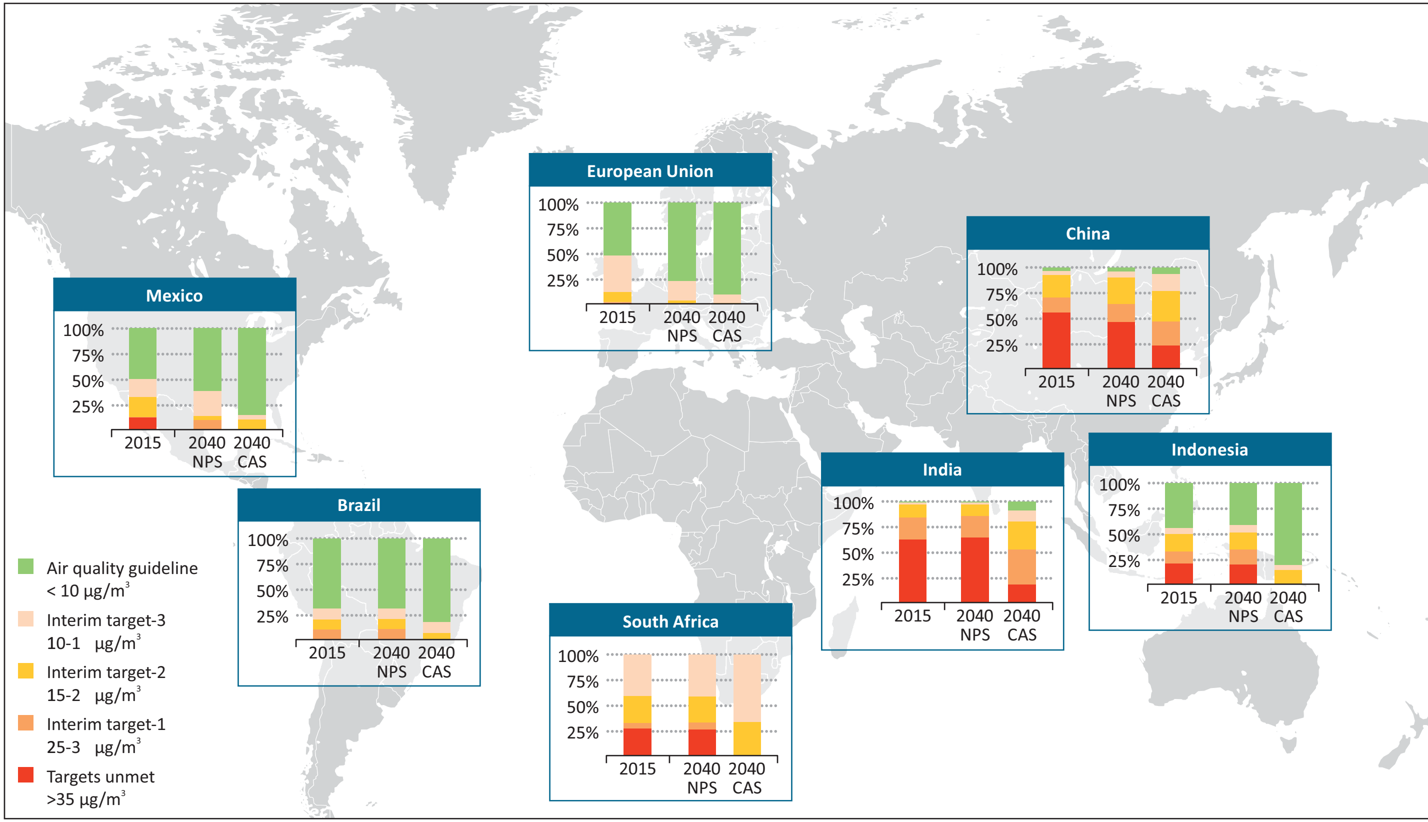
3

An air quality goal can be expressed in both broad, qualitative terms and incorporate specific, quantitative and time-bound targets. An example of the former is enshrined in the European Union (EU) approach, which aims ″to achieve levels of air quality that do not result in unacceptable impacts on, and risks to, human health and the environment". Objectives that are so general in form need to be supplemented by goals that are more specific. These may take various forms, often focusing on an acceptable level of a given pollutant, a limit on the amount of a pollutant emitted by a source or a limit on the amount of a pollutant in a fuel or product; the limits can be graduated and tightened over time. National or sub-national goals may be complemented by those agreed at the international level, such as the UN Sustainable Development Goals (SDGs), several of which have a direct or indirect link to air pollution, e.g. the SDGs on energy, good health and well-being, gender equality, and sustainable cities and communities.

As examples from specific countries and regions demonstrate, the World Health Organization (WHO) Air Quality Guidelines provide a basis upon which to set long-term goals (see Part B for country and regional profiles). The ultimate levels for pollutant concentrations prescribed in these guidelines may seem aspirational and even out of practical reach for some countries, given their starting points today. In such instances, it can be preferable to designate a goal that combines ambition with a strong dose of political realism (as, once an idealistic target is deemed unachievable, its utility as a spur to practical policy action can quickly dissipate). In this connection, the WHO interim targets can be helpful in establishing more attainable milestones along the way towards an end-goal. China's 2013 Action Plan on Air Quality, for example, establishes a roadmap to reduce the natural mean annual concentration of particulate matter $(PM)_{2.5}$[1] in key cities to 35 micrometres per cubic metre ($\mu g/m^3$), which is the interim target-1 in the WHO guidelines. For household air pollution, the WHO Indoor Air Quality Guidelines also provide a valuable source of guidance regarding household fuel combustion and emissions in such settings (WHO, 2014). In the Clean Air Scenario, countries around the world all achieve significant progress towards the WHO interim and guideline levels for $PM_{2.5}$ (Figure 3.1).

[1] Size is an important factor in determining the health impacts of PM: "coarse particles" are between 2.5 and 10 micrometres (µm) in diameter and "fine particles" are smaller than 2.5 µm.

**Figure 3.1 ▷ Share of population that meets WHO guideline and interim levels for $PM_{2.5}$ by country and scenario**




This map is without prejudice to the status of or sovereignty over any territory, to the delimitation of international frontiers and boundaries, and to the name of any territory, city or area.

Note: NPS = New Policies Scenario; CAS = Clean Air Scenario. Sources: IEA; IIASA.

Setting a long-term goal for air quality can be an important catalyst for action; but it will be insufficient unless backed by a well-designed and integrated strategy to achieve it. Air pollution policy cannot be viewed in isolation: it is closely linked not only to policies for energy, but also to those dealing with public health, climate change, transport, trade, agriculture, biodiversity and other issues. An integrated approach takes into account the potential impacts of action in one area on another and the co-benefits and disadvantages of the interactions. It relies in turn on a clear institutional framework defining responsibilities, good data and communication, adequate financial resources and technical capabilities, and well-functioning systems for enforcement, evaluation and improvement (Clean Air Asia, 2016).



Governance of an air quality strategy is particularly complex (Table 3.1). The first-movers on policy are often not at national level: city and regional governments, responding to local concerns, frequently play an important pioneering role in developing a policy response to poor air quality. Municipal agencies are typically responsible for monitoring and reporting on ambient air quality, as well as informing the public about the risks of air pollution: where air pollution is most visible (either in the atmosphere, in its impacts or in terms of being widely measured and reported), it is most likely to stimulate redress. In many cases, sub-national governments have been early adopters of policies subsequently taken up by national policy makers: for example, vehicle emissions standards in California, Tokyo and several Indian cities were later adopted by their respective national governments.

Air pollution, however, often originates from sources outside the geographic boundary and jurisdiction of the local municipalities where it causes harm. This can limit the ability of city or regional authorities to tackle the problem effectively. In practice, involvement from central government – and good co-ordination between different levels of administration – is essential to ensure effective policy design and enforcement. In addition, since some air pollution sources can be international in scope, the development and enforcement of policies sometimes must be co-ordinated across multiple borders. A comprehensive air quality strategy and regulatory structure typically includes a range of initiatives brought together under a common framework that expresses overall goals and approaches.

At the national level, environment ministries are generally responsible for the overall policy framework for air quality. However, responsibility for air quality policy cuts across several other government departments, most notably the energy, health, transport, industry and agricultural ministries (Table 3.2). Energy ministries are a particularly important piece of the air quality puzzle, due to the scale of energy-sourced pollutants in the total picture and their general oversight of issues relating to fuel quality and use. A well co-ordinated process that involves a range of national and international actors, while harnessing local and municipal initiative, is essential to the design and implementation of an effective clean air strategy.

**Table 3.1** ▷ **Indication of lead responsibility for different air pollution policies in selected regions**

| Type of measure | China | India | United States | Canada | Japan | European Union |
|---|---|---|---|---|---|---|
| **Ambient air quality standards** | National / municipal | National / state[1] | National / state[2] | National / provincial / municipal | National / municipal | National / EU level |
| **Industrial emission standards** | National / municipal | National / state[1] | National / state / municipal[2] | Provincial / municipal | National | National / EU level |
| **Power sector emission standards** | National / municipal | National | National / state / municipal[2] | National / provincial | National | National / EU level |
| **Passenger-vehicle emission standards** | National / municipal[3] | National / municipal[4] | National / state[5] | National | National / municipal | National / EU level |
| **Heavy-duty vehicles** | National / municipal[3] | National / municipal[4] | National / state[5] | National | National / municipal | National / EU level |
| **Fuel standards** | National / municipal[6] | National | National | National | National | National / EU level |
| **Buildings standards** | National / municipal | National | State / municipal | National / provincial | National / municipal | National / EU level |
| **Low-emission zoning** | Municipal | Municipal | n/a | n/a | Municipal | National/ municipal |
| **Tradeable permits** | n/a | n/a | National[7] | n/a | n/a | n/a |
| **Taxes on fuel and emissions** | National | National | National | Provincial / municipal | National | National |
| **Subsidies/ financial incentives** | National / municipal | National[8] | State[9] | n/a | n/a | National |

Note: n/a = not applicable.

[1] State pollution control boards can set more stringent standards than the existing national standards in their respective states.

[2] State air agencies develop emissions reduction strategies to ensure that they attain and maintain the National Ambient Air Quality Standards for all control regions within their borders.

[3] Several Chinese cities have introduced a higher standard than that set by national regulations.

[4] In the case of passenger vehicles, it is national policy to provide better quality fuels and vehicles in some Indian cities prior to nationwide implementation. In the case of heavy-duty vehicles, some cities have moved to stricter standards more quickly than national level regulations.

[5] Due to the pre-existing standards and particularly severe transport-related air pollution problems in the Los Angeles metropolitan area, the state of California (US) promulgates its own automobile emissions standards. Other states may choose to follow either the national standard or the stricter California standards.

[6] Cities and regions in China may develop and implement their own fuel-quality standards without requiring national level approval. Large cities such as Beijing and Shanghai have opted for more stringent fuel-quality standards after negotiating a dedicated fuel supply with China's major state-owned oil companies.

[7] $SO_2$ allowance trading under the Clean Air Act.

[8] LPG subsidy scheme to promote substitution away from solid biomass use for cooking.

[9] The California Air Resources Board has introduced incentives for low-emission vehicles and zero-emission vehicles.

**Table 3.2 ▹ Indicative involvement of national ministries and sub-national administrations with selected pollution control measures**

| Type of measure | National ministries | | | | | | Sub-national / municipal |
|---|---|---|---|---|---|---|---|
| | Environ-ment | Energy | Transport | Industry | Finance | Health | |
| Ambient air quality standards | ● | | | | | ● | ● |
| Industrial emissions reduction | ● | | | ● | | | ● |
| Power sector emissions reduction | ● | ● | | | | | ● |
| Light-duty vehicle emissions reduction | ● | | ● | | | | ● |
| Heavy-duty vehicle emissions reduction | ● | | ● | | | | ● |
| Fuel emissions reduction | ● | ● | ● | ● | | | ● |
| Low emissions zoning | ● | | ● | | | | ● |
| Tradeable emissions permits | ● | ● | ● | | ● | | |
| Taxes on fuel and emissions | ● | ● | ● | | ● | | |
| Subsidies/ financial incentives | ● | ● | ● | | ● | | |



## 2. Putting in place a clean air strategy for the energy sector

**Strategies to reach ambitious air quality goals should draw on the range of measures in the Clean Air Scenario, including a cost-effective choice of direct emissions controls and other measures that bring co-benefits for other environmental, energy security and access objectives.**

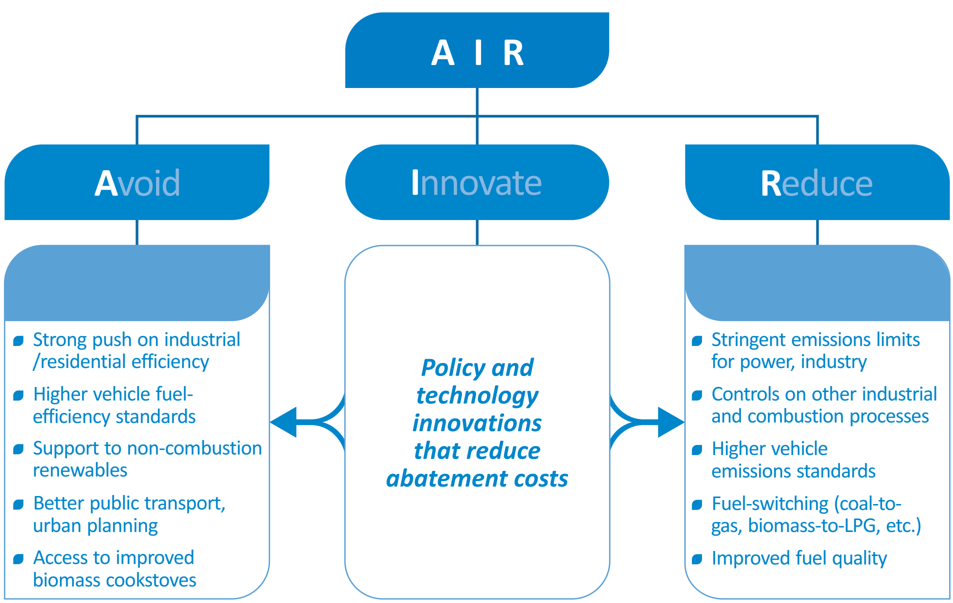
The Clean Air Scenario provides a suite of policies that can achieve long-term improvement in air quality. The scenario draws upon examples of national and regional clean air legislation, which set out overall objectives for air quality and paths to their realisation. It takes into account multiple "best practice" documents for more specific air pollution emissions standards, such as the Euro VI standards in the transport sector or the "Menu of Control Measures"[2] that the US Environmental Protection Agency (US EPA) provides to help state and local air agencies comply with National Ambient Air Quality Standards (NAAQS) (including information on their efficiency and cost effectiveness). The Clean Air Scenario also encompasses the impact of broader energy and climate policies, e.g. the EU 2030 energy and climate framework, that accompanies policies to combat air pollution. All of these sources can be tapped to populate a coherent and integrated air quality strategy.

[2] *www.epa.gov/criteria-air-pollutants/menu-control-measures-naaqs-implementation.*

A clean air strategy for the energy sector will vary in approach based on the contexts of countries and cities, as well as their capacities to develop and implement them. There is no uniform policy prescription for air quality that is applicable to all countries and regions; such an approach would be neither possible nor desirable for a problem that is so diverse in local circumstances. The intention with the Clean Air Scenario is rather to provide a toolbox of proven policies and technologies, which – adapted in various combinations to different national and regional settings – can bring about a cost-effective reduction in pollutant emissions and related impacts. A consistent strategy should include not only the policy instruments, but also clear steps and timelines to adopt and monitor them, attention to enforcement and evaluation, consideration of potential co-benefits and an anticipation of future trends affecting pollutant emissions (energy demand growth, population growth etc.). For example, China's Air Quality Action Plan contains measures to increase emissions controls, adjust the energy structure and promote clean energy supply, optimise its industrial sector and accelerate technology transformation. Alongside this, it contains steps to improve the regulatory system and supervision, including integrated regional co-ordination, and to establish monitoring, alerting and emergency response systems for air pollution episodes.

For the policy aspects, this *World Energy Outlook Special Report* offers a simple typology (Figure 3.2) for practitioners in the energy sector to conceptualise and develop, with others, energy-specific action plans to tackle air pollution, building on the groups of actions discussed in Chapter 2.

**Figure 3.2 ▷ An "A-I-R" typology of energy sector actions on air pollution included in the Clean Air Scenario**




Note: For more detail on the policy measures included in the Clean Air Scenario, see Chapter 2, Table 2.1.

As detailed in Chapter 2, the classification considers policies that *avoid* pollutant emissions, either by providing the energy services more efficiently or because they are provided in a way that does not involve the combustion of fossil fuels or bioenergy. It also includes policies that *reduce* the impact of such combustion, either by mandating control technologies that reduce the resulting emissions, or by introducing measures that otherwise reduce their impact once emitted (e.g. regulations on stack heights, improved ventilation), or by encouraging a switch to combustion of a less-polluting fuel (e.g. gas instead of coal, or a lower-sulfur oil product). In addition, there is a range of supporting measures, such as pollution charges, emissions trading schemes or the removal of fossil-fuel subsidies that create changes in relative pricing as an economic incentive to change behaviour. These can result in either a reduction or an avoidance of pollutant emissions, depending on how they affect the investment calculations or operational decisions. Some of these measures can be formulated relatively quickly, such as the reform of subsidies to polluting fuels or the introduction of stricter efficiency standards, but implementation may face significant barriers and it still takes time for measures of the latter type to work through into the stock of existing equipment or the vehicle fleet. Other measures typically require significant investment and transition periods to implement in full, such as a shift in the energy mix in favour of low-carbon sources.



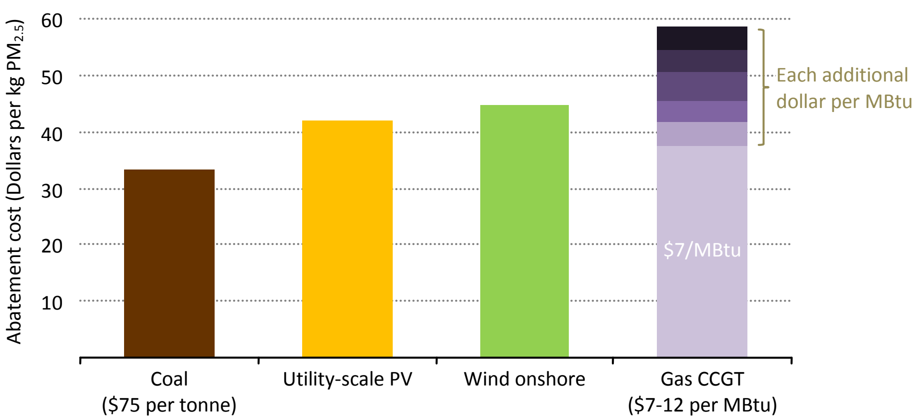
The 'I' in the A-I-R typology belongs to "Innovate", a critical component of all action designed to re-shape the future. The level of innovation included in the Clean Air Scenario is consistent with a steady pace of technology learning and cost reduction, in line with historical averages, rather than the step-change that could arise in the event of technology breakthrough. Technology is nonetheless a significant component of the anticipated improvement in outcomes, especially the structural transformation in electricity supply from non-combustion sources such as wind and solar. Countries looking to implement air quality strategies today can benefit from the accumulated research and development effort made to date in pollution control technologies and energy technologies, with an expected further decrease in costs and improvement in reliability from increased deployment over time.

### *Choice of policy measures*

The detailed choice of policy measures in different countries and regions in the Clean Air Scenario is determined by particular local circumstances, relative costs and a consideration of co-benefits in relation to other policy objectives. The priority accorded to some policy areas requires no elaboration, especially the emphasis on universal access to clean cooking facilities in countries where this has yet to be achieved. Tackling household air pollution via the provision of improved cookstoves or via fuel switching to liquefied petroleum gas (LPG) is one of the most cost-effective ways to reduce the human cost of air pollution, even if, as discussed later in this chapter (Spotlight), implementation remains challenging in practice. But, in other areas, the air quality choices may be less self-evident. In the power sector, for example, the decision to build a coal-fired power plant with advanced pollution controls, or a gas-fired unit, or to use hydropower, wind or solar technologies, is dependent on a range of variables, including fuel and capital costs, the location of the planned facility and the interaction with other policy objectives, notably carbon dioxide ($CO_2$) reduction goals.

Decisions based solely on air quality criteria may not be optimal when all other factors are considered. In India, for example, we estimate that the cheapest way to reduce air pollutant emissions in new power plants is to ensure that advanced controls are installed on coal-fired generation. The example given in Figure 3.3, for new generation facilities starting operation in 2025, shows that this is the most cost-effective approach to reduce PM emissions, ahead of generation from wind, solar photovoltaics (PV) and natural gas: the same ranking applies for reductions of sulfur dioxide ($SO_2$) and nitrogen oxides ($NO_X$). This cost advantage is why new coal-fired plants equipped with such controls continue to be built in India in the Clean Air Scenario. Yet this is obviously not the whole story. Other policy considerations, notably India's climate pledge to increase the share of non-fossil fuel capacity in the electricity mix and to reduce the carbon intensity of the economy, dictate a strong increase in deployment of solar and wind power. Balancing a power system in which variable renewables meet one-third of power demand growth also requires flexibility from other sources, a role for which natural gas-fired plants are well suited, as well as a much more resilient transmission grid.

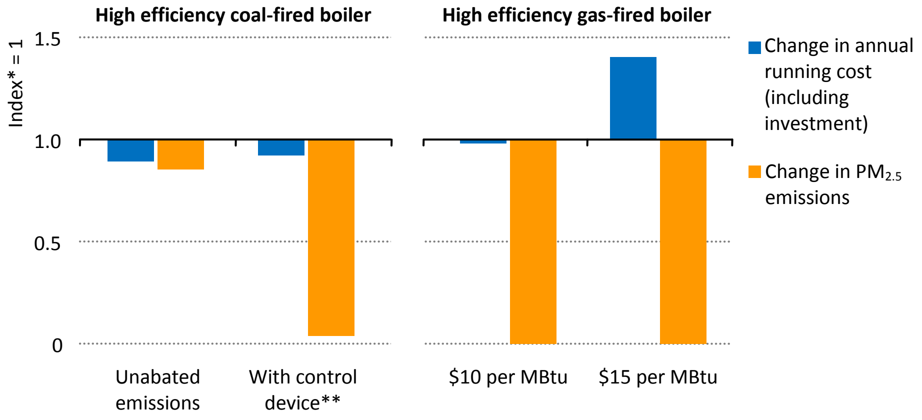
**Figure 3.3 ▷ Indicative abatement costs for $PM_{2.5}$ reductions in new power plants in India, 2025**




Notes: The costs shown are the costs for $PM_{2.5}$ abatement, relative to a benchmark of ultra-supercritical coal with no emissions control technologies. The coal-fired plant utilises ultra-supercritical technology and advanced control technologies. The costs for natural gas are shown with a range of gas input prices, from $7 per million British thermal units (MBtu) to $12/MBtu.

A second illustration concerns the decision-making process for a new medium-capacity industrial boiler in China in 2025 (Figure 3.4). Many existing industrial boilers are due for retirement or replacement in the coming years, in part because of stricter regulatory requirements or the imposition of bans on small, inefficient coal-fired boilers in urban areas. Outside the steel and cement industries, we project net additions to China's industrial capacity, adding to demand for process heat. Three technology and fuel choices are considered for reductions of $PM_{2.5}$, assessed against a baseline of an inefficient coal-fired model without emissions controls. A high-efficiency coal boiler brings some benefits in this assessment, lowering operating costs and resulting in the avoidance of a share of pollutant emissions. However, this is a less attractive solution, in terms of emissions reductions, than the combination of high-efficiency with emissions controls in the case of a coal-fired boiler, or a switch to natural gas. Even with China's introduction of a carbon price (assumed to be $17/tonne by 2025), coal appears the more competitive option of the two, unless the input price for industrial natural gas users is brought down to below $10/MBtu, which is at the lower range of anticipated industrial gas prices. However, where natural gas infrastructure is in place, air quality considerations do help the penetration of gas as a fuel for smaller installations, as the addition of emissions control devices to coal-fired units becomes progressively less cost-effective the smaller the boiler.

**Figure 3.4 ▷ Indicative $PM_{2.5}$ abatement options to replace a low efficiency coal-fired industrial boiler in China, 2025**




*Index is relative to a low efficiency coal-fired industrial boiler with unabated emissions; ** Application of best available technology for emissions controls.

In limiting the emissions of a given pollutant, policy makers may face a choice between different policy instruments, e.g. between direct controls on emissions (via strict emissions limits or the obligation to install a particular control technology) and more market-based approaches, e.g. pollution charges or emissions trading schemes, that offer an economic incentive to shift to less-polluting behaviour. Direct controls have been the instrument of choice in many countries' environmental policies, but well-designed market-based instruments can often reach a similar outcome more efficiently (Box 3.1).

**Box 3.1 ▷ $SO_2$ allowance trading system in the United States**

Cap-and-trade systems are now a recognised tool of environmental policy. The pioneer was a system to limit emissions of $SO_2$ introduced in the United States via amendments to the Clean Air Act in 1990. Total $SO_2$ emissions at power plants covered by the law were subject to a declining cap, in line with a defined policy objective (the final 2010 $SO_2$ cap was set at 8.95 million tonnes, around half of 1980 power sector emissions). In turn, each regulated facility received allowances for a certain volume of emissions. If its annual emissions were higher than its allocation of allowances, it could trade (buy) allowances to compensate or reduce emissions, whether by installing pollution controls, changing fuels or producing less. If it had an excess of allowances, it could trade (sell) allowances or bank them for later use. Whereas a policy of direct controls would have imposed a single timeline for emissions reductions or the installation of specific control technologies, the market-based system allowed plant operators as a whole to find the least-cost path to compliance, including abatement options that may not have been commercially available at the time the system was introduced.

This $SO_2$ allowance system achieved its long-term annual emissions goal in 2007 (total emissions continued to fall thereafter, because of other regulations that imposed tighter emissions controls). Compliance rates were close to 100%, helped by monitoring and verification from US EPA and automatic penalties for each excess tonne of $SO_2$ not covered by allowances. Compliance costs were estimated to be significantly lower than they would have been under direct controls, by between 16-25% according to one study(Keohane, 2003), although deregulation of the rail freight market also played a part by expanding cost-competitive access to shipments of low-sulfur coal(Schmalensee & Stavins, 2013). As subsequent experience has demonstrated, emissions trading schemes are not a panacea; it can be difficult to calibrate the level of ambition, given uncertainty of the cost of achieving reductions, and to resist pressure from participating firms for an overly generous initial allocation of allowances. Yet, the performance of the $SO_2$ allowance system in the United States provides a useful example of a system that delivered on its promise.

### *International co-operation*

Because pollutants can be carried long distances in some instances, international governance comes into play. There are some long-standing examples of co-operation between countries on air pollution, such as the Convention on Long-range Transboundary Air Pollution, a legally binding instrument to deal with air pollution on an international basis, which entered into force in 1983.[3] Initially spurred by research demonstrating the connection between sulfur emissions and the acidification of Scandinavian lakes, it has been supplemented by eight protocols that commit the parties to cut their emissions of

[3] There are 51 parties to the Convention, mainly European states, but also the United States and Canada.

specific pollutants. In addition, some air pollutants feature prominently in other international discussions, notably on climate change, or have other cross-border implications, such as pollution that is embedded in goods that are produced locally and then traded internationally (Spotlight).

**SPOTLIGHT**

### Who is responsible for pollution embedded in internationally traded goods?[4]

Who is ultimately responsible for emissions of air pollutants? Is it the plant that produces the goods and, in doing so, generates the emissions, or is it the consumers, who demand and purchase the goods produced and may even be in another country? To what extent can countries shape their import strategy to support compliance with environmental policies? To help answer these questions, it is first necessary to adjust the traditional accounting framework for pollution to take into account where the production and consumption of the related goods takes place.

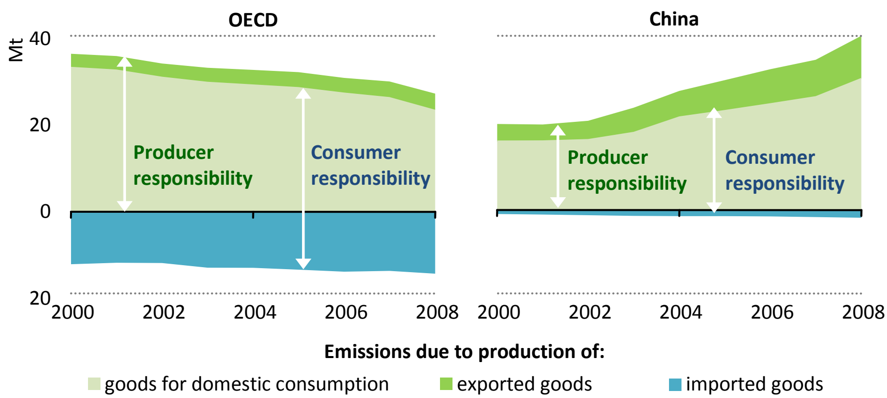
The standard "production-based" paradigm assigns responsibility for pollutant emissions to the country within which the goods are produced. This approach is simple, straightforward and well established: it provides information about emissions trends associated with production for both domestic demand and exports. The "consumption-based" approach attributes the pollutants embodied in goods to the country of final use, quantifying the amount of emissions linked to consumption in each country. Switching from one approach to the other can highlight some underlying economic shifts that help to explain trends in emissions(Rocco, Pavarini, & Colombo, Forthcoming). For example, between 2000 and 2008, sulfur oxide ($SO_X$) emissions in OECD countries declined by 25% (or 9.2 million tonnes [Mt]), but over the same period $SO_X$ emissions embedded in imported goods grew by 18% (or 2.2 Mt) (Figure 3.5). Therefore, around one-quarter of the domestic emissions reduction that occurred was at the cost of emission increases in other countries. In contrast, in China over the same period, $SO_X$ emissions doubled (20 Mt) due to rapid economic growth and industrialisation; but around 30% of the increase in China's $SO_X$ emissions was attributable to the production of goods and services for export.

Policy development based solely on production-based accounts of pollutants could lead to production shifting to another country, possibly with less stringent pollution controls and less-efficient technologies. This shows that a local reduction in pollution relating to production is not a sufficient condition to guarantee global improvement in emissions, and may not be optimal. The consumption-based approach provides complementary

[4] This analysis is part of ongoing research on the value of energy and emissions embedded in trade being conducted by M. Rocco, C. Pavarini and E. Colombo at the Politecnico di Milano.

information to enhance the accuracy of supply chain analysis, allowing a better understanding of the life-cycle emissions of various products. This can lead to increased awareness among consumers that might affect their purchase decisions. It can also be a valuable aid to decision makers in the process of environmental policy design at the local and global level.

**Figure 3.5 ▷ Emissions of sulfur oxide embedded in goods and services produced and consumed in selected regions**




Source: Analysis from Politecnico di Milano, based on data retrieved from the World Input Output Database (Timmer, 2015).

There are other recent examples of the importance of air pollution being recognised in high-level international fora. In May 2015, the World Health Assembly (the decision-making body of the WHO) adopted a resolution on air pollution and health that identifies 13 measures that member states should strive to implement. These include actions enabling health authorities to raise awareness of the dangers of air pollution, developing guidelines to limit exposure and working with relevant private and public sector actors on sustainable solutions. The United Nations' SDGs put a further global spotlight on air quality, targeting indoor air quality through access to clean energy for all.

## 3. Effective monitoring, enforcement, evaluation and communication

**Air quality measures in the energy sector need adequate provisions for monitoring and enforcement, alongside regular evaluations of their impact and effectiveness. Transparency and timely public communication provide the means to keep a strategy on course, build confidence in the mitigating actions and inform stakeholders how they can contribute.**

Putting policies in place is not enough to reach the goal of improved air quality. Effective monitoring and enforcement is critical to securing the targeted improvements. Evaluation helps to check the impact of the policies in practice and to modify the approach as necessary. Public information and engagement is vital to keep an air quality strategy on track. Responsibilities in these areas extend widely within the energy sector (power plants, primary energy supply) and beyond (environmental, public health and transport agencies, for example), as well as at different levels of government (city monitoring of ambient air pollution, such as AirParif in Paris, for example).



### *Monitoring*

Reliable base data are a first condition of good policymaking. Monitoring regimes need to identify the pollutants to be covered, specify the number and type of monitoring locations, the frequency and duration for which monitoring will take place and the type of equipment to be used. In some cases, real-time, automated testing for multiple pollutants may be required, while in others it may require periodic or random testing. Such networks also need to grow and evolve in line with the cities and technologies they are monitoring. The cost of monitoring equipment is declining, with new monitoring devices becoming available for around $1 500 per unit, allowing governments to establish a countrywide network of mobile and stationary air monitoring stations at greatly reduced expense (UNEP, 2015). Declining costs and rising public awareness has also stimulated additional monitoring by businesses, civil society, academia and members of the public. Monitoring results must be converted into meaningful reporting that polluters, policy makers (including enforcement authorities) and the public can readily understand and act upon.

Monitoring networks are increasing and improving in many countries, but their coverage and the capacity to develop them is still very uneven. While the level and type of monitoring that is required is dictated by local factors, there are many cities and countries where the number of monitoring stations remains well below what might be considered the minimum effective level. Increased public concern in a number of countries is likely to increase the priority of investment in these facilities. To this end, a range of guidance, standards and best practice on air quality monitoring is available from the WHO, US EPA, European Commission Joint Research Centre (EC JRC) and others. Following best practice benefits not only a particular jurisdiction but, if consistently applied, can bring additional benefits by making the results comparable across jurisdictions.

Action on monitoring must go hand-in-hand with the use of pollution modelling tools and the compilation of emissions inventories. Together, these activities can be an effective way to project pollution levels and dispersion. Combining air quality monitoring and reporting with broader datasets, such as data on vehicle registration, transport usage and health, can help policy makers better understand the underlying causes or impacts. The technical and the human capacity to implement and run such a monitoring network is dependent, *inter alia*, on adequate financial resources – a fact that must be recognised early on in the formulation of strategies to improve air quality. Shortcomings in one area significantly undermine the effectiveness of the whole.

### *Enforcement*

Clean air policies can be rendered ineffective if not systematically enforced, making good compliance regimes a cornerstone of air quality policy. Depending on the measure in place, there are different enforcement tasks, from checking standards for individual control technologies or quality of fuel, verifying the scale of emissions from industrial or power production, collecting pollution charges or administering trading schemes, to limiting the concentration of ambient pollution in municipalities or countries. Poorly funded, inadequately trained enforcement bodies can undermine the effectiveness of otherwise well-chosen policies: a well-designed air quality strategy therefore needs to pay close attention to capacity building among the relevant enforcement bodies.

In Europe, EU air quality directives require member states to limit the exposure of their citizens to average and maximum levels of pollutants. Responsibility for ensuring compliance with national air quality objectives is often in turn delegated to local or municipal authorities. In the United Kingdom, for example, if air quality is below the required standard, the relevant local authority must declare an "Air Quality Management Area" and produce an action plan showing what is to be done to meet the required standards. Ensuring compliance at the national level is not straightforward: in Europe, the standard for median exposure to $PM_{10}$ is exceeded in twenty-two EU countries, and for $PM_{2.5}$ in seven countries. The enforcement response at EU level can vary from allowing time extensions for countries to achieve compliance, naming and shaming, or imposing fines and referring countries to the European Court of Justice.

Testing compliance with a particular technology standard should (in theory at least) be relatively straightforward, but this is not always the case. For example, while there are performance indicators for clean cookstoves, such as the International Workshops Agreement Tiers of Performance framework, which includes efficiency, PM emissions and carbon monoxide (CO) emissions, there is no single laboratory protocol for testing performance and only an overall framework for rating cookstoves, as opposed to a global standard. As a result, even many "cleaner" solid fuel cookstoves available on the market produce emissions causing concentrations of PM in excess of the WHO Indoor Air Quality Guidelines under normal use conditions.

Problems with compliance are by no means limited to the developing world. Vehicle emissions standards in the European Union and United States (which are replicated in other countries) require vehicles to go through testing under defined driving cycles. While the standards compel vehicles to comply with rigorous testing, and the test-values of vehicle emissions have decreased in line with stricter standards, the gap between real-world and test condition emissions, in some cases, has been growing, so while standards are technically being reached, real-world emissions are not improving at the same rate (Box 3.2).

### Box 3.2 ▷ Regulatory limits and on-road emissions in transport

It is essential not only that regulatory standards be enforced, but also that the standards themselves are matched by real-world usage. A series of studies conducted in recent years have confirmed a growing discrepancy between official and real-world fuel consumption and emission values for new passenger cars (e.g. EC JRC, 2011a and 2011b; ICCT, 2013 and 2014). For $NO_X$ on Euro 6 diesel vehicles, emissions in real-world conditions are about five to seven-times higher than in official tests (INFRAS and TUG, 2015) (ICCT, 2014). Similar discrepancies have been identified with heavy-duty vehicles in some cases, such as when fitted with Selective Catalytic Reduction-based emission controls and operated in low-load, urban applications (e.g. transit buses) (ICCT, 2012).

Recent revelations about the defeat devices used by Volkswagen to allow its diesel cars to comply with emissions limits during testing, while permitting higher emissions during normal on-road use, have raised public awareness about this issue. They have also focused attention on some underlying weaknesses in the tests used to determine new vehicle emissions limits, which include:

- Flexibility in the definition of the test conditions relating to vehicle aerodynamics and tyre rolling resistance.
- Test conditions that do not produce typical engine load or ambient condition and, thus, emission performance that is not equivalent to real-world conditions.
- Production discrepancies between the "representative" vehicle configuration used in laboratory tests and the vehicles actually sold.

Shortcomings also exist in the protocols that determine or detect how the emissions levels of vehicles are verified; how driver-related factors (e.g. driving style) and environmental conditions are accounted for; and how penalties are imposed if there is non-compliance. Efforts are underway – in Europe and elsewhere (with moves towards a harmonised global light-duty vehicle test procedure) – to narrow the gap between theoretically achieved limits and on-road emissions. Vehicle test procedures need to reflect more closely real-world driving conditions, reducing opportunities to exploit existing tolerances. On-road testing should cover fuel consumption and the emission of other pollutants (it currently focuses on $NO_X$ only). Full transparency relating to the data on vehicle compliance is vital to ensure the integrity of the process and to help rebuild public trust. In the United States, for example, information on new vehicle certification is publicly available, which has led manufacturers routinely to over-comply with legal limits by 50% or more (US EPA, 2013).

A recent comparative analysis of current vehicle testing and compliance schemes in the European Union and the United States highlighted the value of independent confirmatory testing by public authorities to verify emissions performance (ICCT, 2015). Enforcement authorities also need to be able and willing to issue penalties, including the capacity to require vehicle recalls, in cases of non-compliance or fraud, to help guarantee the efficacy of measures over the vehicle life.

Achieving air quality goals often requires the effective enforcement of interconnected energy and pollution standards. In the United States, the US EPA enforces fuel-quality standards with a programme combining fuel registration, extensive inspections, fuel-quality testing, reporting and strict penalties for non-compliance. The US EPA puts the burden of proof of compliance on refineries, importers and fuel handlers, and follows up with mandated independent testing. Developing the necessary institutions and infrastructure takes time and effort: in Indonesia, for example, the enforcement of air quality standards and emissions testing is hampered by relatively low vehicle fuel quality and the fact that there is a shortage of refinery capacity capable of producing low-sulfur fuels.

### *Evaluation*

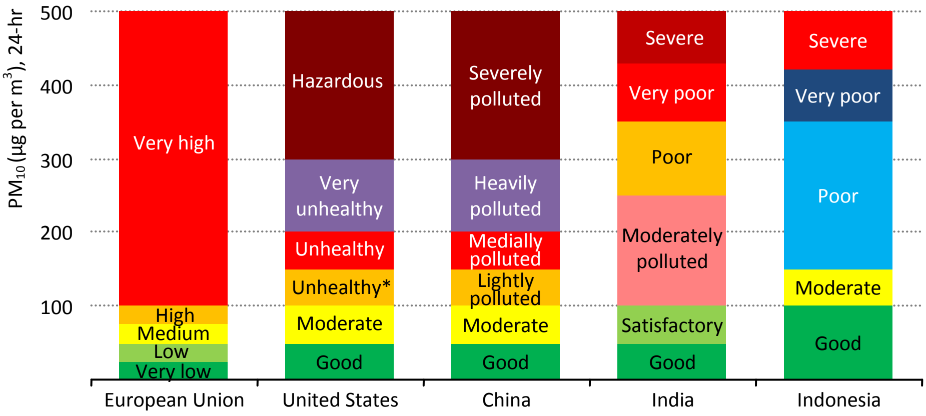
Evaluation is an essential part of the policy process, allowing for a thorough review of policy intentions and actions from a variety of angles. An evaluation should assess whether a policy measure is well-designed to fulfil its stated purpose and, after the event, whether it was implemented as planned. If it did not deliver the intended impact, i.e. the intended effect on emissions, or had unanticipated consequences for related sectors, then the reasons need to be carefully evaluated and used to shape future policy design. This process of continuous learning is particularly valuable for a multi-faceted issue like air quality, operating at the intersection of different policy areas.

### *Communication*

Technological advances and increased public awareness about air quality are combining to enhance the value of effective communication about air quality, quickly making it a core aspect of any modern air quality strategy. Such communication may be a regulatory requirement (such as under European regulations and the US Clean Air Act) but, even if not, should be pursued. A range of organisations may be involved in air quality communication, including environmental, energy and transport agencies that are monitoring, collating and reporting on the pollution, public health agencies reporting on health aspects, civil society groups seeking to raise awareness, the broadcast media and social media (allowing people to raise the issue through their own networks). The exact role of energy ministries and the broader energy sector in ensuring effective air quality communication varies, but typically focuses on those areas for which energy has lead policy responsibility. Given the interests of various ministries and levels of government in air quality issues, the need to co-ordinate and not contradict is an important one.

A distinction can be made between information for the public and information for policy makers and industry. For policy makers, air quality information is an essential component of the policy evaluation process. For power plants, larger industrial facilities, waste management facilities, etc., site-specific monitoring/enforcement reports should provide the technical information needed to allow them to understand fully the nature of any air quality problems and to devise cost-effective solutions. On a broader scale, regular national air quality status reports are a common means of summarising air pollution trends, identifying priorities for action and contributing to the analysis of the co-benefits or trade-offs (e.g. climate change, energy use and security). In addition to such reports, there must be more immediate means of communication available for use during high-pollution events.

**Figure 3.6 ▹ Air quality index thresholds for $PM_{10}$ in selected countries**




* Unhealthy for sensitive groups.

Sources: ADB (2014); Clean Air Asia (2016); Government of India Ministry of Environment and Forests (2014).

To communicate air quality information to the public effectively, it is important that the information be in a simple, concise and understandable form. It is preferable that it be accompanied by advice on any necessary mitigating action. This places a particular emphasis on "translating" air quality information into messages that are easy to understand by use of approaches such as colour-coded air quality index or geographic visualisations, and communicating through a variety of channels. An air quality index is a common means to present air quality information, although such indices can vary widely in terms of the type of pollutants monitored, the range of values and the banding (Figure 3.6). Frequency of information and the time horizon of the information should be tailored to give the public advice that they can act upon, but often requires sophisticated air quality monitoring and modelling systems. Air pollution information and health advice ideally go hand-in-hand, to allow those with conditions such as heart, lung problems or asthma to protect their health.

Policy makers need to communicate effectively to the public the reasons for new policy actions. For example, actions to impose bans of car use in cities may be justified by data seen by policy makers, but the public needs to be persuaded of the justification for such a ban and satisfied as to how it is to be implemented. Information gathered for policy makers may be used in the public domain, as a means to highlight good and bad performance, for example by naming the sources (such as vehicle manufacturers), cities or sub-regions with the lowest and highest pollution levels.

# Aligning clean air policies with energy policy objectives

## *Clean air and climate change*

The Paris Agreement on climate change, reached at the United Nations COP21 meeting in 2015 and new energy-related $CO_2$ trends (Box 3.3), bring new vigour to global efforts to address climate change, with countries collectively aiming to keep the global temperature rise to well below 2 $^{o}$C. The Agreement sets out a global goal for greenhouse-gas emissions to peak as soon as possible and then to reduce rapidly in order to achieve a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases in the second half of this century. It also involves an unprecedented breadth of engagement, with 188 countries having pledged to take actions that reduce emissions through their Intended Nationally Determined Contributions (INDCs). The most common energy sector actions cited in the INDCs are energy efficiency (mentioned by 143 countries) and promotion of renewable energy (mentioned by 140 countries). They both result in reduced combustion of fossil fuels, thereby acting to improve air quality as well mitigate climate change. However, numerous studies suggest that current INDCs, (which are included in the modelling of the New Policies Scenario) are not enough to put the world on track to meet the well below 2 $^{o}$C objective (IEA, 2015a). As seen in Chapter 2, they also fall short of adequately addressing air quality concerns.

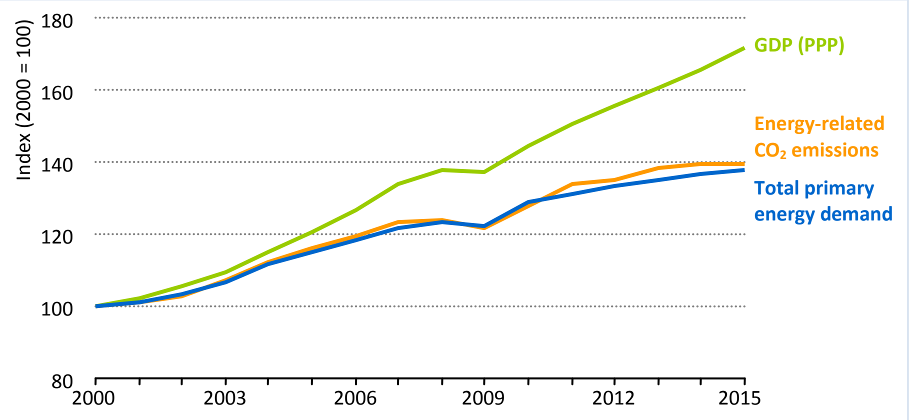
**Box 3.3 ▷ Decoupling economic growth and energy-related $CO_2$ emissions**

The IEA's preliminary estimate for 2015 reveals that global energy-related $CO_2$ emissions stayed flat for the second year in a row, having last seen a significant change in 2012. This represents the clearest sign yet of the decoupling of the previously close relationship between global economic growth, energy demand and related $CO_2$ emissions (Figure 3.7). Given the status of the energy sector as by far the world's largest contributor to greenhouse-gas emissions, this news added to the sense of positive momentum following the Paris Agreement.

Electricity generated by renewables played a critical role, having accounted for around 90% of the growth in electricity generation in 2015; wind power alone produced more than half of the increase. There have been only four periods in the past 40 years in which emissions stood still or fell compared with the previous year, with three of those – the early 1980s, 1992 and 2009 – being associated with global economic weakness. In contrast, the recent stall in emissions comes in a period of economic expansion.

China and the United States registered a decrease in energy-related emissions of 1.5% and 2%, respectively, while their economies grew by 6.9% and 2.5%. In the US, reductions were mainly due to a shift from coal to natural gas for power generation. The decrease in China was linked both to its economic transition towards less energy-intensive growth and to major efforts to decarbonise the power mix. However, the decline observed in the two major emitters was offset by higher emissions in many other economies in Asia, the Middle East and a slight increase in Europe.

**Figure 3.7 ▷ Change in global economic output, energy demand and energy-related $CO_2$ emissions**




Note: GDP (PPP) = gross domestic product on purchasing power parity basis.

Sources: Historical data to 2013 from the IEA Data Centre; data for 2014-2015 are preliminary and based on *WEO* analysis.

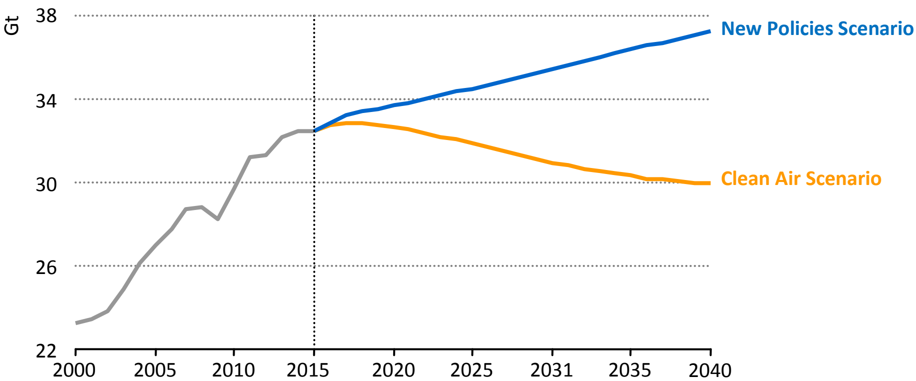
### *Air quality and climate change co-benefits*

In many countries, the imperative of improving air quality is strong motivation for action that also has benefits for the climate. For example, China's commitment to curb air pollution from coal use in industry and power generation, by promoting the use of cleaner energy sources (including renewables, nuclear and natural gas), forms the heart of its climate change response. In the United States, US EPA regulation of mercury, $SO_2$ and $NO_X$ is reinforcing the trend for electricity generation to move from coal to natural gas. The Clean Air Scenario presented here provides precisely this type of win-win for air quality and climate change, with major cuts in key energy-related pollutants occurring hand-in-hand with reductions in energy-related $CO_2$ emissions. The Clean Air Scenario therefore conforms to one critical goal agreed in Paris, as it delivers an early peak in global greenhouse-gas emissions, around 2020 (Figure 3.8). Considerably stronger policy efforts would be required, however, to raise the probability of this becoming a scenario that keeps the long-term rise in global average temperatures to well below 2 °C.

Two areas of clear cross-benefit (for air quality and climate change) are actions to reduce emissions of black carbon, a major component of PM, and of methane (Box 3.4). Black carbon – emitted due to incomplete combustion, particularly from household biomass stoves and diesel vehicles – affects the climate in multiple ways. It absorbs incoming sunlight, leading to warming in the atmosphere, settles on the ground accelerating the melting of Arctic and alpine ice and, along with other pollutants that form aerosols, it affects the formation of clouds, so having a knock-on influence on increased warming. The United Nations climate process – the 1992 United Nations Framework Convention on Climate Change (UNFCCC), and its subsequent agreements (including the Paris Agreement)

– focus on stabilisation of greenhouse-gas levels and do not address non-gas climate forcers. In consequence, action on black carbon proceeds, for the most part, through coalitions outside the UNFCCC, such as the Climate and Clean Air Coalition (CCAC). Mexico was the only country to set an explicit target for black carbon in its COP21 climate pledge.

**Figure 3.8 ▷ Global energy-related $CO_2$ emissions by scenario**




Note: Gt = gigatonnes.

**Box 3.4 ▷ Methane reductions: a double win**

Methane is one of the group of chemicals known as volatile organic compounds. Locally, the build-up of methane poses a hazard due to its flammable nature, while it is also a contributor to background ozone levels and a potent greenhouse gas. Over a 20-year period, it has around 85-times the effect of $CO_2$ on global warming and, in a standard 100-year comparison some 30-times the effect.[5] Cutting methane emissions is therefore a promising means of tackling near-term warming as the necessary long-term cuts in $CO_2$ emissions are implemented.

Energy-related methane emissions were estimated at 100 Mt in 2013, of which a little over half (55 Mt) came from the oil and gas sector (IEA, 2015b). The majority of these emissions derive from upstream operations.[6] Minimising methane releases from upstream oil and gas operations is a pragmatic way to achieve short-term climate mitigation, via a range of cost-effective approaches such as detecting and fixing equipment leaks, implementing reduced emissions completion technologies ("green

[5] There are different ways to evaluate the effects of methane on climate change. Those quoted here are consistent with the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC, 2013).

[6] A recent report by the US EPA (2016) suggests that methane emissions from upstream oil and gas activities in the United States may be more than double the levels estimated previously. For natural gas, this recalculation is offset by a revised estimate of the emissions from transportation, storage and distribution. However, these major revisions, in the country with one of highest levels of transparency regarding emission levels, highlight the degree of uncertainty that still exists in estimating methane emissions levels from oil and gas operations.

completions") for unconventional gas wells and deploying technologies that capture the vented gas associated with liquids unloading.[7] Capturing the methane that is currently emitted to the atmosphere would also be a significant additional source of gas supply: the volumetric equivalent of the 55 Mt from the oil and gas sector is around 80 billion cubic metres, roughly equal to annual gas production in Algeria.

### *Trade-offs between air quality and climate change objectives*

3

Individual air pollutants have differing, and sometimes contrary, effects on climate change that must be taken into account to avoid unintended climate consequences (Box 3.5). The choice of policy instrument to tackle air pollution can also have important implications for $CO_2$ emissions. For example, an exclusive focus on direct emissions controls, rather than the package of measures adopted in the Clean Air Scenario, could result in increased commitments to high-carbon energy infrastructure, such as coal-fired power plants. Given the long lifetime of such assets, such a "locked-in" high-emissions infrastructure would become a barrier to achieving the rapid decarbonisation in the power sector required to meet global climate change objectives. The Clean Air Scenario helps avoid this lock-in, due to its focus on energy efficiency and renewable-based power generation.

**Box 3.5 ⊳ Air pollution effects on climate change**

Many air pollutants form aerosols (small collections of particles) in the atmosphere. These aerosols have an impact on climate change through two mechanisms of similar magnitude: the interaction of incoming sunlight with the pollutants themselves and the effect that aerosols have on cloud formation. The Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment report found, with high confidence, that aerosols decrease warming overall and therefore offset part of the positive warming of greenhouse gases (IPCC, 2013). Individual air pollutants have differing impacts. Emissions of $SO_2$ have a clear negative effect on warming. Meanwhile, $NO_X$ pollution is likely to have a net negative impact but the uncertainty is large, and black carbon has a strong positive impact on warming.

Aerosols are not evenly distributed globally. Since 1980, peak aerosol forcing has shifted away from North America and Europe due to pollution controls and towards regions that have seen strong economic growth driven by fossil-fuel combustion, such as East and Southeast Asia (IPCC, 2013). One recent study found that European actions to reduce sulfur levels may have led the Arctic to be 0.5 °C warmer than if such emissions had remained at 1980 levels, with fewer aerosols now offsetting the warming effect of greenhouse gases (Acosta Navarro et al., 2016). The interactions between air pollutants and global warming reinforce the need to address these issues in tandem.

[7] Liquids unloading occur when a (typically older) gas well is cleared of accumulated liquids in order to maintain production; depending on the technique used, this can involve intentional venting of methane to the atmosphere.

The inverse situation also exists: measures to address climate change, adopted in isolation from the aims of air pollution abatement, could lead to more air pollution. For example, an isolated focus on reducing $CO_2$ emissions by encouraging the use of wood stoves, diesel cars or biofuels, could worsen air quality and increase exposure to fine particles. Combustion of bioenergy (biomass for power generation and cooking/heating, or biofuels for transport) still produces air pollutants, even though it can contribute to the reduction of greenhouse gases. Biomass use in power generation and households is rising in some European countries, mostly due to the promotion of biomass through climate policy (EEA, 2015). Adverse air quality impacts can be mitigated if climate policies to promote biomass are coupled with incentives for cleaner burning (WHO, 2015). To this end, the European Union has agreed efficiency standards for solid fuel boilers to apply from 2022, building on existing regulations in many member states (ECEEE, 2015). Rewarding the generally higher fuel economy of modern diesel vehicles (through fuel tax reductions and subsidies to diesel vehicles) also creates tension with air quality goals. Stricter fuel-quality standards bring major benefits in end-use emissions, but can also boost energy own-use in refineries if more extensive processing is required.

#### *Optimising air quality and climate change policies*

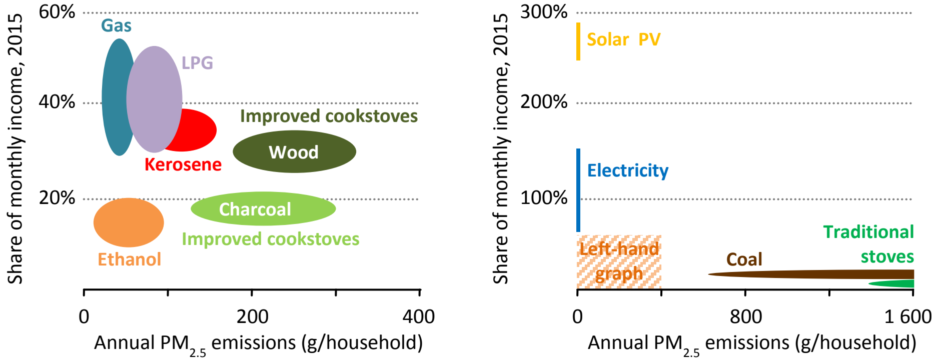
Air pollutants and greenhouse gases arise from many of the same sources in the energy sector. In consequence, an integrated policy approach can pay double dividends, maximising synergies and avoiding conflicts. The IPCC Fifth Assessment Report found that the costs of integrated approaches that simultaneously achieve climate, energy security and air pollution objectives are lower than those that deal with each issue independently (IPCC, 2013). This points to the need to quantify air quality co-benefits and vice versa when assessing climate policy options and co-optimising policy packages. The air quality co-benefits of climate change mitigation have been estimated to fall within the range of \$2 to \$196 per tonne of $CO_2$ ($t/CO_2$), with an average of \$49 $t/CO_2$, with the highest co-benefits found in developing countries (Nemet et al., 2010). Such estimates are only rarely included in integrated assessments of climate policy (Nemet et al., 2010). Co-optimised packages would similarly take into account the negative trade-offs, for example those that may arise from use of biomass.

### Clean air and energy access

The goals of securing universal access to modern, affordable, abundant energy and of guaranteeing clean, healthy air are complementary. Indeed, one of the main motivations for improving energy access, in particular to modern cooking, is the detrimental health impact of the household air pollution that arises from burning solid fuels – an impact particularly felt by women and children in developing countries. Compared with the outcome in the New Policies Scenario, the achievement of universal energy access in the Clean Air Scenario reduces by two-thirds the amount of traditional biomass consumed in households by 2040: the resulting health improvements are large and clear – compared with today, more than 2 million premature deaths as a result of indoor air pollution are prevented in 2040.

The investment required to achieve universal access to electricity is around $1.1 trillion over the period to 2040 – $45 billion per year on average – 50% more than the investment expected in the New Policies Scenario. The investment needed to achieve universal access to clean cooking facilities is considerably more modest: the cost of the improved cookstoves, LPG stoves, gasifiers etc. is only around 5% of the amount required for full access to electricity, although many other challenges remain in practice to achieve the switch to cleaner cooking alternatives (Spotlight). Insofar as there are trade-offs between air quality and access issues, they are related to the cost and the emissions performance of the different clean cooking options (Figure 3.9 shows the case of India). The incomplete combustion of solid biomass in a three-stone fire entails much higher pollutant emissions than those associated with all of the alternatives, including improved or advanced stoves with a chimney and/or fan, LPG, natural gas, electricity and solar. However, the most affordable alternative options, improved or charcoal cookstoves, are also those with higher remaining particulate emissions and health risks (especially given the uncertainties about the actual performance of many of these improved cookstoves, which may not meet the WHO Indoor Air Quality Guidelines under normal use conditions). Lower emissions options become progressively more expensive, and so the barriers to their adoption become higher.

**Figure 3.9 ▷ Investment cost of cookstoves as a share of an Indian household's monthly average income and associated $PM_{2.5}$ emissions**




Notes: g/household = grammes per household. $PM_{2.5}$ emissions are calculated as the absolute level of emissions emitted in one Indian household over a year with their cookstove.

Source: GACC (2016).

**SPOTLIGHT**

### What is holding back households from switching to cleaner alternatives for cooking?

More than 2.7 billion people – 38% of the world's population – rely on the traditional use of solid biomass for cooking, typically using inefficient stoves in poorly ventilated spaces. More than 80% (around 2.2 billion) live in rural areas. The adverse consequences fall predominately on women and children, who not only spend many hours every year collecting fuelwood,[8] but also suffer the worst health effects from the smoky indoor environment.

Numerous considerations are at play in determining whether households switch to cleaner alternatives for cooking, in particular the availability and affordability of alternatives, and public awareness of the consequences of household air pollution. In practice, even when alternatives are adopted, the older option may not be discarded, a phenomenon known as "fuel stacking".

The availability of alternatives mainly depends on the households' location in relation to distribution networks for improved cookstoves or alternative fuels such as LPG. In the latter case, LPG providers typically face difficulties establishing a market in areas where consumption prospects or population density are low or the road infrastructure is poor. Until networks are sufficiently well established to ensure reliable supply, consumers typically (and rationally) prefer to refrain from switching.

The affordability of alternatives is another important criterion, including the relative price of the fuel and the investment cost for the new stove. LPG is often available on a subsidised basis, as in India where the LPG subsidy programme is now one of the world's largest cash transfer programmes. Subsidies are no longer used to affect the end-user price, but rather support the purchase of up to 12 LPG cylinders per household per year via payments to individual bank accounts. To target the subsidy further, this is accompanied by the "Give it Up" campaign, which encourages wealthier segments of the population to voluntarily forego the subsidy and pay the full price.

But where biomass is available for free, or at very low cost, there is often little economic incentive to pay the upfront cost of an improved cookstove, especially when households are unaware of the hazardous impacts of smoke coming from traditional stoves. This is why distribution campaigns for improved cookstoves tend to have an important public awareness component, to educate not only on proper use of the improved stoves but also the health benefits of doing so.[9]

[8] The Global Alliance for Clean Cookstoves estimates that women in India spend around 370 hours per year collecting fuelwood (GACC, 2015); Calvo estimated that this figure was around 800 hours in Zambia and around 300 hours in Ghana and Tanzania (Calvo, 1994).

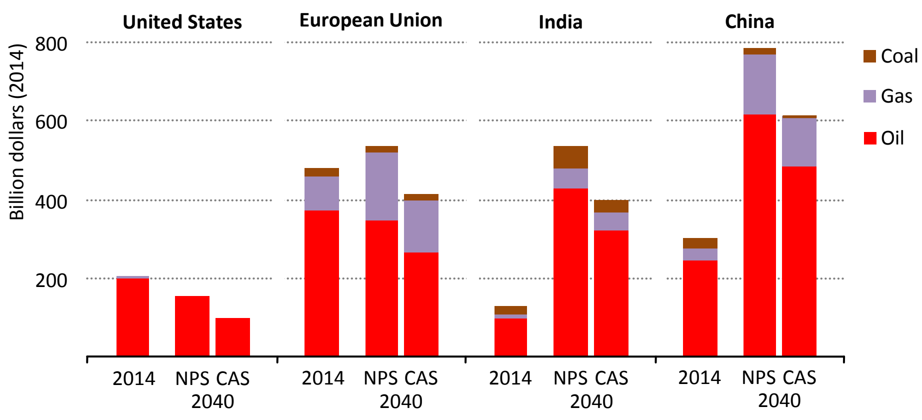
[9] There are examples of strong policies and programmes in this area, but efforts generally are much less widespread than those promoting access to electricity. The Global Alliance for Clean Cookstoves targets 100 million households to adopt clean and/or efficient stoves and fuels by 2020.

## *Energy security and import bills*

The energy security implications of the Clean Air Scenario vary by sector. Some of these implications are common to any decarbonising energy system. The reduction in coal use brings environmental benefits, but also backs out a source of energy that is widely available, relatively easy to store, and used to produce electricity that – within certain technical limits – can readily be modulated to fit power demand. It is replaced in some instances by natural gas and in others by an increasing share of variable renewables, such as wind and solar. This raises the oft-discussed issue of ensuring adequate system reliability (an issue that will be discussed fully in the *World Energy Outlook-2016*), through investment in a combination of improved networks, energy storage, demand response and flexible power plants. The twist to this story in the Clean Air Scenario is that, to the extent that air quality considerations reduce the role of bioenergy in the power sector, the system loses a low-carbon source of flexible generation.

For fossil fuels, the Clean Air Scenario implies a major upgrade of global refining in order to meet the demand for low-sulfur fuels: refining capacity would need to be extensively re-tooled. There would be no technical barriers to such a process, but it could nonetheless be disruptive. Together with the impact of energy efficiency measures on oil demand, there would be increased pressure for consolidation in the industry, with some potential risks to energy security in the transition.

**Figure 3.10 ▷ Fossil-fuel import bills in selected regions by scenario**




Note: NPS = New Policies Scenario; CAS = Clean Air Scenario.

Fossil-fuel import bills can be a major economic concern for some countries and, while the Clean Air Scenario is not designed specifically for this end, it does achieve this desirable co-benefit of improving the balance of payments of net importers. The United States is expected to see an improvement in its overall fossil-fuel import bill even in the New Policies Scenario, as it becomes a net exporter of natural gas and its oil import requirement declines; but it sees a much sharper improvement in the Clean Air Scenario (the import bill going from over $200 billion in 2014 to under $100 billion in 2040) (Figure 3.10). The European Union sees its fossil-fuel import bill switch from an increasing trend in the New Policies Scenario to a decreasing one in the Clean Air Scenario. As the requirement for imported oil, gas and coal is reduced, the import bill ends $120 billion lower than would otherwise be expected in 2040. Large reductions in fossil-fuel import requirements also bring large gains to China ($170 billion lower in 2040 relative to the New Policies Scenario) and India ($135 billion lower).

# PART B
# COUNTRY PROFILES

## PREFACE

Part B of *Energy and Air Pollution: World Energy Outlook Special Report* includes seven country/regional profiles that present an analysis of the current energy and air quality context, as well as the outlook for air pollutant emissions and their impacts. The profiles are of the United States, Mexico, the European Union, China, India, Southeast Asia and Africa. Together, they represent two-thirds of global energy demand in 2013, and 66%, 70% and 81% of global energy-related air pollutant emissions of sulfur dioxide ($SO_2$), nitrogen oxides ($NO_X$) and fine particulate matter ($PM_{2.5}$), respectively, in 2015 (excluding international bunkers). The analysis focuses on the results of the New Policies and Clean Air Scenario with an outlook to 2040.

The profiles are aimed to provide decision makers with a data-rich analysis of current and future emissions by sector and by pollutant, taking into account existing and planned policies, as well as discussing further opportunities for emissions reductions that are achievable with existing technologies and policy practices in order to improve air quality. The profiles also report the health implications of each scenario, and the co-benefits associated with the Clean Air Scenario such as for fossil-fuel import bills and energy-related carbon dioxide ($CO_2$) emissions. The policy, technology and economic assumptions that underlie the New Policies Scenario and the Clean Air Scenario, as well as a global overview of the results, are described in Chapter 2 (Outlook for Air Pollution).

# United States

## Highlights

- Efforts by the United States to control energy-related air pollution date back to the 1960s. They have produced significant results. Despite continued growth in population, GDP and energy consumption, aggregate emissions of six common air pollutants declined by almost 70% between 1970 and today. On a national basis, average air pollution concentrations have also declined and for all six pollutants are now below national limits. Even so, air quality continues to pose serious local challenges, with over 40% of the US population living in areas that do not comply with at least one of the national standards.
- The combined effects of clean air regulations, and energy and climate policies will help further to improve the outlook for air quality: in the New Policies Scenario, $SO_2$ and $NO_X$ emissions each fall by more than 50% by 2040, relative to today, while $PM_{2.5}$ emissions drop by one-third. The reductions stem from a range of measures, but strengthening emissions standards in transport and reducing emissions in the power sector with lower emitting technologies are central.
- Additional measures in the Clean Air Scenario can further improve the outlook for air quality in the United States: $SO_2$ emissions fall by an additional 50% by 2040, relative to the New Policies Scenario, $NO_X$ by around 40% and $PM_{2.5}$ by about 15%. These improvements deliver important co-benefits: the fossil-fuel import bill falls as oil demand drops by 1.9 mb/d in 2040 relative to the New Policies Scenario, natural gas demand by around 50 bcm and coal demand by 255 Mtce. $CO_2$ emissions are around 1.1 Gt lower than in the New Policies Scenario, helping to achieve climate change targets.

## *The energy and air quality context*

The United States has a long history of addressing air pollution and has made great strides in improving air quality since the federal government first began controlling air pollution in the 1960s. The overarching regulatory framework for addressing air pollution is the Clean Air Act, introduced in its modern form in 1970 and amended significantly in 1977 and 1990. It embodies a co-operative approach between the federal government and the states. It has three main components: ambient air quality standards, emissions standards and permitting requirements. The cornerstone is the set of National Ambient Air Quality Standards (NAAQS) set by the US Environmental Protection Agency (US EPA) for six common air pollutants: carbon monoxide (CO), lead, nitrogen dioxide ($NO_2$), sulfur dioxide

($SO_2$), ozone and particulate matter (PM) (with $PM_{10}$ and $PM_{2.5}$ regulated separately[1]). Two standards are defined for each pollutant: a primary standard to protect human health and a secondary standard to protect non-health related public welfare (such as visibility and damage to crops and buildings). These standards define maximum pollutant concentration levels averaged over a specified period and have been revised over the years (Table 4.1). The Clean Air Act requires that individual states develop a plan, subject to US EPA approval, to attain and maintain the NAAQS for all control regions within their jurisdiction. Control regions that the US EPA determines are in violation of NAAQS are designated as "non-attainment areas" and become subject to controls that are more stringent. For each non-attainment area, states must submit specific plans to reach attainment within a set timeframe. States that fail to submit a plan, or submit plans that are found to be inadequate in terms of implementation or enforcement, may be subject to sanctions such as withholding of federal highway funding.

**Table 4.1 ▷ National ambient air quality standards in the United States for selected pollutants**

| Pollutant | | Primary/ Secondary | Averaging time | Level | Form | Last revised |
|---|---|---|---|---|---|---|
| $NO_2$ | | Primary | 1 hour | 100 ppb | 98th percentile of 1-hour daily maximum concentrations, averaged over 3 years | 2010 |
| | | Both | 1 year | 53 ppb | Annual mean | 1971 |
| Ozone ($O_3$) | | Both | 8 hours | 0.070 ppm | Annual 4th-highest daily maximum 8-hour concentration, averaged over 3 years | 2015 |
| PM | $PM_{2.5}$ | Primary | 1 year | 12.0 μg/$m^3$ | Annual mean, averaged over 3 years | 2012 |
| | | Secondary | 1 year | 15.0 μg/$m^3$ | Annual mean, averaged over 3 years | 1997 |
| | | Both | 24 hours | 35 μg/$m^3$ | 98th percentile, averaged over 3 years | 2006 |
| | $PM_{10}$ | Both | 24 hours | 150 μg/$m^3$ | Not to be exceeded more than once per year on average over 3 years | 1987 |
| $SO_2$ | | Primary | 1 hour | 75 ppb | 99th percentile of 1-hour daily maximum concentrations, averaged over 3 years | 2010 |
| | | Secondary | 3 hours | 0.5 ppm | Not to be exceeded more than once per year | 1971 |

Notes: ppb = parts per billion; ppm = parts per million; μg/$m^3$ = microgrammes per cubic metre.

Source: *www.epa.gov/criteria-air-pollutants/naaqs-table*.

[1] Size is an important factor in determining the health impacts of PM: "coarse particles" are between 2.5 and 10 micrometres (μm) in diameter and "fine particles" are smaller than 2.5 μm.

The Clean Air Act also authorises the US EPA to set national emissions standards for new stationary sources or existing sources undergoing major modification. These New Source Performance Standards (NSPS) have been defined for all categories of major industrial sources, e.g. fossil fuel-fired power plants, petroleum refineries, steel plants and landfills. They are designed to ensure that the emissions standards set by the states meet at least a minimum level, though states are free to set standards that are more stringent. While the standards do not mandate particular kinds of technology, they are technology-based in that they are established on what the US EPA determines to be the "best system of emissions reduction" and taking cost into consideration. Standards are enforced through financial penalties for non-compliance. Like the NAAQS, the NSPS are reviewed periodically and may be strengthened over time. The Clean Air Act also requires that all major new and modified stationary sources of pollutants obtain pre-construction permits under the New Source Review programme. The permitting process entails site-specific, technology-based review of proposed control technology and requires compliance with specified standards, which are more stringent in non-attainment areas. Major existing stationary sources are required to obtain operating permits under the Title V permitting programme; these specify all applicable Clean Air Act requirements that a plant must meet and compliance must be re-certified on an annual basis.



The federal government also addresses air pollution from mobile sources. National measures to regulate vehicle emissions were introduced in the 1970s, including vehicle emission standards to reduce photochemical smog, rules that led to the eventual phase-out of leaded gasoline and the first fuel-economy standards for cars and light trucks. Under the authority of the Clean Air Act, the US EPA currently sets tailpipe emission standards for light-duty vehicles that limit particulates, nitrogen oxides ($NO_X$), hydrocarbons (HC) and CO from vehicle exhaust and fuel system leaks (i.e. "evaporative emissions"), and also imposes limits on the sulfur content of gasoline and diesel fuel. Regulation of pollutant emissions from heavy-duty vehicles (HDVs), such as trucks and buses, were originally set by reference to emissions from both the engines and the vehicles, with HDV fuel-efficiency standards being super-imposed since 2011. Emissions from a wide variety of non-road engines and vehicles have been regulated since the early 1990s.

On a nationwide basis, emissions of the controlled air pollutants ("criteria pollutants") have declined significantly since the modern Clean Air Act was introduced.[2] Despite continued growth in population, GDP and energy consumption, aggregate emissions of all six criteria pollutants declined by around 70% between 1970 and today. Since 1970, $SO_2$ emissions have declined more than 80%. In the power sector, historically the largest source of $SO_2$ emissions, reductions were achieved through increased use of low-sulfur coal and flue-gas desulfurisation. The decline in $SO_2$ emissions was particularly steep in the decades following the Clean Air Act Amendments of 1990 that established an $SO_2$ allowance trading programme, an innovative market-based approach to control acid rain (see Chapter 1). In

[2] All emissions and air quality trends quoted in this paragraph were determined using data available at: *www3.epa.gov/airtrends/aqtrends.html#airquality*.

the period since 1970, $NO_X$ emissions have declined by more than 50%, with steeper declines achieved since the late 1990s, mostly due to reduced emissions from transportation, but also from fuel combustion in the power and industry sectors. $PM_{2.5}$ emissions, which have been regulated since 1997, declined about 30% between 2000 and today. In all cases, there was an associated decline in average national ambient pollutant concentrations, which are now below, and for some pollutants well below, current national standards for all six criteria pollutants. The US EPA has made an assessment of the costs and benefits of the Clean Air Act Amendments of 1990: costs were around $380 billion, while the cumulative net benefits were valued at $12 trillion, over the period 1990-2020 (in 2006 dollars) (US EPA, 2011). These net benefits are derived mainly from the prevention of premature deaths as a result of improvements in ambient PM; by 2020, the 230 000 avoided PM related deaths in that year account for about 85% of monetised annual net benefits of $2 trillion.

Despite these achievements, air quality continues to pose challenges in the United States, in part because of the implementation over time of increasingly stringent air quality standards. About 128 million people (41% of the US population) live in areas that are currently in non-attainment for at least one or more NAAQS, including 121 million people for ozone (8-hour)[3] and 36 million for $PM_{2.5}$ (annual and/or 24-hour) (US EPA, 2015). Current regulatory efforts are focused on ensuring that emissions of criteria pollutants are reduced to bring non-attainment areas into compliance with the primary (health-based) NAAQS. In this context, emissions that cross state lines and contribute to pollution downwind have been a persistent problem in many areas of the country. In response, US EPA is implementing the Cross-State Air Pollution Rule, which requires 28 states in the eastern half of the United States to reduce power sector emissions of $SO_2$ and $NO_X$, in order to assist with attainment of ozone and PM NAAQs. Other air pollution rules targeting the power sector will bring about ancillary improvements in air quality. For example, the recent Mercury and Air Toxics Standards, which limit toxic emissions (including mercury) from coal- and oil-fired power plants for the first time, are expected to yield co-benefits in terms of PM reductions by reducing $SO_2$ (a PM precursor) and directly emitted $PM_{2.5}$.

The energy sector is the largest contributor to emissions of air pollutants in the United States and ongoing efforts to combat air pollution are in the context of its rapid transformation. In 2015, the energy sector accounted for about 4.4 million tonnes (Mt) of $SO_2$ emissions (around half from coal combustion in the power sector), 12.8 Mt of $NO_X$ emissions (almost 45% from oil-combustion in transport) and 1.0 Mt of $PM_{2.5}$ emissions (of which around 30% from biomass use in the residential sector and almost 30% from transport). Coal use in the power sector is down about 20% over the last decade reflective of the boom in shale gas developments, with an associated significant decline in air pollutants. Other relevant policy efforts by the US administration include a focus on increasing energy efficiency (especially in the buildings and transport sectors) and reducing

[3] According to the 75 ppb ozone NAAQS set in 2008. The standard was revised down to 70 ppb in 2015, but non-attainment designations for the revised standard are not expected until 2017.

carbon dioxide ($CO_2$) emissions from the power sector (through the Clean Power Plan). These efforts, along with other measures, form the basis of the US climate pledge at COP21, which commits the United States to a greenhouse-gas emissions reduction of 26-28% by 2025 relative to 2005 and will have associated benefits in terms of cleaner air. The Clean Power Plan, in particular, is expected by the US EPA to yield significant reductions in conventional pollutants, such as $SO_2$ and $PM_{2.5}$.

**Box 4.1 ▹ Los Angeles: The world's first "smog capital" and its ongoing battle for cleaner air**

The Greater Los Angeles (LA) area, home to almost 19 million people, is in a geological basin bounded by ocean and mountains. With its automobile-centric culture, bustling industry and ports, sprawling development and sunny climate with often-stagnant winds, the LA basin is a natural pollution trap. When the first full-blown smog crises erupted during World War II, the precise cause was a mystery. LA took a countywide approach to addressing it, creating the nation's first air pollution control district in 1947. By the 1950s, hydrocarbons and $NO_X$ from vehicle exhaust, combined with the catalysing effect of sunlight, had been identified as the principal source of photochemical smog. Power to control air pollution in the area shifted from the county to the state, culminating in creation of the California Air Resources Board (CARB) in 1967. Recognising California's unusually severe air quality problems, CARB was granted an exceptional federal waiver to set more stringent vehicle emissions standards than those at the federal level. Subsequent CARB revisions have consistently outpaced federal standards (other states eventually were allowed to adopt California standards).

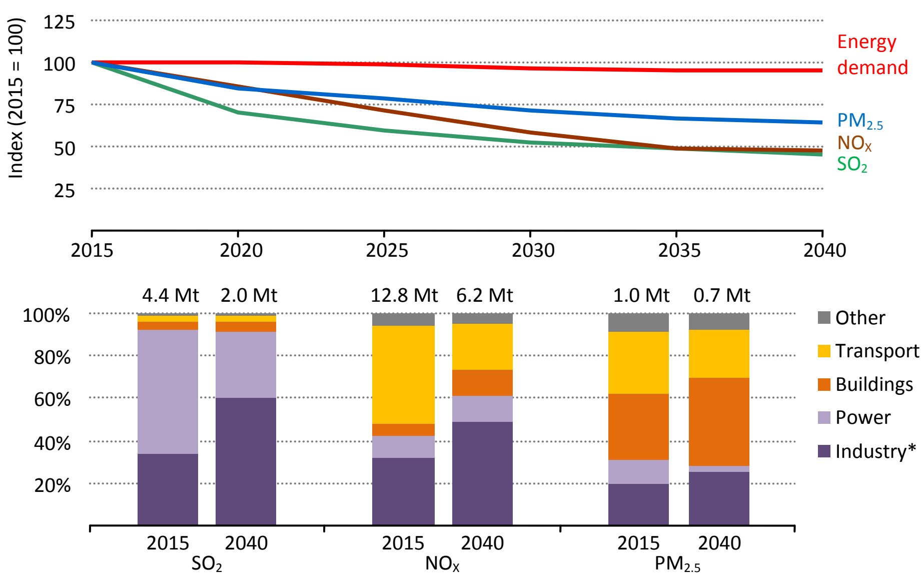
Despite these positive developments, during the 1970s and 1980s, smog levels in the LA basin were still notoriously bad; if judged by the 2008 federal ozone standard, they routinely would have violated federal limits on more than 200 days per year. However, the tide had begun to turn. The US EPA assumed broad responsibility for regulating motor vehicle pollution and the automobile industry responded by developing catalytic converters. These devices revolutionised pollution control from vehicle exhaust systems and were installed on new cars beginning in 1975 in order to meet federal exhaust emission standards. Institutional changes within the region also helped: to address transboundary pollution originating in LA, the more inclusive South Coast Air Quality Management District was formed in 1976. It produced the first multi-faceted blueprint for bringing the LA region into compliance with air quality standards over the long term, influencing ambition statewide and beyond. One outcome was that CARB adopted increasingly stringent requirements for reformulated gasoline in the 1990s, lowering emissions of smog precursors.

Marked improvements in regional air quality have resulted from these and other efforts. Peak ozone concentrations are roughly one-third of what they were in the late 1970s and the number of days exceeding the 2008 federal standard has dropped to less than 100. Stage 1 and Stage 2 smog alerts are no longer issued and public health advisories, which are triggered by even stricter thresholds, fell from 107 in 1990 to zero in 2014. Due to declines in PM, it has been estimated that the life expectancy of the average LA inhabitant is now about 20 months longer than in 1970 (Greenstone, 2015). Yet, as will be evident, major challenges remain. The LA basin is still in "extreme" non-attainment status for ozone (8-hour) and "moderate" and "serious" non-attainment for $PM_{2.5}$ (annual and 24-hour, respectively). Complying with the 2015 revised federal ozone standard of 70 ppb by the 2030s is one major element in the challenge. The region has opted for a strategy that emphasises reducing $NO_X$ emissions, as these are also important precursors to PM.

## *The outlook for air quality to 2040: the New Policies Scenario*

Meeting the US climate change pledge will require significant changes to the way energy is being produced and used, with profound implications for energy-related air pollution. In the New Policies Scenario in the period to 2040, the use of coal declines by 36% and oil by 26% below today's level, while the use of low-carbon energy forms (including bioenergy) grows rapidly and expands its share in the energy mix by ten percentage points (to 27%). Overall energy demand in 2040 is 3% below today's level as a result of energy efficiency efforts, even though the economy grows by around three-quarters and the population by almost 20% (Figure 4.1).

**Figure 4.1 ▷ Emissions by air pollutant and by energy sector in the United States in the New Policies Scenario**




* Includes transformation (except power generation).

Sources: IEA; International Institute for Applied Systems Analysis (IIASA).

In particular, the power sector is set to decarbonise rapidly with low-carbon technologies increasing their share in power generation from around one-third today to almost 50% by 2040. The principal contribution to reducing energy demand comes from the transport sector, as total fuel consumption falls by 15% below present levels, driven by fuel-economy standards for both passenger and freight vehicles.

Together with specific air pollution policies, these energy trends significantly affect the outlook for air pollutant emissions. $SO_2$ emissions fall by more than 50%, to 2 Mt in 2040, largely driven by changes in the power sector (the main source of $SO_2$ emissions today), where regulatory efforts bring down coal use and increase the share of low-emitting technologies (such as renewables). Similarly, $NO_X$ emissions drop by more than 50%, to 6.2 Mt in 2040, with about two-thirds of the decline achieved in the transport sector. $PM_{2.5}$ emissions fall by 35%, to 0.7 Mt in 2040, with almost half of the decline resulting from reduced oil use in the transport sector and more than one-quarter from lower coal use in power generation.

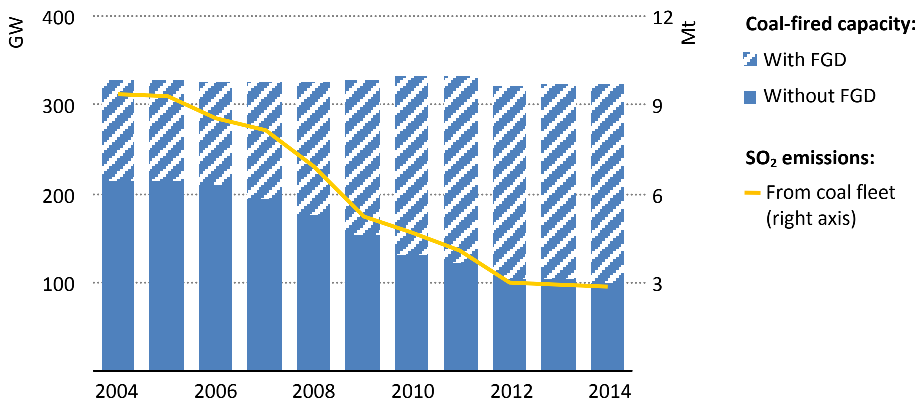


*Outlook for the power sector*

Strong regulatory action underpins the projected significant transformation of the power sector over the outlook period to 2040. In the short term, the Mercury and Air Toxics Standards (commonly known as MATS) motivate much of the ageing coal fleet to either be retired or refurbished with additional control technology. In the longer term, the Clean Power Plan, with its target of reducing $CO_2$ emissions by 32% from 2005 levels in 2030, influences trends in the power sector. In addition, the Carbon Pollution Standard, setting a limit for new plants of 1 400 pounds of $CO_2$ emissions per megawatt-hour (MWh) (about 635 grammes per kilowatt-hour), effectively requires new coal plants to have a $CO_2$ capture unit installed. Policy measures that support renewables, at the federal and state levels, along with other state and regional greenhouse-gas mitigation initiatives, play a major role in achieving long-term goals for both $CO_2$ and air quality in general.

The combination of these policies results in a sharp drop in coal-fired power generation (by around 35%) in the period to 2040. Much of this coal-fired output is displaced by gas-fired plants, which see a strong increase in output. Yet, the strongest increase – both in relative and absolute terms – comes from renewables, which grow two-and-a-half times between today and 2040. While this change in the power mix plays an important role in containing emissions growth over the period, the main driving force is air pollution regulation. The NSPS of the Clean Air Act define emissions limits for power plants: for example, they typically need to comply with a PM limit of 6.4 nanogrammes per Joule (ng/J) (approximately 23 milligrams [mg]/$m^3$) – similar to the limit in China and roughly half that of the European Union. $SO_2$ limits are also dependent on the age of the power plant. Broadly speaking, plants that were built recently or modified are required to comply with the $SO_2$ emissions limit of 65 ng/J (approximately 160 mg/$m^3$). The use of certain low-sulfur coals is expected to allow up to 30% of the fleet to comply with emissions standards without installed $SO_2$ control technology. $NO_X$ standards also depend on the age of the plant, with more stringent standards for recently built stations. $NO_X$ regulation also affects the large combined-cycle gas turbine fleet, with over 40% of the capacity having control technology for $NO_X$ in place today.

**Figure 4.2 ▷ Coal power capacity equipped with flue-gas desulfurisation and related $SO_2$ emissions in the United States**




Note: FGD = flue-gas desulfurisation; GW = gigawatts.

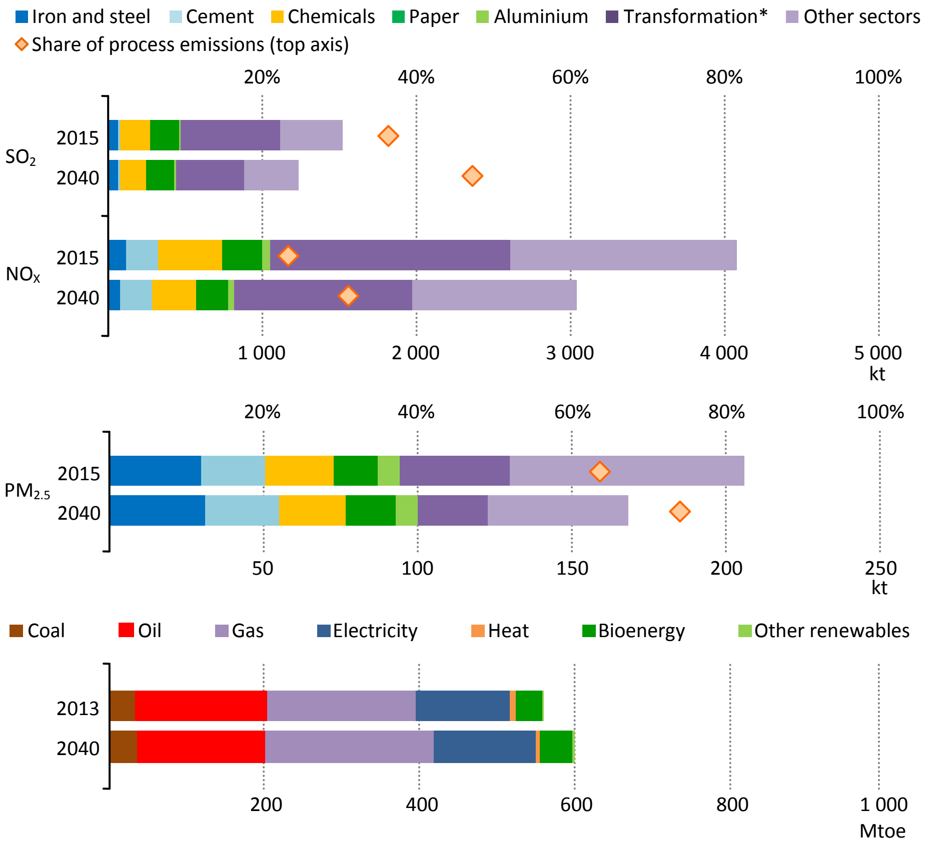
Sources: IEA analysis; US Energy Information Administration; US Environmental Protection Agency.

In the New Policies Scenario, $SO_2$ emissions from power generation drop by more than three-quarters, mostly from reduced coal burn (emissions intensity decreases faster than the drop in output, as the oldest plants, with the highest emissions, are retired first). Much of the reduction is achieved over the medium-term, as some 70 gigawatts (GW) of coal-fired power plants are retired. $NO_X$ emissions decrease by over 40% to 2040. As with $SO_2$, this result is driven by a reduction in coal use, although rising $NO_X$ emissions from additional gas-fired generation moderate part of the decline. $PM_{2.5}$ emissions from power generation are already at a very low level in the United States (the power sector accounts for less than 15% of the $PM_{2.5}$ emissions). Even so, with the reduction in coal-fired power generation and the increase from natural gas and renewable sources, $PM_{2.5}$ emissions from power generation drop by over 80% in the period to 2040. At the end of the period, the power sector is responsible for less than 5% of $PM_{2.5}$ emissions on a nationwide basis.

### *Outlook for the industry and transformation sector*

The United States has registered significant declines in air pollutant emissions from the industry and transformation sector over the past decades, driven by stringent policy interventions. Among the keys to historical (and current) emissions reductions is the National Ambient Air Quality Standards programme (NAAQS). As for the power sector, today's applicable emissions limits for the industry and transformation sector are based on the New Source Performance Standards. For $SO_2$, regulations at state level define the maximum sulfur content for coal and fuel oil use. These regulations are sometimes more stringent in the vicinity of urban areas in order to maximise the reduction of local impacts. In US industrial facilities, flue-gas desulfurisation processes are deployed widely, while primary control measures to reduce sulfur content tend to be employed less. The exceptions are small facilities that cannot afford costly post-combustion control technology devices and therefore may use low-sulfur fuels.

**Figure 4.3 ▷ Air pollutant emissions and energy mix in the industry and transformation sector in the United States in the New Policies Scenario**




Notes: Mtoe = million tonnes of oil equivalent; kt = kilotonnes. * Transformation refers to fossil fuels (e.g. oil refining, oil and gas production, liquefied natural gas terminals), but excludes power and heat generation. The industry and transformation sector includes non-energy uses (mainly petrochemical feedstocks).

Sources: IEA; IIASA.

In the New Policies Scenario, established regulations drive further reductions in emissions from the US industry and transformation sector for all major pollutants (Figure 4.3). $SO_2$ emissions decrease by about 20%, $NO_X$ emissions by one-quarter and $PM_{2.5}$ emissions by almost 20% by 2040, relative to 2015, largely by cuts in combustion-related emissions. The absolute reduction of $NO_X$ emissions is large, as emissions are very high today (more than three-times the level in the European Union). $SO_2$ and $PM_{2.5}$ emission levels are already low, as a result of past efforts: their level today is more comparable to that of Europe. The particular challenge is to further reduce emissions from small manufacturing industries and from the energy transformation sector (other than power generation), in particular refineries, and to control emissions from the growing chemical and petrochemical sectors. Combined, these sectors account for about 80% of $SO_2$ and $NO_X$ emissions from the industry and transformation sector today, and this share is maintained in 2040 in the New Policies Scenario. Energy policy efforts that aim at improving energy efficiency (such as the Energy Star Program for the industry sector or tax incentives for efficient technologies) also help to limit emissions growth in the New Policies Scenario, offsetting the effect of higher production.

### *Outlook for the transport sector*

Tailpipe emissions standards in the United States date back to the federal Clean Air Act of 1963, which directed the government to establish automobile emission standards. The United States was the first country to establish a national framework for controlling the impacts of cars on air quality. Until 2008, US national standards treated separately the emissions from cars in different size categories: small cars of less than 1 700 kilograms (kg), large vehicles of less than about 2 600 kg (including light trucks, minivans and small sport utility vehicles), and vehicles weighing more than 2 600 kg. Today, the standards are generally the same for all light-duty vehicles (labelled "Tier 2"), with a few exceptions. These US standards differ from European regulations by subjecting all vehicles in a given category to the same emission limits, regardless of fuel type.

After many subsequent updates, the US EPA finalised a new phase of vehicle and fuel standards in 2014, labelled "Tier 3" (Table 4.2). Tier 3 standards extend the "useful life" of vehicles[4] beyond previous federal limits (120 000 miles or 10 years) to match the definitions used by the CARB (150 000 miles or 15 years) and also extend the light-duty vehicle (LDV) emissions standards to some vehicle classes that had previously been subject to standards for heavy-duty vehicles (HDVs). Tier 3 will be phased in over the period 2017-2025 and is expected to reduce per kilometre emissions of volatile organic compounds (VOCs) and $NO_X$ over the vehicle's useful life by 80% and of PM by 70% (ICCT, 2014).

Emissions regulation for HDVs has tended to lag slightly behind that for LDVs; the most recent standards were put in place between 2007 and 2010. The 2010 standards remain in place and, to date, no new standards have been proposed to replace them. In terms of ultra-low sulfur diesel, a limit of 15 parts per million (ppm) sulfur was mandated in 2007 as

[4] The "useful life" mandates the minimum distance or time over which emissions standards must be met. Compliance and enforcement programmes were set up to ensure that in-use emissions meet this requirement in the United States.

a way to encourage the adoption of tailpipe emissions control technologies that require very lower sulfur fuels (e.g. catalytic diesel particulate filters and $NO_X$ catalysts). Sulfur in gasoline will be limited to 10 ppm, bringing this fuel quality requirement into line with Europe, Japan and Korea.

**Table 4.2 ▷ Emissions limits for selected air pollutants in road transport in the United States**

| Target | Fuel | Standard | Implementation for all sales and registrations | PM limit | $NO_X$ limit | Sulfur limit | Unit |
|---|---|---|---|---|---|---|---|
| **LDVs** | Gasoline/ diesel | EPA Tier 2 | 2009 | <0.02 | 0.07** | - | g/mile |
| | | EPA Tier 3 | 2017-2025* | 0.003 | 0.030-0.086 | - | g/mile |
| **Motorcycle** | Gasoline/ diesel | EPA 2010+ | after 2010 | - | 0.8*** | - | g/km |
| **Heavy-duty vehicles** | Gasoline/ diesel | EPA 2010 | 2010 | 0.01 | 0.2 | - | g/bhp-hr |
| **Fuel quality** | Gasoline | EPA Tier 2 | 2007 | - | - | 30 | ppm |
| | | EPA Tier 3 | 2017 | - | - | 10 | ppm |
| | Diesel | EPA Tier 2 | 2007 | - | - | 15 | ppm |

* The regulation for fleet average limits for $NO_X$ will become more stringent over time from 2017 to 2025. ** Reflects the regulation limit for Bin 5 that represents the fleet average requirement among the stringency categories (Bins 1-8). *** Applies to manufacturer average emissions of HC+$NO_X$.

Notes: g/mile = grammes per mile; g/km = grammes per kilometre; g/bhp-hr = grammes per brake horsepower-hours.

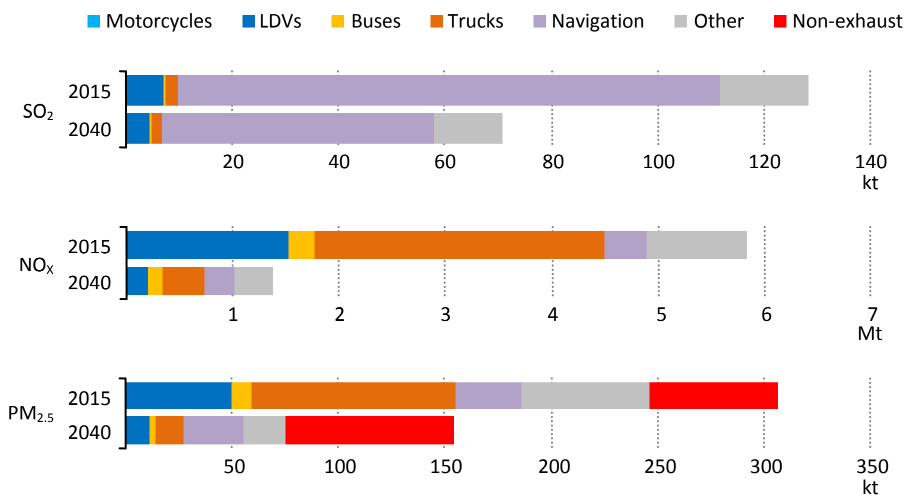
In the United States, transport contributes nearly half of all energy-related $NO_X$ emissions today (Figure 4.4). More than one-quarter of transport $NO_X$ emissions comes from LDVs and about half from HDVs (in particular trucks), with much of the remainder coming from rail and shipping at a combined 20%. In the New Policies Scenario, transport-related $NO_X$ emissions are substantially reduced in the period to 2040. Transport oil demand declines from around 12 million barrels per day (mb/d) today to about 8 mb/d in 2040, mostly as a result of fuel-economy standards, as the uptake of alternative fuels remains limited (electric cars make up around 10% of LDV sales in 2040 and the use of natural gas accounts for only 10% of total road transport fuel consumption). However, current and forthcoming pollutant emissions regulations reduce transport-related $NO_X$ emissions considerably, from 5.8 Mt in 2015 to around one-quarter of this level by 2040. About half of these reductions are realised through emissions control of trucks, reflecting their dominance in total emissions today. Much of the remaining reduction comes from the LDV fleet.

Tailpipe emissions standards are similarly effective in reducing transport emissions of $PM_{2.5}$. Transport currently contributes around 30% of total energy-related $PM_{2.5}$ emissions, about 20% of which arise from non-exhaust emissions from driving (i.e. abrasion, brakes and tyres). By 2040, transport-related $PM_{2.5}$ emissions are cut in half in the New Policies

Scenario. More than half of tailpipe emissions reductions from road vehicles are from freight trucks and one-fourth from LDVs: the latter reduction has a disproportionately high benefit for human health, because more than 70% of road passenger vehicle-kilometres are driven in urban areas by 2040, up from around two-thirds today (less than half of road freight activity takes place in densely populated urban regions). As a consequence of effective tailpipe control of $PM_{2.5}$, the share of non-exhaust $PM_{2.5}$ emissions in all transport-related $PM_{2.5}$ emissions grows to more than half by 2040.

Transport-related $SO_2$ emissions contribute only 3% to energy-related $SO_2$ emissions today. They arise largely from domestic shipping. As a result of US regulations that will encourage the reduction of sulfur concentration in automotive fuels to the level set by the global leaders, $SO_2$ emissions from transport decline by about 45% in the New Policies Scenario.

**Figure 4.4 ▷ Air pollutant emissions by transport type in the United States in the New Policies Scenario**

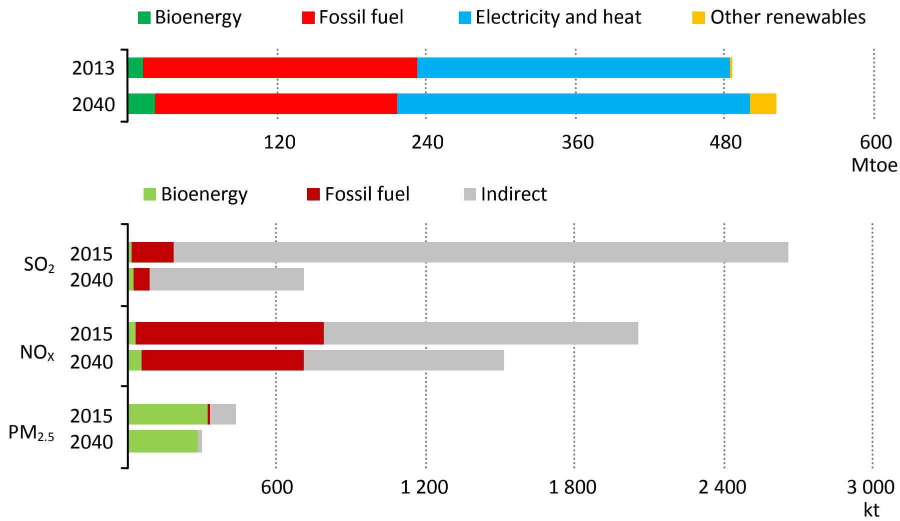



Sources: IEA; IIASA.

### *Outlook for the buildings sector*

In the United States, space and water heating account for around 60% of energy demand in the buildings sector. The combustion of fossil fuels in boilers and stoves emit $NO_X$ and $SO_2$ (and, to a lesser extent, $PM_{2.5}$). Buildings account for only a small share of $SO_2$ emissions, compared with power generation and industry, having decreased by a factor of four over the last two-and-a-half decades, even though oil consumption decreased by only one-third. Similarly, since 1990, natural gas use in the buildings sector to satisfy heating and cooking needs has remained relatively flat, while $NO_X$ emissions decreased by around half and account for only about 6% of energy-related $NO_X$ emissions today. By far the largest source of $PM_{2.5}$ emissions in the buildings sector is the use of bioenergy, although it accounts only for 5% of heating in buildings today, while oil accounts for around 10% and natural gas for two-thirds; the amount of $PM_{2.5}$ emitted by the buildings sector is equivalent to that of the industry and power sectors combined. To address this, in 2015 US EPA released an update of its New Source Performance Standards for residential wood burning equipment. The new NSPS strengthens standards for new woodstoves and establishes the first federal air standards for several types of previously unregulated wood heaters and includes pellets stoves. The new standards do not apply to existing equipment. The main aim is to reduce PM emissions. Other pollutants are also expected to be reduced. Until 2020, new woodstoves (including those types that were exempt from US EPA's 1988 NSPS for Residential Wood Heaters) will have to meet the PM emissions limits currently set by the State of Washington for non-catalytic stoves (4.5 grammes per hour). By 2020, woodstoves will have to meet higher limits (2 grammes per hour). In the meantime, woodstoves can qualify for the voluntary hangtag programme if they already meet the 2020 requirements.[5] US EPA has also put in place the voluntary Indoor airPLUS labelling programme based on the Energy Star requirements for new homes, in order to provide indoor air quality protection.

**Figure 4.5 ⊳ Energy demand in buildings and related pollutant emissions by fuel in the United States in the New Policies Scenario**




Sources: IEA; IIASA.

Pollutant emissions in the buildings sector decline by 2040 in the New Policies Scenario, although $NO_X$ and $PM_{2.5}$ reductions are not as marked as those achieved in other sectors. The decrease of $SO_2$ and $NO_X$ pollutants in the buildings sector is mostly due to energy

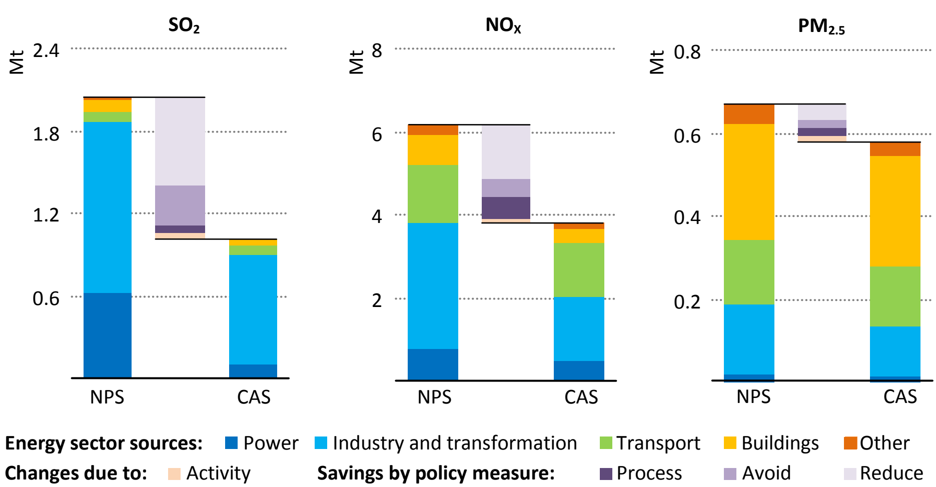
[5] The voluntary hangtag programme for wood-burning devices is a labelling programme designed to provide an incentive to manufacturers to meet the federal 2020 standards earlier.

efficiency policies and a switch to renewables and electricity, while $PM_{2.5}$ emissions decrease as a result of the NSPS. Even though the number of households increases by around 20%, relative to today, and the heated floor area by 35%, heating demand remains flat due to improved insulation and more efficient boilers and stoves as a result of the Energy Star Program. As oil demand to satisfy heating requirements decreases, $SO_2$ emissions continue to fall, to half their current level by 2040 (Figure 4.5). Natural gas demand in the buildings sector slightly decreases, but this leads to only a small decrease of $NO_X$ emissions. The share of the buildings sector in total energy-related $NO_X$ emissions (currently 6%) increases to 11% by 2040. While bioenergy used in wood heaters grows, the new NSPS help to decrease slightly the $PM_{2.5}$ emissions currently associated with their use. However, the overall share of buildings in total energy-related $PM_{2.5}$ emissions grows by 11 percentage points, to more than 40% by 2040. Although electricity and heat demand in the buildings sector increases by 13% to 2040, indirect emissions related to electricity use in buildings decrease for all pollutants by 2040, as a result of pollutant emissions regulation applicable to the power sector.

## *Improving the outlook for air quality to 2040: the Clean Air Scenario*

While longstanding efforts have delivered significant results in reducing air pollutant emissions and more progress from existing and proposed measures are foreseen in the New Policies Scenario, the United States can achieve further cuts in energy-related air pollution. In the Clean Air Scenario, $SO_2$ emissions fall by 50% below the level reached in the New Policies Scenario by 2040, saving an additional 1 Mt of emissions (Figure 4.6). $NO_X$ emissions fall by around 40%, saving an additional 2.4 Mt in 2040, while $PM_{2.5}$ emissions drop by around 15% to 90 kilotonnes below the level of the New Policies Scenario.

**Figure 4.6 ▷ Pollutant emissions savings by measure in the United States in the Clean Air Scenario relative to the New Policies Scenario, 2040**



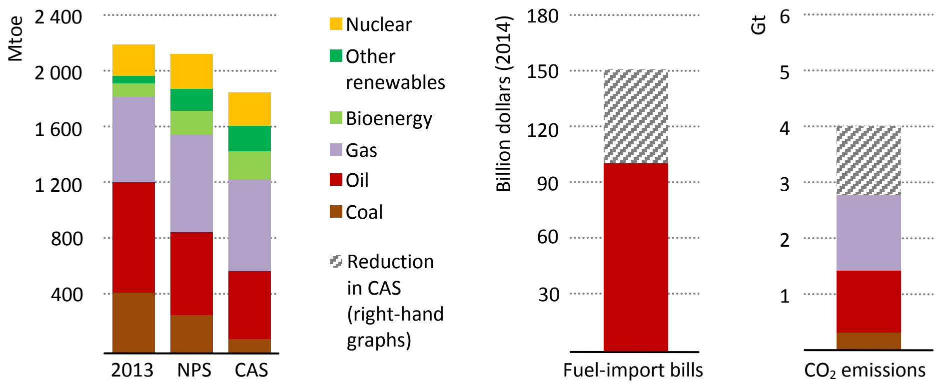

Source: IEA; IIASA.

Pollutant emissions savings are achieved across all sectors in the Clean Air Scenario. Despite the already significant decline in $SO_2$ emissions from the power sector under existing and planned policies, half of the additional savings in the Clean Air Scenario are obtained in power generation, partly through reducing emissions by the use of post-combustion control technologies, and partly through avoiding emissions by further reducing coal use and increasing investment in renewable energy technologies. The industry and transformation sector contributes another 35% to lower $SO_2$ emissions, mainly through reducing emissions intensity. Increasing energy efficiency plays an import role if avoiding $SO_2$ emissions in the chemicals, refining and paper industries.

The industry and transformation sector is also the main contributor to additional $NO_X$ emissions savings in the Clean Air Scenario, contributing around almost two-thirds of the reduction, relative to the New Policies Scenario. In particular, further savings are achieved by limiting emissions in refining (by increasing energy efficiency) and reducing emissions in the chemical and cement industries (by improving post-combustion treatment). $NO_X$ emissions are also cut in buildings (15% of total savings in the Clean Air Scenario), including both in commercial and residential buildings, largely by reducing emissions from the use of gas for heating purposes. In the power sector (12% of total $NO_X$ savings), increasing post-combustion control technologies, raising renewables investment and reducing coal use are the main route to further savings. Given the strong decline in transport $NO_X$ emissions already in the New Policies Scenario, further reductions are more difficult to achieve and are linked to reduced traffic movements and increasing the uptake of alternative fuel vehicles.



**Figure 4.7 ▷ Energy demand and energy sector key indicators in the United States by scenario, 2040**




Note: NPS = New Policies Scenario; CAS = Clean Air Scenario.

$PM_{2.5}$ emissions are further reduced in all sectors in the Clean Air Scenario, relative to levels in the New Policies Scenario. The largest savings in the industry and transformation sector (which accounts for almost half of total $PM_{2.5}$ savings relative to the New Policies Scenario) come from the iron and steel industry, at around one-quarter of the total savings. The buildings sector is responsible for just below 20% of total $PM_{2.5}$ savings, largely as a result of further reducing emissions from biomass stoves. In the transport sector (12% of $PM_{2.5}$ savings), reducing non-exhaust emissions from the driving of automobiles contributes almost two-thirds of the total transport-related savings, mainly through avoiding and shifting traffic to other modes.

Pursuing energy and air quality strategies together brings important co-benefits. By 2040, demand for all fossil fuels is lower in the Clean Air Scenario than in the New Policies Scenario, reducing the associated oil-import bill (Figure 4.7). Oil demand falls by 1.9 mb/d in 2040, relative to the New Policies Scenario, natural gas demand by around 50 billion cubic metres (bcm) and coal demand by 255 million tonnes of coal equivalent (Mtce). The combination of these policies also helps facilitate US climate change goals: in the Clean Air Scenario by 2040, $CO_2$ emissions are around 1.1 gigatonnes lower than in the New Policies Scenario.

# Mexico

## Highlights

- Air pollution is a significant problem in Mexico, both in its urban agglomerations and in rural areas, where reliance on biomass for cooking and other energy uses falls outside the usual patterns among OECD member countries. The situation is compounded by geography: the high altitude of Mexico's largest cities means low levels of atmospheric oxygen that exacerbate incomplete fuel combustion. Mexico highlighted air quality as a main impetus behind its climate pledge for COP21 and set one of the most aggressive targets for reducing black carbon emissions.
- Despite a 30% increase in energy demand to 2040, air pollutant emissions in Mexico do not show a commensurate rise in our projections, with $SO_2$ emissions falling by half. This decoupling stems from a combination of policies to control air pollution emissions, fuel switching (particularly in power generation) and increasing efficiency. $NO_X$ emissions fall by 30% and $PM_{2.5}$ emissions by nearly 15%. However, the impact of air pollution on health persists, with the number of premature deaths attributable to outdoor air pollution rising from 12 500 cases per year today to 15 500 in 2040, and those from household air pollution declining only modestly to 12 200 cases in 2040.
- Mexico has the opportunity – using tried and tested measures – to make further improvements to air quality beyond those seen in the New Policies Scenario. By promoting access to clean cooking and adopting more stringent emissions standards in transport, the Clean Air Scenario leads to drastic improvements. The industry, power and transport sectors contribute to a 60% drop in total $NO_X$ emissions relative to the New Policies Scenario, while further success in providing access to clean cooking helps to reduce $PM_{2.5}$ emissions by around 65%. In aggregate, these reductions deliver significant health benefits: the number of premature deaths associated with air pollution in the New Policies Scenario is halved by 2040, while the average life expectancy increases by almost two months in 2040 in the Clean Air Scenario relative to the New Policies Scenario.

### *The energy and air quality context*

Local air pollution has been a top priority for energy and health policy makers in Mexico since the early 1990s when Mexico City was cited as having the worst air quality of any city in the world. This was the culmination of decades of industrialisation and urbanisation, which saw the urban population expand from around 12 million in 1950 to almost 100 million in 2015. But it also reflected the energy choices made to meet burgeoning demand: for example, by 1990, Mexico was still using oil to generate more than half of its electricity.

In response to a growing problem that was taking an increasing toll on public health, the government introduced a large number of policies and controls. The General Law of Ecological Balance and Environmental Protection (LGEEPA) is the overarching legal framework for air quality improvement. It assigns responsibility for implementing programmes to reduce emissions to the federal government, which operates by allowing local authorities to design their air quality programmes and submit them to the Ministry of Environment (SEMARNAT). The primary policy, PROAIRE, currently covers 13 metropolitan regions – the country's major urban centres. The content of each PROAIRE differs according to the region in which it was designed, but consistently contains three components:

- Monitoring of pollutants.
- Annual vehicle emissions testing (with cars that fall below a certain standard permitted to be used on only 4-out-of-5 work days).
- A contingency plan for periods of peak pollution that might include a rotating ban on private car use and require some manufacturing activity to cease on days of particularly high pollution.

These programmes have had a significant impact: in Mexico City, sulfur dioxide ($SO_X$) and nitrogen oxides ($NO_X$) emissions are nearly three-times lower today than they were in 1992 (Ireland, 2014). Despite the improvements, a number of Mexico's largest cities still have annual average $PM_{2.5}$[1] levels that far exceed the objective set by the World Health Organization (WHO). The WHO guideline is a maximum of 10 micrometres (µm) per cubic metre ($m^3$) and both Mexico City and Monterrey average more than twice this level. This can be explained, in part, by the fact that three of its five largest cities, including Mexico City, are at an elevation higher than 2 000 metres. At this altitude, atmospheric oxygen levels can be up to one-quarter lower than at sea level, contributing to the incomplete combustion of fuels. This leads to higher particulate matter (PM) and carbon monoxide emissions from cars and trucks and partially accounts for the fact that Mexico's transport sector has a PM emissions factor that is double that of the OECD average. The government is well aware of the problem. In its climate pledge to COP21, Mexico highlighted air quality as one major consideration underlying its targets. It has set one of the most aggressive targets in the world for reducing black carbon emissions (a component of $PM_{2.5}$), pledging to reduce such emissions by 51% by 2030 compared with a business-as-usual scenario. The pledge also sets out a target to increase the share of low-carbon sources for power generation to 43% (from 21% in 2015), which promises to reduce air pollution from the power sector.

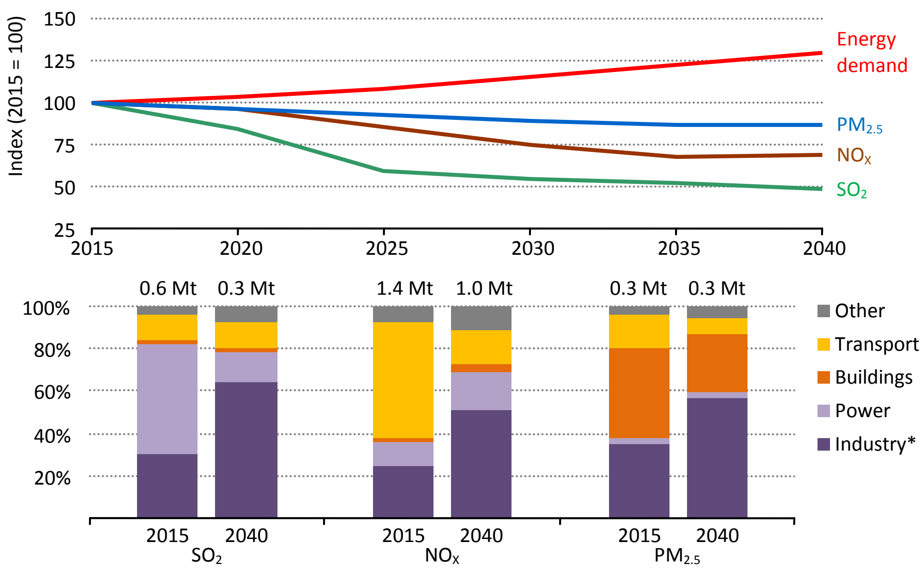
[1] Fine particulate matter with particle diameter smaller than 2.5 micrometres.

## *The outlook for air quality to 2040: the New Policies Scenario*

With rising incomes and population, energy demand in Mexico is expected to increase by about one-third above current levels by 2040.[2] Today's energy sector in Mexico is unique in that oil makes up more than half of total energy demand and natural gas another third, while coal plays a relatively minor role (7%) compared with other countries. The strong policy push expressed through existing regulation and the climate pledge made at COP21 will help to diversify this energy mix, in particular by increasing the use of renewables. The effects of government action can already be seen in declining $SO_2$ emissions, in particular, and our projections in the New Policies Scenario show a strong decline in oil-based power generation, helping to cut overall $SO_2$ emissions from the energy sector by half by 2040 (Figure 5.1). Other pollutant emissions also decrease in our projections. Despite a continued rise in demand for mobility and industrial activity, $NO_X$ emissions fall to 1.0 million tonnes (Mt) by 2040, a decrease of one-third below today's level, while $PM_{2.5}$ emissions decrease only modestly to almost 15% below today's level, as declines in emissions from the buildings and transport sectors are partially offset by increases in the industry and transformation sector.

5

**Figure 5.1 ▷ Emissions by air pollutant and by energy sector in Mexico in the New Policies Scenario**




* Includes transformation (except power generation).

Sources: IEA; International Institute for Applied Systems Analysis (IIASA).

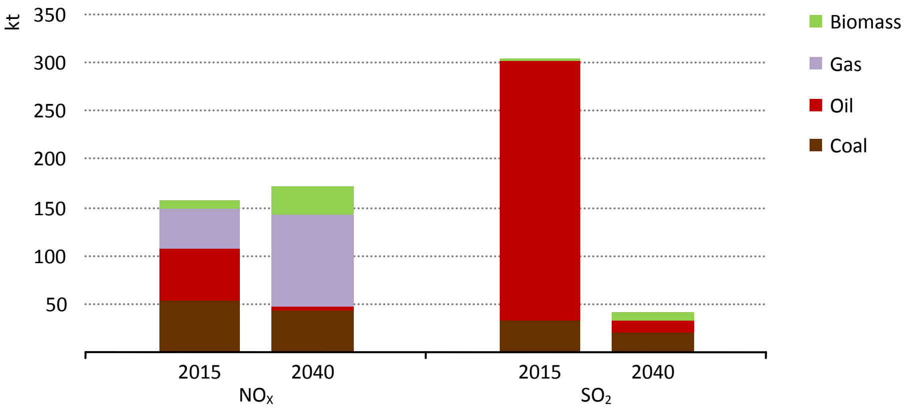
[2] The *World Energy Outlook-2016*, to be released on 16 November 2016, will feature an in-depth analysis of the prospects of the energy sector of Mexico.

### *Outlook for the power sector*

Recently implemented reform shapes the outlook for Mexico's power sector by facilitating the necessary investments to meet growing electricity demand, propelling a transition away from oil (oil-fired power plants currently account for some 15% of power output and produce almost 90% of the sector's $SO_2$ emissions) and lowering overall system cost. Mexico's electricity demand grows by almost 200 terawatt-hours (TWh) over the *Outlook* period to 2040 as household power demand, e.g. for air-conditioning, electric appliances and cooking, doubles and industrial power consumption increases by almost 60%. With coal contributing only around 10% to Mexico's power generation today, dust emissions from power plants, measured at the country level, are not a major issue. In terms of $NO_X$ emissions, around one-third stems from coal-fired and another third from oil-fired power plants, with natural gas contributing just over one-quarter. The remainder of power plant $NO_X$ emissions come from biomass-fired power plants. In 1994-1996, Mexico established limits for $SO_2$, $NO_X$ and $PM_{2.5}$ emissions from new and existing power plants. They have not been updated and they now represent the high-end of the allowable emissions range compared with regulations in many other OECD countries. For example, the limit for $SO_2$ in Mexico is almost ten-times as high as that in the United States.

The outlook for air pollutant emissions is largely determined by the overarching changes planned for the power sector. In its energy sector reform package, the Mexican government has outlined a plan to shift entirely away from oil-based power generation, giving preference to natural gas and renewables. This transformation is already underway: the share of oil in power generation has fallen by ten percentage points since 2005. In the New Policies Scenario, oil-fired power generation virtually disappears by 2040, underpinning a drop of $SO_2$ emissions in the power sector of nearly 90% (Figure 5.2). Gas-fired generation increases by three-quarters between today and 2040, with an additional 40 gigawatts (GW) of combined-cycle gas turbines coming online over the projection period. $NO_X$ emissions from gas-fired generation more than double over the *Outlook* period, offsetting, in absolute terms, the decline in $NO_X$ emissions from oil-fired power plants as the stringency of standards for $NO_X$ emissions from gas-fired power generation is assumed to remain lax outside of critical areas, such as Mexico City. The combined share of renewables (without biomass) and nuclear doubles from 17% today to over 35% in 2040, meeting the bulk of additional power demand without adverse effects on air quality. In light of the strong decline in $SO_2$ emissions and Mexico's relatively minor use of coal-fired power generation, policy action to set stringent emission levels may generally appear to be less pressing than in other countries; but where power plants are located in the vicinity of urban communities, the main impact of pollutants on air quality is felt locally and will require policy attention.

**Figure 5.2 ▷ Air pollutant emissions of $NO_X$ and $SO_2$ from power generation by fuel in Mexico in the New Policies Scenario**




Note: kt = kilotonnes.

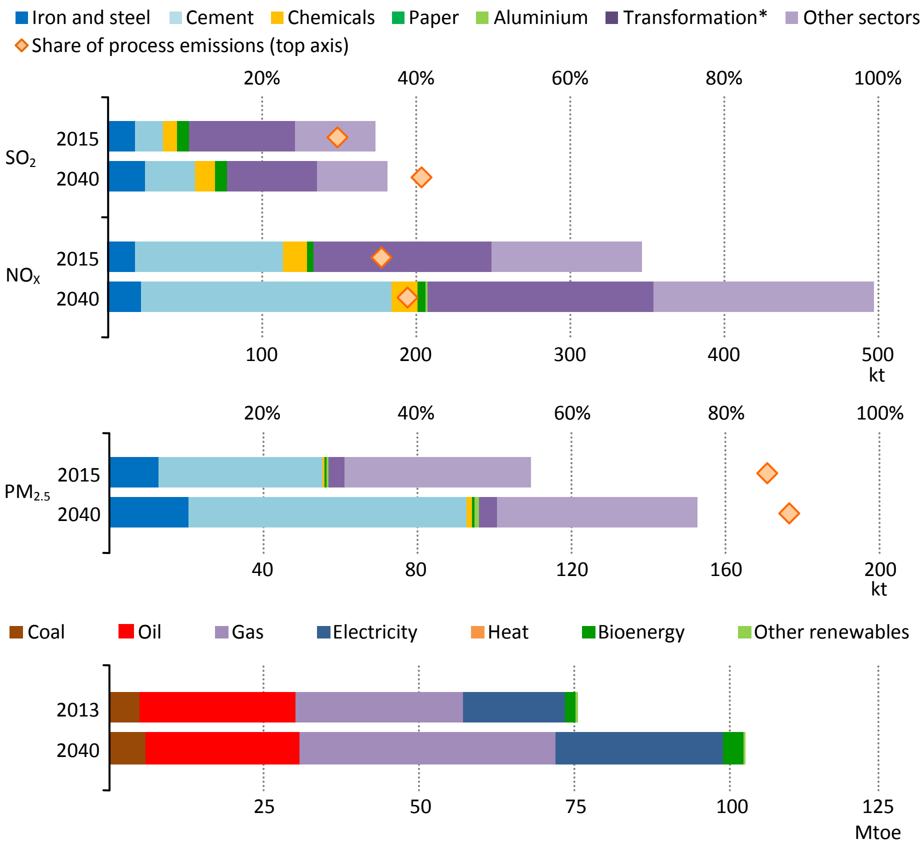
Sources: IEA; IIASA.

## *Outlook for the industry and transformation sector*

Mexico first established emissions standards for air pollutants from industrial combustion plants in 1994; the latest revision, in 2012, incorporated stricter $SO_2$ emission limits. The emission limits for $SO_2$, $NO_X$ and PM depend on the nominal thermal capacity of industrial facilities. One key feature of the Mexican legislation is that emission limits vary according to the plant location, with three different levels of stringency, according to population density and other considerations. Limits are far more stringent in highly populated areas, like Mexico City, than in other areas. For example, the PM limit is almost six-times higher in the Mexico City metropolitan area than in the rest of the country. There are also specific regulations for petroleum refining processes and plants manufacturing sulfuric acid or cement.

These stricter $SO_2$ emissions regulations and planned energy policies help stabilise industry-related $SO_2$ emissions in the New Policies Scenario (Figure 5.3). Despite the regulations in place and the additional energy efficiency policies assumed to be adopted, industry-related $NO_X$ and PM2.5 emissions rise by over 40% by 2040. The cement sector, by some distance, is the largest contributor to this increase, as cement production increases by more than 80% by 2040 in the New Policies Scenario. Non-energy intensive industries also contribute to $NO_X$ emissions growth, due to an increase in the use of natural gas in small- and medium- enterprises.

**Figure 5.3** ⊳ **Air pollutant emissions and energy mix in the industry and transformation sector in Mexico in the New Policies Scenario**




Notes: Mtoe = million tonnes of oil equivalent; kt = kilotonnes. * Transformation refers to fossil fuels (e.g. oil refining, oil and gas production, liquefied natural gas terminals), but excludes power and heat generation. The industry and transformation sector includes non-energy uses (mainly petrochemical feedstocks).

Sources: IEA; IIASA.

## *Outlook for the transport sector*

In the transport sector, measures have evolved from the definitive phase-out of lead in gasoline (1997) and the introduction of three-way catalytic converters in new gasoline cars (1993) to the comprehensive standards introduced in 2004 that set $NO_X$ and $PM_{2.5}$ emissions limits based on a mix of US Tier 1/2 and Euro 3/4 standards.[3] In the Mexican regulatory system, vehicle manufacturers are given the option of choosing compliance

[3] See the country profiles for the United States (Chapter 4) and the European Union (Chapter 6) for more detail.

testing under either the United States or the European Union (EU) standards. In both instances, limit values and emission durability requirements (obliging vehicles to comply with emissions limits for a certain period beyond the time of sale) differ somewhat from the original US and EU regulations. A gradual phase-in schedule progressively raised the stringency for different model years of regulated vehicles from 2004-2007 ("Standard A") to 2010 ("Standard C").

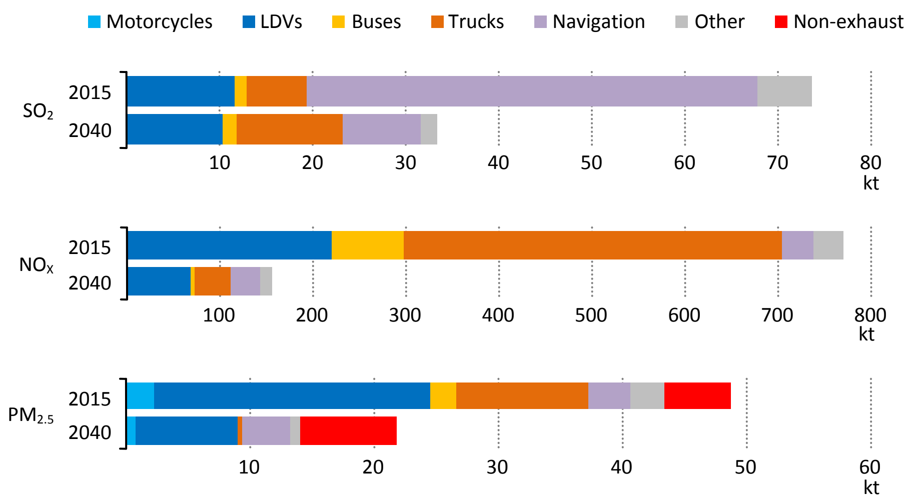
For heavy-duty vehicles (HDVs), emissions standards were adopted in 2006, and by 2008, these were set to require compliance with either US 2004 or EU IV standards. However, the timeline for compliance was extended in June 2014. Modifications to the standards, passed in 2015, set a timetable for adoption of standards equivalent to either US EPA 2010 or Euro VI (Euro 6 for medium-duty vehicles) in 2018, leaving the choice of standard to be applied still at the discretion of the regulated bodies.

In tandem with tailpipe emissions standards, Mexico set a timeline for the adoption of stricter fuel quality limits. By 2009, sulfur concentration in gasoline was required to be reduced from 1 000 parts per million (ppm) to 30 ppm on average (and 80 ppm maximum) and sulfur in diesel was not to exceed 15 ppm. However, this timeline was not met and the government has since reinvigorated its ambitions by announcing similar standards for gasoline, which came into effect in January 2016. Efforts were also made in late 2015 to unify the specifications for ultra-low sulfur diesel, by forming 11 "national distribution corridors" to which the existing limit of 15 ppm, enforced in Mexico City, Guadalajara and Monterrey, would be extended. Mexico plans to bring the nationwide specification down to this level (from 500 ppm) by July 2018. In an effort to further facilitate a move towards low-sulfur fuels, the government has announced reforms that will grant import permits for gasoline and diesel to any interested importers.

Apart from vehicle and fuel standards, the Mexican government is seeking to reduce the distance travelled by city residents by means of an alternative urban design to the pattern so prevalent in the 1980s and 1990s when the most populous cities became more dispersed while expanding in size. The hope is that higher population density will reduce the length of journeys by private road users and also make public mass transit more attractive.

Transport is the main contributor to $NO_X$ emissions in Mexico today, making up around 55% of total energy-related $NO_X$ emissions. In the New Policies Scenario, full implementation of the pollution norms for cars and HDVs reduces $NO_X$ emissions from transport considerably, by 80% in 2040 (Figure 5.4). The share of transport in overall $NO_X$ emissions drops to around 15% in 2040 as the pace of decline in transport emissions is faster than in other sectors, given the stringency of the norms. Emissions of $PM_{2.5}$ drop by more than 50%, almost wholly achieved in road transport, as emissions from other sectors remain stable. $SO_2$ emissions, which come mainly from maritime traffic today, are cut by more than half through the adoption of fuel quality regulation. Tougher regulation also brings down the $SO_2$ emissions of HDVs, although the net effect is still an increase, as activity grows even more strongly.

**Figure 5.4 ▷ Air pollutant emissions by transport type in Mexico in the New Policies Scenario**




Note: LDV = light-duty vehicles.

Source: IEA; IIASA.

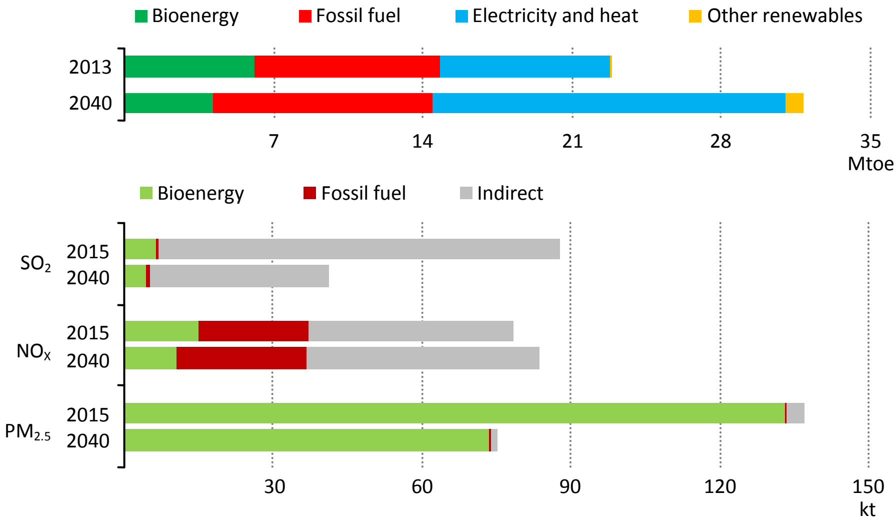
### *Outlook for the buildings sector*

Mexico is one of the only countries in the OECD in which biomass use in cooking is still significant: around half of rural households (13 million people) rely on firewood or charcoal as their primary fuel for cooking. Yet improvements have been made: the number of people using cleaner fuels has increased by 1.9% per year over the last 25 years, well beyond the rate of growth of population and per-capita income, which both rose by 1.3% per year on average. Despite this progress, the high reliance on solid fuel use in rural areas means the residential sector contributes over 40% of total $PM_{2.5}$ emissions today.

Government policies to bring natural gas infrastructure to cities yield success in the New Policies Scenario, with urban households increasingly switching from liquefied petroleum gas (LPG) to natural gas. Gas increases its share in energy consumption in buildings from 4% today to 11% in 2040. Rural areas benefit as the LPG no longer required in cities is made available to displace some of the biomass. People in remote areas still rely on free solid biomass, but the increasing use of improved cookstoves, which have higher efficiencies and lower $PM_{2.5}$ emission intensities, helps to alleviate some of the associated problems.

Emissions of all three pollutants from the buildings sector decrease, supported mainly by the switch away from the traditional use of solid biomass to more modern and efficient forms of energy. This transition offsets the increase of $SO_2$ and $NO_X$ emissions from higher use of natural gas in heating and cooking stoves (Figure 5.5). Although electricity demand doubles to 2040, indirect emissions of both the $SO_2$ and $PM_{2.5}$ related to electricity production decrease by around 55-70%, while indirect $NO_X$ emissions increase by only 14% by 2040 as the power sector increasingly switches away from oil. Growth in electricity demand – to serve increasing demand for space cooling and appliances (refrigerators and washing machines) – is moderated by energy efficiency programmes.

**Figure 5.5 ▷ Energy demand in buildings and related pollutant emissions by fuel in Mexico in the New Policies Scenario**




Sources: IEA; IIASA.

## *Improving the outlook for air quality to 2040: the Clean Air Scenario*

Mexico has the opportunity to reduce air pollution beyond the level reached in the New Policies Scenario. Underpinned by effective policies promoting access to clean cooking, as well as more stringent emissions standards in the industry and transformation sector, air quality improves significantly in the Clean Air Scenario, with important consequential improvements in health of the population across the country. In the Clean Air Scenario, both Mexico's urban and rural populations benefit: the proportion of the population enjoying air quality compatible with the WHO guideline of pollution below 10 micrometres per cubic metre ($\mu g/m^3$) increases from around 50% today to around 85% in 2040 (compared with 62% in the New Policies Scenario) (Figure 5.6).





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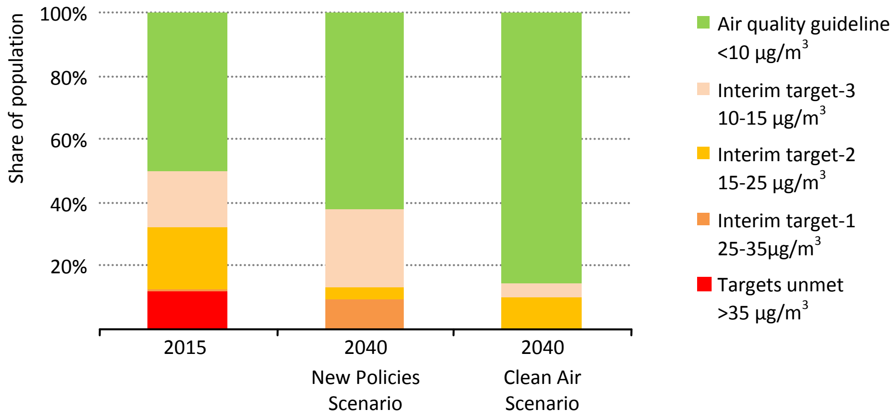
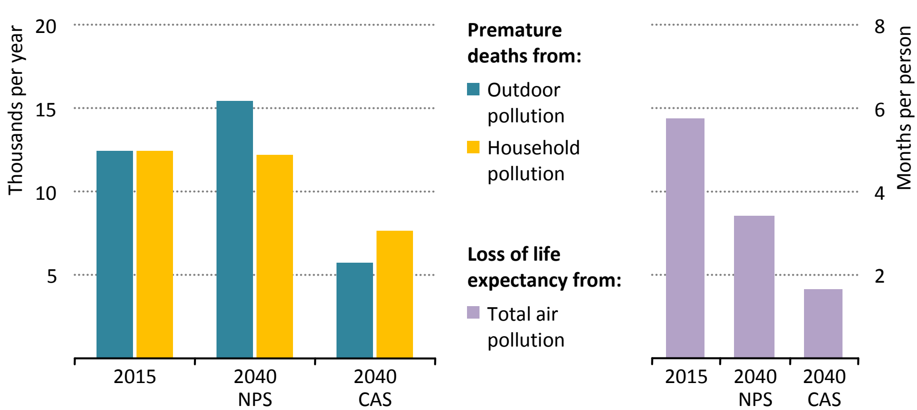
**Figure 5.6 ▷ Population in Mexico exposed to different $PM_{2.5}$ concentration levels according to WHO targets, by scenario**




Source: IIASA.

The improvements in air quality achieved in the Clean Air Scenario considerably reduce the negative effects of energy-related air pollution on people's lives (Figure 5.7). The number of premature deaths caused by outdoor air pollution in 2040 in the Clean Air Scenario falls by more than 50% compared with today, to 5 700 per year, more than 60% lower than the level achieved in the New Policies Scenario. Premature deaths associated with household air pollution (mainly due to the use of solid biomass in rural areas) are almost 40% lower than today, at 7 700 cases per year in 2040 in the Clean Air Scenario (compared with 12 200 cases in the New Policies Scenario). These improvements are also linked to longer lives: average life expectancy increases by almost two months in 2040 in the Clean Air Scenario compared with the New Policies Scenario.

**Figure 5.7 ▷ Premature death cases and loss of life expectancy in Mexico by scenario**

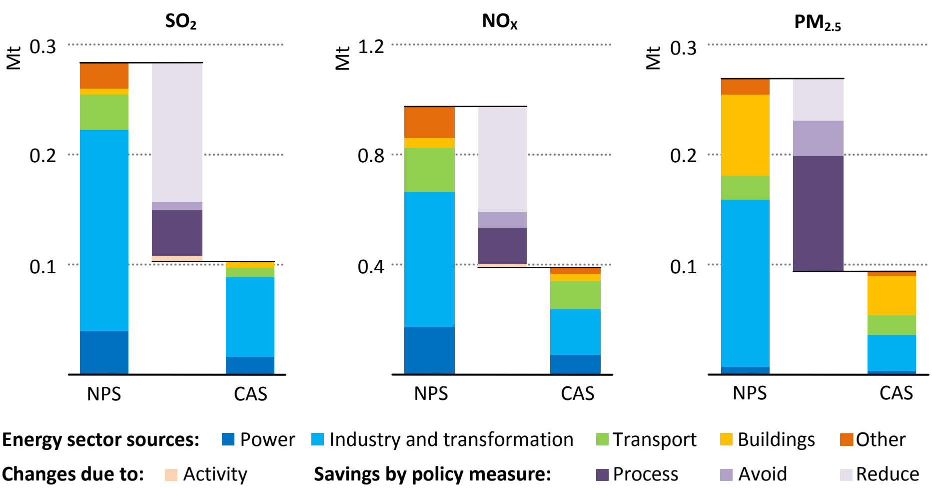



Note: NPS = New Policies Scenario; CAS = Clean Air Scenario.

Source: IIASA.

$PM_{2.5}$ emissions fall to around 90 kilotonnes (kt) in 2040 in the Clean Air Scenario, about two-thirds below the level reached in the New Policies Scenario (Figure 5.8). The reduction in $PM_{2.5}$ is achieved through more stringent emissions standards in the industry and transformation sector, which contribute around 65% of the decrease in $PM_{2.5}$ emissions, relative to the New Policies Scenario. Many of the gains are captured in the first ten years to 2025, as the problems of polluting processes, notably in the cement industry, can be addressed early through increased investment and plant upgrades. A further 20% reduction in $PM_{2.5}$ emissions is achieved through policies affecting the residential sector, which reinforce the proliferation of clean cookstoves and the partial switch from solid biomass to LPG in rural areas. The infrastructure requirement to facilitate this latter switch, including laying distribution pipelines in areas that currently do not have them means that a large part of the improvement in household air quality is only achieved after 2025. Transport is another contributor to $PM_{2.5}$, reductions with emissions from the sector reduced by one-third in 2040, relative to the New Policies Scenario. Much of the additional improvement is achieved early through the imposition of more stringent emissions standards to what is a rapidly evolving vehicle fleet.

**Figure 5.8 ▷ Pollutant emissions savings by measure in Mexico in the Clean Air Scenario relative to the New Policies Scenario, 2040**

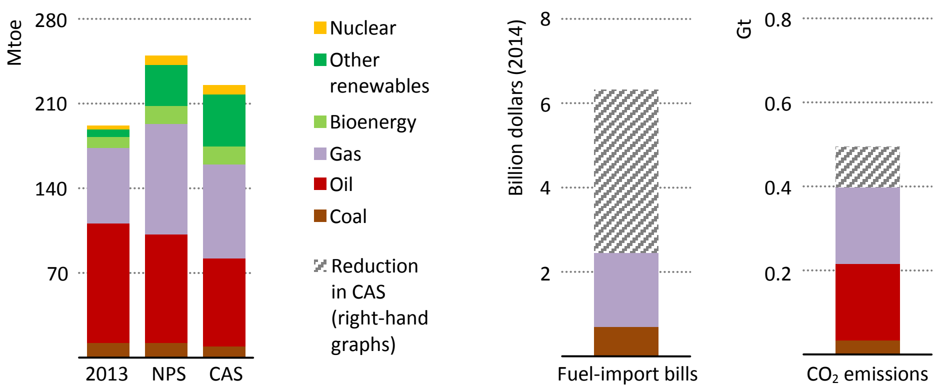



Sources: IEA; IIASA.

Emissions of $NO_X$ fall by around 60% in 2040 in the Clean Air Scenario, relative to the New Policies Scenario. Almost 60% of the additional reduction by 2040 is a direct result of better standards to address emissions from the industry and transformation sector, in particular process-related emissions in the cement industry. The power sector is another major contributor, producing around 15% of the savings, as the combined effect of stricter pollutant standards and increased renewables deployment. Although the transport sector contributes less than other sectors to the savings (around 10%), the air quality improvement and, so, the health impact of the improvements to passenger light-duty vehicles is widely felt, given that they are primarily driven in cities which generally experience the worst local pollution problems.

$SO_2$ emissions also fall further in the Clean Air Scenario, decreasing by around 65% below the level reached in the New Policies Scenario. The largest single contributor to the incremental reduction in $SO_2$ emissions is the cement industry, where the reduction is almost as large as that delivered by the entire power sector, relative to the New Policies Scenario. In the power sector, a partial switch away from the most inefficient thermal plants towards renewables complements stricter post-combustion control policies.

**Figure 5.9 ▷ Energy demand and energy sector key indicators in Mexico by scenario, 2040**




Note: NPS = New Policies Scenario; CAS = Clean Air Scenario.

Apart from a reduction in the pollutants that have a direct impact on human health and well being, there are associated benefits of the policies in the Clean Air Scenario, in which the use of both oil and natural gas declines by around 17%, relative to the New Policies Scenario, lowering the associated import bills (Figure 5.9). The decline in fossil-fuel demand also has the significant effect of reducing $CO_2$ emissions, which fall by more than 95 Mt in 2040 in the Clean Air Scenario relative to the New Policies Scenario, a drop of almost 20%. As a result, the policy measures of the Clean Air Scenario help Mexico to decouple $CO_2$ emissions from economic growth, putting Mexico on the same path as the wider OECD. Emissions are reduced by more than 10% in 2040 relative to today, helping Mexico to achieve its climate change pledge.

# European Union

## Highlights

- The European Union has taken important steps to improve air quality over the past decades. Between 1990 and 2013, $SO_X$ emissions fell by almost 90% and $NO_X$ emissions by more than half; $PM_{2.5}$ emissions dropped by almost one-fifth since 2000. The main policy instruments adopted include: increasingly stringent Euro standards for road transport; the Large Combustion Plant Directive and its successor, the Industrial Emissions Directive, for the power and industry sectors; and the EcoDesign Directive, the VOC stage I and the Paints Directive for the buildings sector. Even so, air pollution is still the single-largest environmental health risk in the European Union today: in 2015, the premature death of an estimated 340 000 people was attributed to outdoor air pollution, average life expectancy was reduced by six months and around half of the European Union's 510 million inhabitants were exposed to $PM_{2.5}$ concentration levels above the WHO guideline.
- Energy demand in the European Union in the New Policies Scenario is projected to decrease by 15% from today to 2040, with the share of renewables in primary energy demand more than doubling. $NO_X$ emissions decline by 55% as regulation to combat air pollution becomes more stringent, in particular in road transport, and energy efficiency increases. $SO_2$ emissions fall by 47% by 2040 due to reduced coal use in power generation, energy efficiency measures in buildings and the lower emissions intensity of coal-fired power stations. $PM_{2.5}$ emissions fall by less than 20% through 2040 as higher use of biomass in households and in power generation partly offsets declining emissions from fossil fuels.
- In the Clean Air Scenario, stricter pollution control standards, further improvements in energy efficiency in buildings and a higher penetration of renewables in power generation help to cut air pollutants further, particularly $PM_{2.5}$. These measures not only help to reduce the number of premature deaths in the European Union in 2040 to less than 180 000, more than 20% below the level of the New Policies Scenario, but also reduce the number of people being exposed to $PM_{2.5}$ concentration levels above the WHO guideline to less than 10% by 2040. Important co-benefits include the reduction of the EU fossil-fuel import bill by around $120 billion and a reduction of $CO_2$ emissions by 260 Mt (or 13%) in 2040.

## *The energy and air quality context*

The European Union (EU) has seen a steady decline of pollutant emissions: nitrogen oxides ($NO_X$) pollutants have been cut by more than half and sulfur oxides ($SO_X$) emissions by almost 90% since the 1990s, while particulate matter[1] $(PM)_{2.5}$ emissions have fallen almost one-fifth since 2000 (EEA, 2015a). This is despite the fact that economic growth averaged 1.6% per year since 1990 and the population increased from 478 million in 1990 to around 510 million today. Fine particulate emissions derived from coal and biomass combustion in households, and from commercial and institutional buildings, however, bucked the trend, rising by around 9% and 11% respectively in the EU over the period from 2003 to 2012 (EEA, 2015a) from the recent surge in the use of biomass in boilers for heating, as an alternative to coal (as a means of tackling climate change). Biomass use in the buildings sector in 2015 accounted for more than 40% of total $PM_{2.5}$ emissions in the EU (compared with around 33% on average in OECD countries). Industrial processes and the combustion of coal in the power and industry sectors are still the largest sources of sulfur dioxide ($SO_2$) emissions, and the transport sector is responsible for more than half of $NO_X$ emissions.

Legislation to reduce air pollution in the EU has a long and varied history dating back to the 1970s. The four daughter directives of Directive 96/62/EC, together with the Ambient Air Quality Directive from 2008, set limits on target values for certain pollutants. Since 2010, the National Emission Ceilings Directive determines emissions ceilings. In addition, source-specific legislation now covers power plants and industrial emissions (through the Medium- and Large Combustion Plant Directive and the Industrial Emissions Directive), road and off-road vehicle emissions, and fuel-quality standards. Where, despite these provisions, air quality standards are not met in particular localities, the EU requires the implementation of air quality management plans designed to reduce concentrations below the relevant standards. Despite these efforts, EU limits and target values for $PM_{2.5}$ continue to be exceeded in 17 member states (EEA, 2015a).

While reductions in the emissions of many pollutants have resulted in a notable decrease of ambient concentrations ($SO_2$ for example), this is not the case for all pollutants – the complex atmospheric chemistry involved can prevent reductions in the emissions of certain pollutants from generating a corresponding drop in concentrations of some final pollutants. For example, although there have been substantial reductions in the emissions of many of the precursors for PM and ozone in Europe, the associated concentrations generally have decreased slowly. The European Environment Agency (EEA) estimates that 17% of the urban population in the EU in 2013 lived in areas where the air quality 24-hour limit for $PM_{10}$ set by the EU was exceeded (61% of the urban population, if the stricter World Health Organization [WHO] air quality standards were applied) (EEA, 2015b). The direct resultant

[1] Size is an important factor in determining the health impacts of PM: "coarse particles" are between 2.5 and 10 micrometres (μm) in diameter and "fine particles" are smaller than 2.5 μm.

economic costs are estimated at €23 billion (such as through loss of crop production) and the external costs at €330 - 940 billion (EC, 2013).

Shortfalls in the attainment of some objectives should not detract from recognition of significant achievements in other areas. For example, the exposure of ecosystems to excess levels of acidification has been significantly reduced as a result of the decline achieved in $SO_2$ emissions, one of the main acidifying compounds. Reductions in $SO_2$ emissions resulted from a combination of regulations at EU and member state level, fuel switching from high-sulfur coal to less emission-intensive forms of electricity generation (such as natural gas and renewables) and continued improvements in energy efficiency. Air quality regulations such as the EU Large Combustion Plant Directive (LCPD) and the Industrial Emissions Directive (IED), together with regulations at individual member state level, led to the installation of advanced emissions control technologies on many coal-fired plants throughout Europe. Further reductions in emissions of $SO_2$ and other pollutants resulted from: the expansion of nuclear power in the 1980s; the increased use of natural gas-fired plants since the 1990s; and the EU energy and climate package for 2020, which incentivises the use of renewables and energy efficiency. As a result, between 1980 and 2013, coal use in the power sector dropped by almost 15% and in the industry and transformation sector by around 60%.

Reductions in $SO_2$ emissions have not been matched by a parallel improvement in the eutrophication levels of ecosystems, mainly because $NO_X$ emissions and ammonia ($NH_3$) from agriculture, which contribute to eutrophication, have not fallen as much as $SO_X$ emissions. Atmospheric concentrations at levels critical to eutrophication occur across most of continental Europe: around 63% of European ecosystem areas — and 73% of the protected natural sites — were exposed in 2010 to air pollution levels exceeding eutrophication limits (EEA, 2015c). In 2015, $NO_X$ emissions in Europe were 6.6 million tonnes (Mt), with the transport sector furnishing 51% of the total. $NO_X$ emissions have decreased by around 40% over the last ten years due to the strengthening of emissions regulations in the transport and power sectors. In the transport sector, the introduction of vehicle emissions standards for passenger vehicles, light-duty vehicles (LDVs) and heavy-duty vehicles (HDVs) has been the main instrument for change. According to the EEA, for example, the progressive tightening of vehicle standards since 2000 has delivered a 40% reduction in $NO_X$ emissions from diesel vehicles (EEA, 2016). The most recent vehicle emissions standard, EURO 6/VI, is widely considered as one of the most stringent controls on vehicle emissions of $NO_X$, but securing compliance under real-life conditions is a major problem (see Chapter 1). Despite all of these efforts, $NO_X$ emissions, particularly from nitrogen-based fertilisers for agriculture, still pose significant threats of eutrophication.

**Box 6.1 ▹ Paris: local solutions in a European context**

The Paris metropolitan area is home to 12 million people, or almost 20% of France's population, and generates around one-third of the country's gross domestic product. Its climate and geographic morphology favour atmospheric pollutant dispersion and leaching[2], but these factors are offset by high emissions levels, due to high population density and activity levels. The situation is no longer pressing for certain pollutants, such as $SO_2$ (which has been reduced by 20% over the last 50 years in the Paris metropolitan area, due to lower emissions from industrial activities) and lead (which has been removed from transport fuels). The lower benzene content of fuels has also improved the situation. However it is estimated that between 1 and 4 million inhabitants are still exposed to $NO_2$ and $PM_{10}$ concentrations above the established limits, especially along main streets. Ozone levels also periodically exceed the levels regarded as safe for human health.

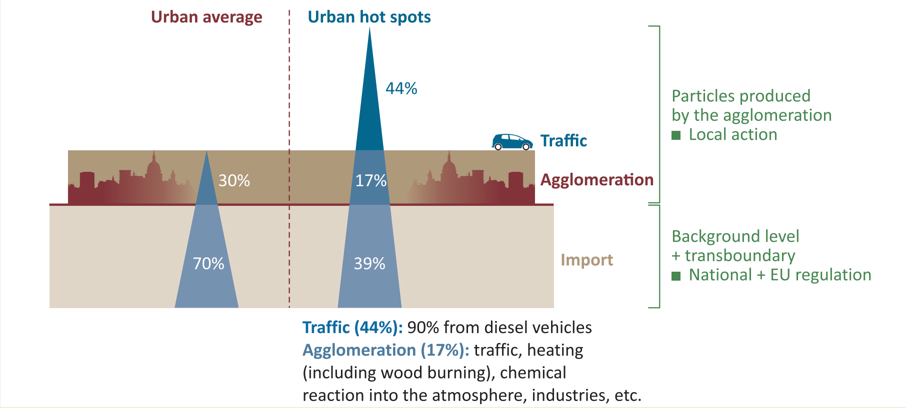
The two principal sources of pollution in the Paris region are transport and heating. Road transport accounts for over half of $NO_X$ emissions (of which 80% come from passenger diesel cars and trucks) and 30% of primary $PM_{10}$ emissions. Heating, including biomass burning, is responsible for 20% of $NO_X$ emissions in the region and 25% of primary $PM_{10}$ emissions. In the City of Paris, a successful mobility plan – including access to shared bikes and electric vehicles, restricted bus lanes and trams – decreased car use by an estimated 25% (and increased the use of public buses) between 2002 and 2012. Together with the rising efficiency of the vehicle fleet, this led to a decrease of 30% of $NO_X$ emissions and 35% of $PM_{10}$ emissions over the period. The decrease would have been greater in the absence of higher national fiscal incentives that increased the purchase of diesel cars (and thereby increased $NO_X$ and $PM_{10}$ emissions). These countervailing trends also partly explain why the concentration of nitrogen dioxide ($NO_2$) in the atmospheric concentrations remained relatively stable during those years. In 2015, the municipality took the further step of banning the circulation of trucks and buses that are older than 15 years during work days, a measure seen as the first step towards banning old, pre-Euro 5, diesel cars by 2020.

In addition to regularly unacceptable levels of certain pollutants, Paris experienced 16 days of acute pollution in 2015. Such episodes, prevalent in the spring, are typically due to ammonia emissions from outside the city, stemming from the use of fertilisers, combined with meteorological conditions that favour higher baseline pollution levels in the metropolitan area. Emergency measures to reduce peak intensity in such circumstances include suspending charges for the use of regional public transport and limiting circulation (banning, in turn, the use of vehicles with even and uneven numbered licence plates). Other measures taken by the City of Paris include making residential parking free and providing financial incentives for the use of Autolib (electric car sharing).

[2] The loss or extraction of certain materials from a carrier into a liquid.

Further air quality improvements require integrating European, national and local approaches: it is estimated that 39% of particulate matter that Paris citizens are exposed to in places with high pollution comes from outside the metropolitan area (Figure 6.1). Improvements also rely on integrated mitigation measures for different sources of pollution: not only do transport policies matter, but the use of biomass in the Paris region also needs to be disincentivised, industrial emissions need to be lowered and agricultural sources of PM need to be addressed.

**Figure 6.1 ▻ Sources of $PM_{2.5}$ concentration in metropolitan Paris**



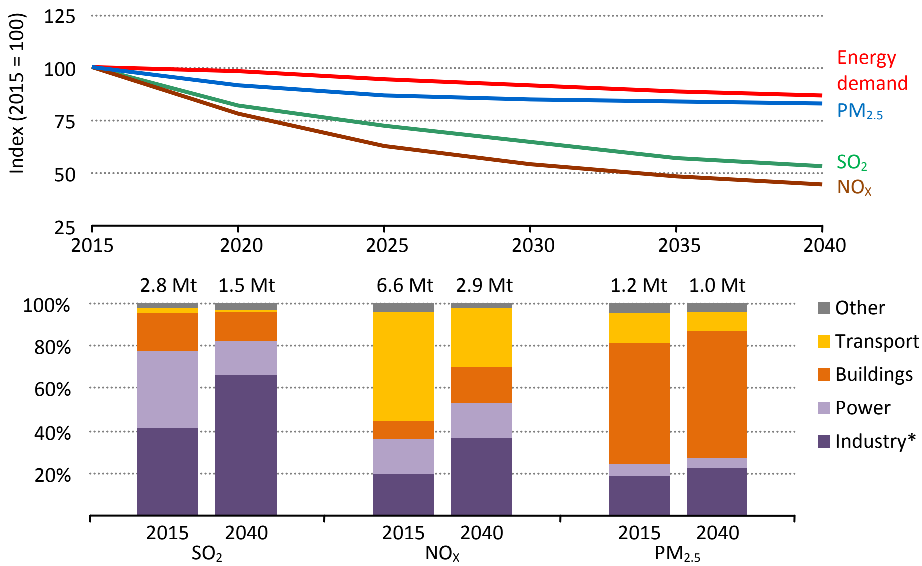

Source: adapted from Airparif and LSCE (2011).

Information is the cornerstone of mitigating the impact of air pollution. In 1979, Airparif was established as the independent air quality monitoring network of the Paris region and constantly monitors several pollutants. Each day, Airparif forecasts expected levels of pollution, especially when air quality is particularly bad, and informs the authorities (which may then adopt short-term measures), the general public and the media. Airparif is also charged with testing the efficiency of intervention measures under consideration by the authorities or those already implemented.

## *The outlook for air quality to 2040: the New Policies Scenario*

Total energy demand in the European Union has been in decline for the past decade and this decline is projected to persist through to 2040 due to the existing energy policy framework. The EU's climate pledge at COP21, backed by the most recent EU's energy and climate package for 2030, committed its member states to a combined decline in greenhouse-gas emissions of at least 40% by 2030 relative to 1990, and an increase of the share of renewables in the energy mix to at least 27%. These commitments are supported by a non-binding target to increase energy efficiency. As a result, total annual energy demand is projected to fall by 15% by 2040 in the New Policies Scenario, while the economy expands by 55%. Improved fuel efficiency and the use of alternative fuels help reduce oil demand in the EU by almost 40%, while coal demand drops by 65%, as renewables (and to a lesser extent natural gas) increase in the power mix. In the effort to further decarbonise the buildings sector, biomass use in the residential sector expands by 1.2% per year on average.

**Figure 6.2 ▷ Emissions by air pollutant and by energy sector in the European Union in the New Policies Scenario**




* Includes transformation (except power generation).

Sources: IEA; International Institute for Applied Systems Analysis (IIASA).

The trends for the major air pollutants mirror these energy sector trends (Figure 6.2): energy-related emissions of air pollutants are cut for each of the three through 2040, the largest declines occurring in $NO_X$ emissions (reduced by 55%) and $SO_2$ emissions (reduced by 47%). The drop in overall $SO_2$ emissions is in large part a result of lower coal use in the power sector, while the decline in $NO_X$ emissions is driven by the transport sector. In the transport sector, reductions are achieved through a combination of stringent air pollution standards, such as the Euro 6 norm, and lower overall fuel consumption, due to efficiency policy. $PM_{2.5}$ emissions fall much less steeply: despite a decline of around 50% in the transport sector, total $PM_{2.5}$ emissions fall by less than 20% through 2040, as increasing $PM_{2.5}$ emissions from biomass use in the residential and power sectors slow the decline in total emissions.

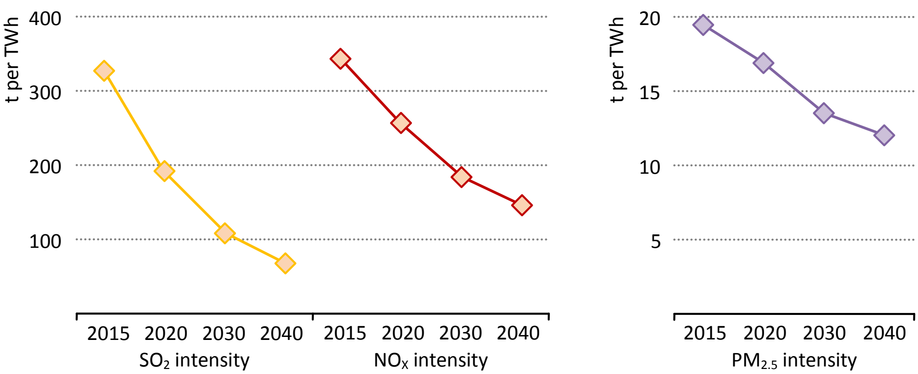
### *Outlook for the power sector*

The European power sector undergoes a major transformation over the *Outlook* period as a result of the EU's vigorous energy and climate policies. Electricity demand growth is largely held in check by a strong push for energy efficiency. Power generation from coal plummets by more than three-quarters (a larger decrease than that achieved in any other major power system) while output from renewable energy technologies doubles, even though some countries, such as Poland, continue to rely on coal to a larger extent than the EU average. The growth in renewables is dominated by the deployment of wind and solar photovoltaics (PV), although biomass also grows strongly. Nuclear power sees a slight decline, some 10%, over the *Outlook* period, although the significant uncertainties around nuclear power in Europe mean that deployment levels may well end up lower. Natural gas provides flexibility and reliability and is, despite its relatively high cost, a key component in Europe's carbon-constrained power system. The share of gas-fired power in the European power mix increases from 16% to 20% by 2040.

The European Union has one of the world's most stringent sets of controls over emissions from power stations. The LCPD and its successor, the IED, have underpinned a substantial reduction of pollutant emissions from power plants over the last decade. Over the medium term, the directive continues to lead to the retirement of plants that cannot comply with the regulation: in the period 2016-2023, plants can opt out of meeting the emissions limit values, but with their operational hours capped, thereafter they have to retire. In terms of particulate matter, the power plants are required to emit less $PM_{2.5}$ than 10-30 milligrammes per cubic metre ($mg/m^3$) (depending on the plant capacity and whether it is a new or existing facility). New power stations have to emit no more $SO_2$ than 150-400 $mg/m^3$ (depending on the plant capacity), while the range for existing plants falls between 200 and 400 $mg/m^3$. $NO_X$ emissions are regulated at between 200 and 300 $mg/m^3$ for existing plants and 150 and 300 $mg/m^3$ for new plants.

6

**Figure 6.3 ▷ Emissions intensity in the power sector by pollutant in the European Union in the New Policies Scenario**




Note: t = tonnes; TWh = terawatt-hours.

Sources: IEA; IIASA.

A combination of decarbonisation efforts and stringent regulations underpins the EU's air pollution emission trends over the *Outlook* period (Figure 6.3). Today $PM_{2.5}$ emissions are already at a very low level, at 60 kt (5% of the EU's total $PM_{2.5}$ emissions). Coal-fired plants account for some 60% of $PM_{2.5}$ emissions, while contributing 28% of the EU's power output.

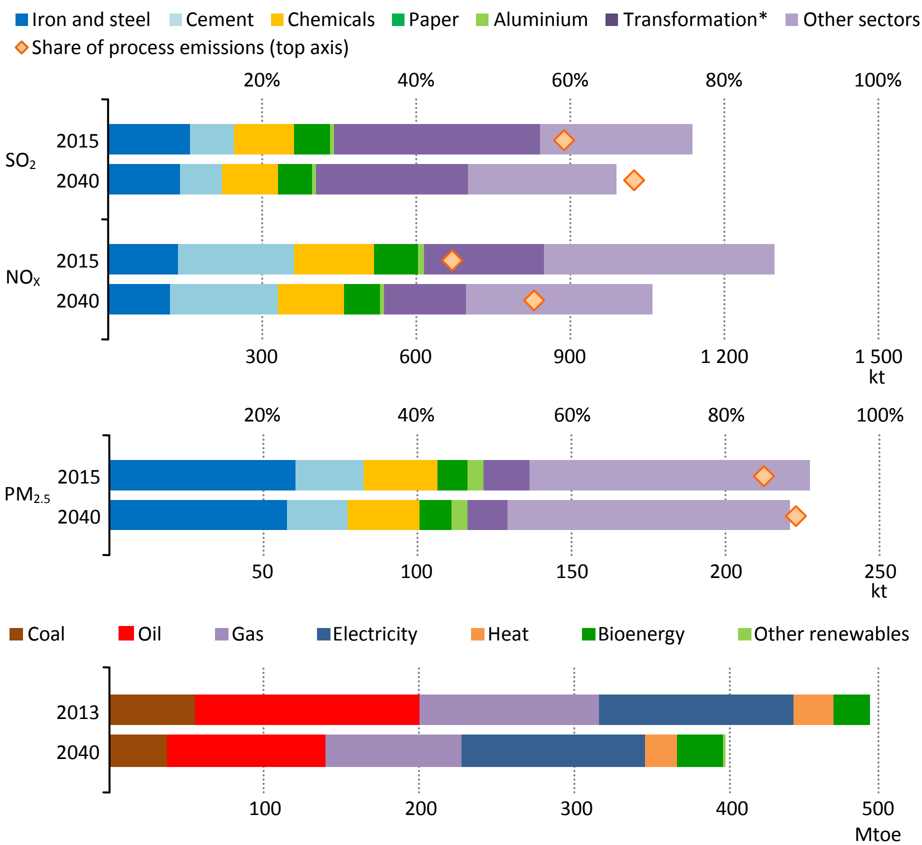
Biomass combustion for power generation is responsible for over 35% of the $PM_{2.5}$ emissions in the EU power sector – a contribution that is disproportionately higher than the fuel's 6% share in the power mix. $PM_{2.5}$ emissions from the power sector drop by one-third between today and 2040, a reduction solely attributable to lower coal use, although a quarter of the reductions achieved by displacing coal are offset by increases due to the growing deployment of biomass. Despite having halved its $SO_2$ emissions over the past five years, the power sector is the main contributor to $SO_2$ emissions in the EU, accounting for more than 35% of the total. The almost 80% reduction in $SO_2$ emissions from power generation over the *Outlook* period is in line with the drop in coal-fired generation, the main source of $SO_2$ emissions. The power sector currently emits one-sixth of the $NO_X$ emissions in the EU. By 2040, $NO_X$ emissions are more than 50% lower than today. While $NO_X$ emissions from coal-fired power generation decrease by over 80%, emissions from natural gas and biomass plants increase by more than 20% and nearly 30% respectively.

### *Outlook for the industry and transformation sectors*

Regulation of air pollutant emissions from industry has a long history in the EU, and progress has been strong: over the last ten years alone, combined emissions of $SO_2$, $NO_X$ and $PM_{2.5}$ declined by nearly 40%. As with the power sector, the LCPD from 2001 (which applies to large thermal plants, such as those in petroleum refineries and integrated steel mills) and the IED from 2010 (which targets facilities with a thermal input above 50 megawatts thermal [$MW_{th}$]) have been instrumental in achieving recent progress. The IED covers a large variety of industry and transformation sectors, such as metal production and processing, minerals, chemicals, waste management and pulp and paper production. It sets emission limits determined by best available technologies and systems by sub-sector and requires their application at all installations covered by the directive. The new Directive for Medium-size Combustion Plants, adopted in November 2015, targets emissions sources with a rated thermal input between 1 and 50 $MW_{th.}$ It requires compliance with its emissions limits by December 2018 for new industrial installations within this category and for existing installations by 2025 or 2030, depending on their size. Additionally, the Liquid Fuels Directive regulates the maximum sulfur content of fuel oil used for combustion.

Today, the largest contributors to industrial $SO_2$ and $PM_{2.5}$ emissions in the EU are the refining, iron and steel and chemicals sub-sectors, while, for $NO_X$ emissions, the cement industry is the largest industrial source. Policies to promote energy efficiency and fuel switching, as well as policies to reduce air pollution, all contribute to a further decline in air pollutants in the EU in the New Policies Scenario. $SO_2$ and $NO_X$ emissions are each reduced to around 1 000 kilotonnes (kt) by 2040, cuts of 13% and 18% respectively relative to 2015 (Figure 6.4). Policies to improve energy efficiency are mainly responsible for the decrease in $SO_2$ and $NO_X$ emissions from the industry sector, while additional air quality measures help to offset the effects of modestly increasing industrial production. Further reductions come from a decline in emissions from the refining sector as well as from energy transformations in other sectors. $PM_{2.5}$ emissions, in contrast, remain at about 220 kt – a similar level to today – as more stringent control measures and energy efficiency compensate for increasing industrial activity.

**Figure 6.4 ▷ Air pollutant emissions and energy mix in the industry and transformation sector in the European Union in the New Policies Scenario**




Notes: Mtoe = million tonnes of oil equivalent; kt = kilotonnes. * Transformation refers to fossil fuels (e.g. oil refining, oil and gas production, liquefied natural gas terminals), but excludes power and heat generation. The industry and transformation sector includes non-energy uses (mainly petrochemical feedstocks).

Sources: IEA; IIASA.

### *Outlook for the transport sector*

The European standards regulating pollutant emissions from road vehicles ("Euro" standards) are based on multiple amendments and revisions to a 1970 directive issued by the precursor to the European Commission. The first limits on new LDVs tailpipe emissions ("Euro 1") and on emissions from HDVs ("Euro I") were issued in 1992-1993. These standards are applied initially to new vehicle type approvals and are subsequently (typically one year thereafter) extended to all vehicle sales and registrations. Standards regulate per kilometre emissions (by mass) of conventional vehicle pollutants (carbon monoxide [CO], hydrocarbons [HC], $NO_X$, PM); from Euro 5b onwards, the actual amount of particulates emitted is also limited. The LDV Euro norms mandate separate emission limits for passenger cars and for three separate weight categories of light-commercial vehicles, with different limits for diesel and gasoline engines. The standard currently in place for passenger light-duty vehicles (PLDVs) is Euro 6 (Table 6.1) and vehicles are currently tested on a chassis dynamometer according to the New European Driving Cycle.

**Table 6.1 ▷ Emissions limits for selected air pollutants in road transport in the European Union**

| Target | Fuel | Standard | Implementation for all sales and registrations | PM limit | $NO_X$ limit | Sulfur limit | Unit |
|---|---|---|---|---|---|---|---|
| **PLDVs** | Gasoline | Euro 6 | Sept. 2015 | 0.005 | 0.06 | - | g/km |
| | Diesel | Euro 6* | Sept. 2015 | 0.005 | 0.08 | - | g/km |
| **Motorcycles** | Gasoline/ diesel | Euro 4 | 2017/18 | 0.08 | 0.17-0.55 | - | g/km |
| | | Euro 5 | 2020/21 | 0.06 | 0.0045 | - | g/km |
| **Heavy-duty vehicles** | Diesel | Euro VI | Jan. 2013 | 0.02-0.03 | 3.5 | - | g/kWh |
| **Fuel quality** | Gasoline | Euro V | 2009 | - | - | 10 | ppm |
| | Diesel | Euro V | 2009 | - | - | 10 | ppm |

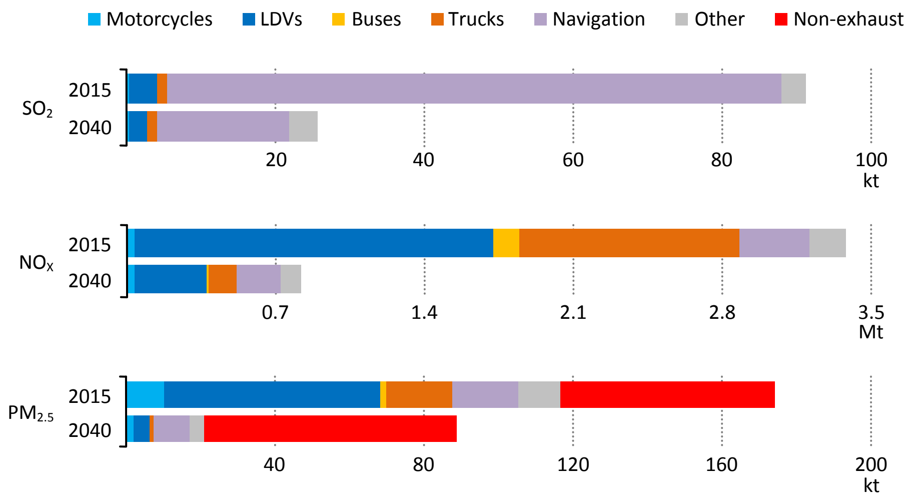
* Real driving emissions may exceed these test-cycle limits by a factor of 2.1 in 2018 and 1.5 in 2022 (see Chapter 3). Notes: PLDVs = passenger light-duty vehicles; g/km = grammes per kilometre; g/kWh = grammes per kilowatt-hour. Limit ranges reflect different vehicle sizes or engines.

Emission standards for HDVs were issued in parallel with the standards for LDVs, but the standards are expressed in terms of energy consumption rather than distance (i.e. grammes per kilowatt-hour rather than grammes per kilometre), to provide rational and consistent standards for vehicles (trucks, urban buses, etc.) operated in widely different duty cycles. The norm currently in place is Euro VI. In addition, fuel-quality standards limit the concentration of sulfur in both automotive gasoline and diesel to 10 parts per million (ppm). This is the most stringent standard worldwide. It also is in place in Japan and Korea and will soon be implemented in the United States, India and China.

In light of recent evidence of a wide gap between test results and real-world performance (which applies to fuel-economy standards as well), the European Commission has opted for new real driving emissions (RDE) tests from September 2017 to determine whether a new car model may be put on the market (although new diesel cars may still exceed the RDE value by 50% up to January 2021). In addition, the EU is moving to a more stringent and representative test procedure, the World Harmonised Light-Test Procedure, together with its associated test-cycle (WLTC).

At 3.4 Mt in 2015, transport contributes more than half of energy-related $NO_X$ emissions in the EU. The atypically high share of almost 50% diesel passenger vehicles in the European fleet means that passenger cars are a significant contributor, at almost 40% of all transport-related $NO_X$ emissions, three times the world average.[3] Freight trucks are the second-largest contributor to transport-related $NO_x$ emissions, at 30%, followed by light-commercial vehicles at around 10%. In the New Policies Scenario, the tailpipe emission control measures currently in place, alongside efforts to improve vehicle testing methods, cut $NO_X$ emissions from transport by around three-quarters in 2040 to some 800 kt, and reduce transport's contribution to total $NO_X$ emissions to around 30%. Tailpipe emissions standards, broadly speaking, are equally effective in reducing $NO_X$ emissions from the light- and heavy-duty fleet; but the importance of controlling $NO_X$ emissions from diesel cars is highlighted by the fact that around 60% of car activity occurs in urban environments (a proportion projected to gradually increase), whereas less than half of vehicle-kilometres travelled by trucks are on urban roads. As a consequence, human exposure to $NO_X$ emissions from passenger vehicles is larger.

**Figure 6.5 ▷ Air pollutant emissions by transport type in the European Union in the New Policies Scenario**




Sources: IEA; IIASA.

Transport currently accounts for nearly 10% of energy-related $PM_{2.5}$ emissions in the EU (about 115 kt). $PM_{2.5}$ emissions from transport are cut by around half by 2040, as a result of tailpipe emissions standards (90% of the reduction) and more efficient vehicles (10%) (Figure 6.5). Exhaust emissions of $PM_{2.5}$ are strongly reduced in the period to 2040, largely due to reductions from LDVs and trucks and because two-stroke motorcycles disappear from Europe's roads. Yet, non-exhaust emissions of fine particulates (from road wear, abrasion, brakes and tyres), which currently account for one-third of transport $PM_{2.5}$ emissions, continue to increase through 2040, due to increasing vehicle activity. They become the dominant source of transport $PM_{2.5}$ emissions by the early 2020s.

[3] In diesel cars, the share of nitrogen dioxide ($NO_2$) over $NO_X$ is higher than for gasoline, which makes diesel cars disproportionally responsible for high $NO_2$ concentrations in cities such as Paris and London.

$SO_2$ emissions resulting from the combustion of transport fuels are a small share (3.3%) of total $SO_2$ in the European context. Current fuel standards are sufficiently stringent to cut total $SO_2$ from domestic transport (including domestic maritime) by upwards of 70%, such that by 2040, the transport sector contributes only 1.7% of total energy-related $SO_2$ emissions.

### *Outlook for the buildings sector*

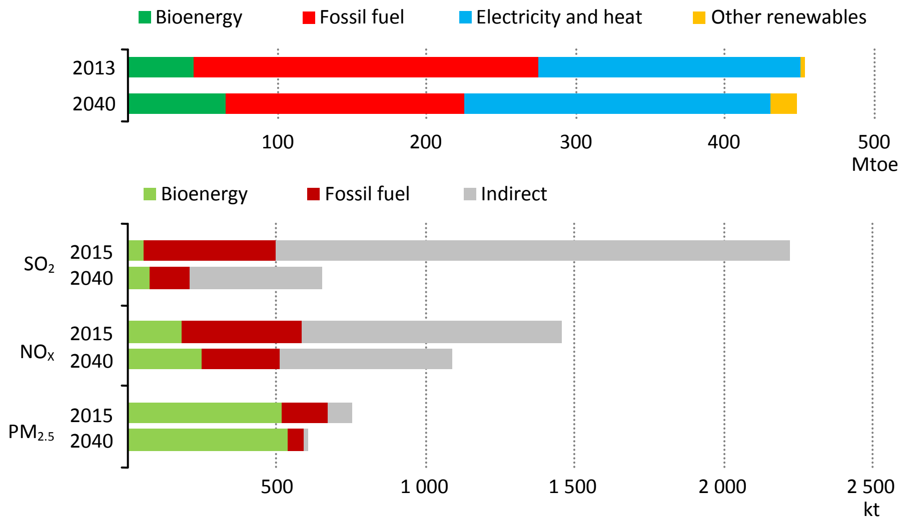
Around three-quarters of the energy consumed in households and non-residential buildings in the EU serves heating needs, mostly space heating and, to a lesser extent, water heating. Although coal accounts for less than 5% of the energy consumed to produce heat in the buildings sector today, it is responsible for almost three-quarters of $SO_2$ emissions from the sector. Around 70% of this coal is consumed in Poland, where half of the population still relies on the use of solid fuels (coal and solid biomass, used interchangeably, depending on the price and the availability) for space heating.

Most Eastern European countries saw their coal consumption in the buildings sector dramatically decrease over the last decade, as households switched to either gas or solid biomass. This led to a decrease in recent years in $SO_2$ emissions, but also to an increase in $PM_{2.5}$ emissions, while $NO_X$ emissions stayed more or less flat. In some Eastern European countries, solid fuels still account for a much more sizeable share of energy consumption in buildings than the European average (e.g. around 40% in Romania and Bulgaria). To address this, and in order to tackle climate change, the European Commission has encouraged the use of renewables (including biomass) over the last ten years. However although biomass is considered to be carbon dioxide ($CO_2$) neutral if harvested in a sustainable way, it leads to higher emissions of PM than other alternatives such as natural gas.

To tackle growing PM emissions from the buildings sector, the European Commission extended the EcoDesign Directive in April 2015 to solid fuel boilers and solid fuel space heaters; the boilers need to meet the requirements from 1 January 2020. This directive includes both requirements for energy efficiency (75-77% depending on the size of the boiler) and for pollutant emissions (PM: 40-60 mg/$m^3$, $NO_X$: 200 mg/$m^3$ for biomass boilers and 350 mg/$m^3$ for fossil-fuel boilers; and CO: 500-700 mg/$m^3$).

Air pollutant emissions from the buildings sector fall in the New Policies Scenario. $SO_2$ emissions from the buildings sector are reduced by almost 60% by 2040 relative to today, mostly due to a decreasing use of coal and (to a lesser extent) oil (Figure 6.6). Despite this strong reduction, the decline is faster in power generation and transport: in 2040, $SO_2$ emissions from the buildings sector are comparable to those of power generation (which are currently about twice as large). $NO_X$ emissions also fall, but not to the extent of the decrease in the transport and power generation sectors, as emissions from biomass use keep rising. As a result, the share of buildings in energy-related $NO_X$ emissions doubles, to 17% in 2040. The implementation of the EcoDesign Directive reduces average $PM_{2.5}$ emissions from solid fuel boilers. However, the gradual increase of bioenergy use in the buildings sector (which expands by almost 50% to 2040, mostly for space heating) keeps emissions up; the combined effect is that $PM_{2.5}$ emissions are reduced by only around 10% by 2040 compared with 2015. The share of the buildings sector in energy-related $PM_{2.5}$ emissions in the EU rises by 4 percentage points to 60% by 2040. The buildings sector as a major consumer of electricity and heat also triggers indirect emissions elsewhere in the energy sector: electricity and heat demand increases by around 15% in the New Policies Scenario to 2040, but the associated indirect emissions fall for each of the three pollutants, given regulatory efforts in the power sector.

**Figure 6.6 ▷ Energy demand in buildings and related pollutant emissions by fuel in the European Union in the New Policies Scenario**



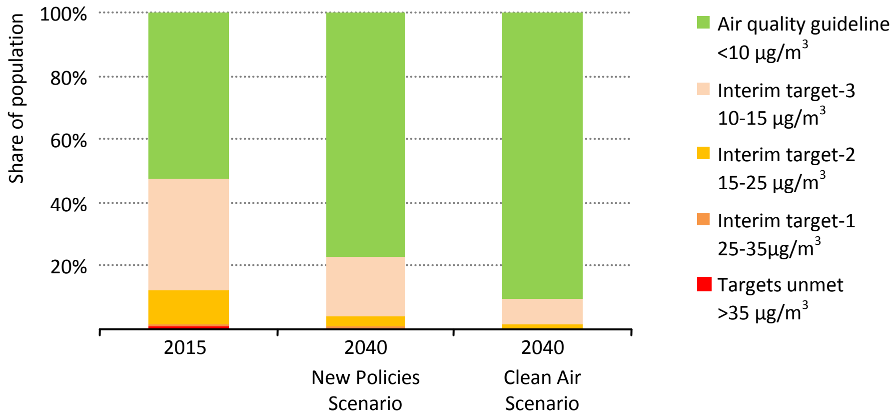

Sources: IEA; IIASA.

## *Improving the outlook for air quality to 2040: the Clean Air Scenario*

Actions taken in the New Policies Scenario reduce the number of people exposed to $PM_{2.5}$ levels above WHO guidelines to about 120 million by 2040 (Figure 6.7). Practicable means are available to go much further. In the Clean Air Scenario, the average $PM_{2.5}$ emissions are cut to a level at which fewer than 50 million people, or roughly 10% of the population, remain exposed to levels exceeding the WHO guidelines.

There would be a concomitant impact on public health. In the Clean Air Scenario, the decrease in average life expectancy due to outdoor air pollution drops from almost five months in 2040 in the New Policies Scenario to less than four months in the Clean Air Scenario (Figure 6.8). The reduction is particularly strong in Eastern European countries, which currently rely to a high degree on solid fuels for heating but progressively switch to less polluting fuel boilers in the Clean Air Scenario. The average loss of life expectancy is reduced by about 30% in Poland, Romania and Hungary. The same trend can be seen in the falling number of premature deaths due to the exposure to $PM_{2.5}$. In the EU as a whole, the

**Figure 6.7** ⊳ **Population in the European Union exposed to different $PM_{2.5}$ concentration levels according to WHO targets by scenario**

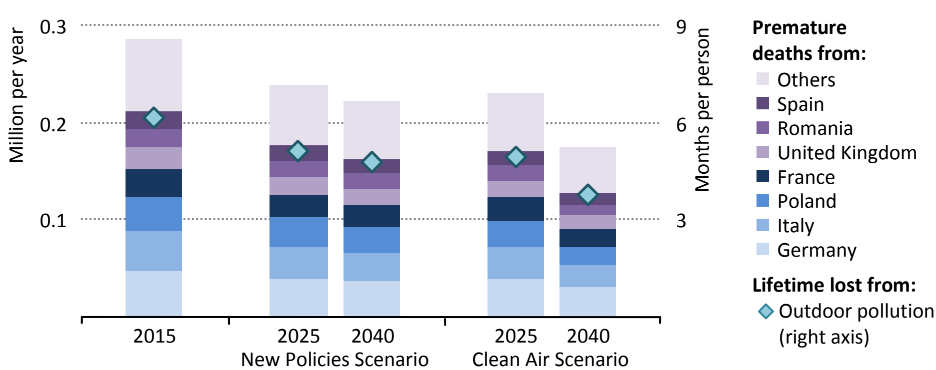



Source: IIASA.

number of premature deaths associated with outdoor air pollution is reduced from 230 000 in 2040 in the New Policies Scenario to below 180 000 in the Clean Air Scenario. The largest relative benefits are seen in Eastern Europe countries, notably in Poland and Romania.

Particulate emissions are reduced by around 30% by 2040 relative to the New Policies Scenario. Residential space heating is a major contributor to $PM_{2.5}$ emissions in the EU today, solid fuel consumption in stoves and boilers in households accounting for roughly half of all $PM_{2.5}$ emissions. Though the need for residential space heating rises through 2040 as a result of the increasing size of dwellings and an increase in the number of households, further constraints on pollutant emissions from solid fuel boilers under the EcoDesign Directive contribute almost 70% of the reduction of $PM_{2.5}$ emissions in the Clean Air Scenario in 2040 relative to the New Policies Scenario, which fall by almost 30% overall.

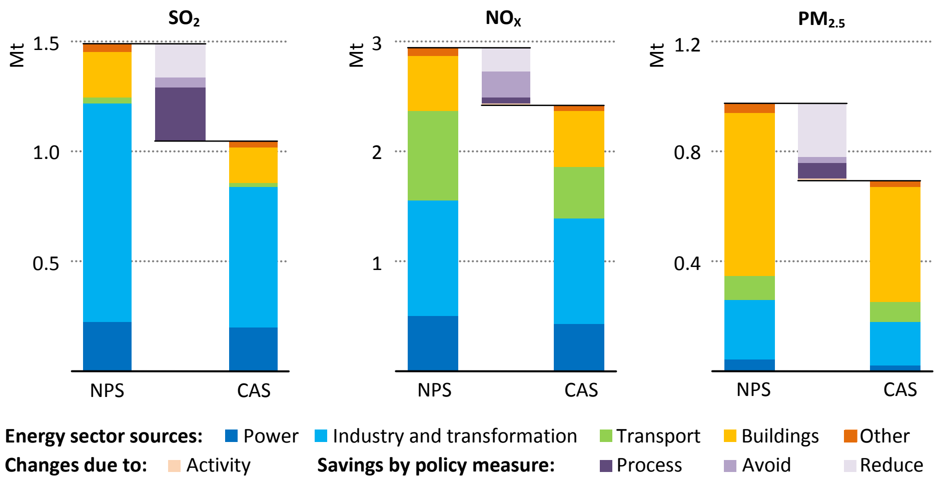
**Figure 6.8** ⊳ **Premature death cases and loss of life expectancy in the European Union by scenario**




Source: IIASA.

The second-largest source of $PM_{2.5}$ emissions is the industry and transformation sector, which together account for almost 20% of today's emissions (Figure 6.9). In the Clean Air Scenario, these emissions are reduced by around 30% in 2040, relative to the New Policies Scenario, as a result of stricter pollution control measures mainly for process emissions in the iron and steel sub-sector, but also in fertiliser production. In power generation, the additional emissions reduction is mainly attributable to improvements in biomass-fired electricity and heat generation. While biomass-fired power plants are responsible for 36% of today's $PM_{2.5}$ emissions from power generation, this share increases to more than 70% in the New Policies Scenario due to a lack of stringent pollution measures. However, measures exist to limit $PM_{2.5}$ emissions from biomass as an input to power generation, including fabric filters or electrostatic precipitators. These measures contribute to reducing $PM_{2.5}$ emissions from biomass use in the power sector by around three-quarters in 2040 in the Clean Air Scenario relative to the New Policies Scenario.

**Figure 6.9 ▷ Pollutant emissions savings by measure in the European Union in the Clean Air Scenario relative to the New Policies Scenario, 2040**



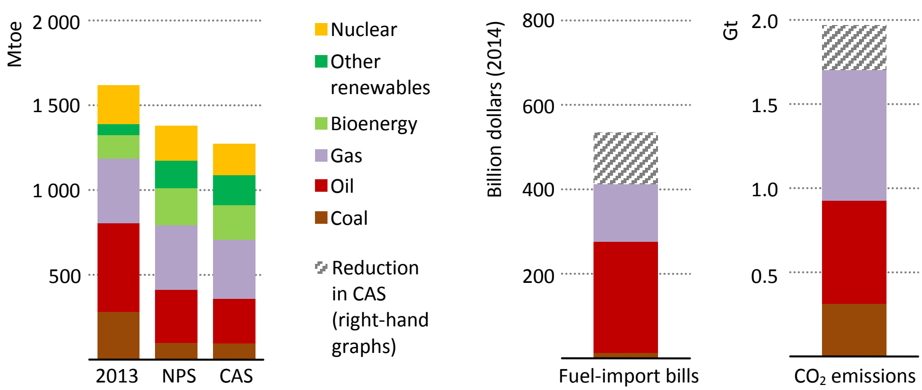

Sources: IEA; IIASA.

$NO_X$ emissions (which today originate predominantly from transport) are further reduced by almost 20% by 2040 in the Clean Air Scenario relative to the New Policies Scenario. Around half of the emissions reduction is a result of more stringent pollution standards (together with full compliance) in particular for LDVs and trucks. Energy efficiency and fuel switching also play an important role: each effect reduces $NO_X$ emissions by around 120 Mt by 2040 in the Clean Air Scenario relative to the New Policies Scenario.

Switching to less polluting fuels is a driver for $NO_X$ emission reductions in the transport sector and in power generation. In road transport, although emissions standards are effective if compliance is achieved, a shift from light-commercial diesel vehicles to gasoline hybrid, natural gas and electric vehicles can help reduce emissions further. In non-road transport, greater use of natural gas in the form of liquefied natural gas instead of oil in navigation causes $NO_X$ emissions to fall by around 40 kt. Steady efficiency gains in the use of electricity in industrial motor systems, electric appliances and cooling systems in buildings make another important contribution. Emissions from the cement sub-sector fall significantly: due to the high temperature required for clinker burning in the cement production process, the cement making is an important source of $NO_X$ emissions, but emissions levels can be brought down significantly.

$SO_2$ emissions in the European Union are mainly related to emissions from the industry and transformation sector and from the combustion of coal in the power sector. These are reduced by 30% in 2040 in the Clean Air Scenario relative to the New Policies Scenario. The reduction is mainly a result of stricter pollution control in industry and households and, to a smaller extent, due to energy efficiency. Industrial process emissions are reduced by around 245 kt of $SO_2$ in 2040 relative to the New Policies Scenario, with the biggest contributions coming from ferrous and non-ferrous metals, refineries and cement production.

**Figure 6.10 ▷ Energy demand and energy sector key indicators in the European Union by scenario, 2040**




Note: NPS = New Policies Scenario; CAS = Clean Air Scenario.

The policy package of the Clean Air Scenario achieves not only a major step forward to cleaner air in the EU, but also helps to improve energy security. Greater energy efficiency and a shift of modes in road transport are the main drivers in reducing the oil-import bill by $80 billion in 2040 in the Clean Air Scenario compared with the New Policies Scenario, or more than one-fifth of today's import bills (Figure 6.10). Natural gas consumption falls as a combined effect of energy efficiency in buildings, industry and a higher share of renewables in power generation, leading to savings of about $40 billion in gas imports (relative to the New Policies Scenario) or almost half of the current gas bill. $CO_2$ emissions fall by 260 Mt in the Clean Air Scenario relative to the New Policies Scenario, helping the European Union to meet its COP21 climate change pledge.

# China

## Highlights

- High levels of air pollution are an urgent social and public health challenge in China. Around 1 million premature deaths today can be attributed to outdoor pollution and household air pollution accounts for a further 1.2 million premature deaths. Average life expectancy in China is reduced by almost 25 months because of poor air quality.
- The response of the Chinese government has been intense and broad in scope. Alongside anticipated structural changes in the economy that lead China towards a less energy-intensive model for growth, the implementation of existing and planned air quality and energy policies in the New Policies Scenario leads to a significant reduction in emissions over the period to 2040: $SO_2$ emissions fall by almost 30% and $NO_X$ and $PM_{2.5}$ by around 40%. For $SO_2$ and $PM_{2.5}$, emissions reductions in the industry and transformation sector alone are almost as large as the total amount emitted by the entire energy sector of the United States today.
- The Chinese national average air quality target for $PM_{2.5}$ of 35 µg/m$^3$ is reached during the 2030s in the New Policies Scenario and helps to increase average life expectancy by nine months in 2040. Yet, nearly half of the population still lives in areas in which the air quality target is not met. As a result of this and with an ageing population, 1.5 million people die prematurely in 2040 from outdoor air pollution and almost 1 million people from household air pollution.
- Measures included in the Clean Air Scenario can significantly improve air quality in China. In this scenario, the national $PM_{2.5}$ air quality target is achieved during the 2020s and average life expectancy is improved by 15 months in 2040, relative to today. In 2040, the percentage of the population living in areas respecting the WHO air quality guideline of 10 µg/m$^3$ is almost twice the level achieved under existing and planned policies (albeit still only 6%) and the number of people experiencing levels above 35 µg/m$^3$ falls to less than one-quarter. The number of premature deaths related to outdoor air pollution stabilises at today's level in 2040, while those related to household air pollution decline further to 560 000. Key measures include industrial emissions controls and improved efficiency (for all pollutants), tighter standards for heavy-duty vehicles (to mitigate $NO_X$) and access to cleaner cooking (to mitigate $PM_{2.5}$).

## *The energy and air quality context*

Over the past two-and-a-half decades, China has undergone a process of rapid industrialisation and urbanisation. The share of the population living in urban areas has doubled to around 55%, while average per-capita income has grown more than seven-times. Energy demand today is almost 3.5 times higher than it was in 1990. More than 90% of the increase was met by fossil fuels. Coal now generates three-out-of-four units of electricity. Coal and oil are responsible for around two-out-of-three units of energy consumed in the industry and transformation sector (with much of the remainder being electricity); and oil constitutes more than 90% of the energy consumed in the transport sector. In the buildings sector, coal and oil satisfy only one-quarter of total energy demand, but another 38% comes from the use of biomass.

Growth in energy demand has gone hand-in-hand with economic transformation and social development; but there has been a high cost for the environment. According to the Ministry of Environmental Protection, only 8 of the 74 major Chinese cities that are currently subject to air quality monitoring met the national standard for clean air in 2014 (Ministry of Environmental Protection, 2015). In 2013, just three cities met the standard. The main industrial centres of the country, in particular Beijing, Tianjin and the Hebei province, register the highest emissions intensities across all major pollutants.

The relationship between energy and air quality in China has followed the pattern seen in most industrialised countries: the increase in sulfur dioxide ($SO_2$) and nitrogen oxides ($NO_X$) emissions has largely tracked rising coal use in the industry and power sectors, while the proportionate contribution of the buildings sector to particulate matter $(PM)_{2.5}$[1] emissions has been in gradual decline since the mid-1990s, as reliance on the use of traditional biomass declined modestly and emissions from the industry and transformation sector rose. The scale and speed of China's growth has resulted in a significant deterioration of air quality, with the total level of polluting air emissions well above that of other countries in the region. We estimate that today, only about 3% of the population in China enjoys a level of exposure to $PM_{2.5}$ concentrations that complies with the World Health Organization (WHO) guideline, while around 55% of the population is exposed to levels even greater than the most modest WHO interim target-1. Around 1 million premature deaths are attributable to outdoor air pollution today, while an additional 1.2 million premature deaths are attributable to the level of household air pollution. Overall, the average Chinese life expectancy is shortened by 25 months as a result of poor air quality.

The Chinese government has long recognised the gravity of this issue (air pollution prevention and control efforts date back to the 1970s) and is now taking serious efforts to address it. A landmark initiative was the Action Plan for Air Pollution Prevention and

[1] Fine particulate matter with particle diameter smaller than 2.5 micrometres.

Control announced in 2013. The Action Plan is a provincial-level roadmap for the nation's 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 micrometres per cubic metre ($\mu g/m^3$) (WHO interim target-1), and contains detailed measures that address other pollutants. Although the Action Plan is national in scope, it is focused on three regions in particular: Beijing-Tianjin-Hebei area, Yangtze River Delta and Pearl River Delta. These regions have $PM_{2.5}$ reduction targets of 25%, 20% and 15% respectively by 2017 (compared with 2012 levels), with the $PM_{2.5}$ concentration for Beijing capped at an annual average 60 $\mu g/m^3$. The Action Plan includes detailed measures across sectors and fuels, with specific targets for the control of coal consumption in the power and industry sectors, the phase-out of heavily polluting vehicles in transport and a plan for the nationwide introduction of cleaner gasoline and diesel fuels by 2017. Besides setting standards, the Action Plan also introduces new incentives to combat air pollution, such as the monthly disclosure of the ten best and ten worst cities in terms of air quality. The adoption of the Action Plan has been accompanied by major efforts to improve ambient air quality monitoring.[2]

Efforts to combat air pollution are complemented by policies to reduce fossil fuel use in the energy sector, supporting China's ongoing transition towards a less energy-intensive model for economic growth. At COP21, the Chinese government pledged to increase low-carbon fuel use to 20% of the overall energy mix by 2030 (from around 10% today) and to reduce carbon intensity by 60-65% in 2030, relative to 2005. The chances of achieving (or even over-achieving) these targets appear strong: for example, China is investing more in renewable energies than any other country in the world and has adopted stringent energy efficiency standards, in particular in the industry and transport sectors. According to preliminary data, coal use fell in 2015, as did energy-related carbon dioxide ($CO_2$) emissions, despite continued economic expansion.

According to official figures, efforts to reduce air pollution in China have a solid history of achievement. Over the past ten years, total $SO_2$ emissions fell by one-third (largely due to new pollution controls in the power sector) and total $PM_{2.5}$ emissions declined by 19% (due to new industry and transformation sector regulation and a shift away from biomass as a residential fuel). Pollutant emissions from coal combustion peaked sometime around 2010, which is generally recognised as a major achievement. However, total $NO_X$ emissions increased by one-third over the ten years from 2005, with 60% of this increase coming from rapid growth in road transport emissions, with car ownership rising from 15 cars per 1 000 inhabitants in 2005 to nearly 100 cars per 1 000 inhabitants today.

[2] By end-2014, 1 436 monitoring sites were in place (almost 1 000 more than at end-2012), located in 338 prefectural and higher administrative-level cities. They report real-time hourly mean concentrations of the major monitored pollutants ($PM_{2.5}$, $PM_{10}$, $SO_2$, nitrogen dioxide, ground-level ozone and carbon monoxide) and corresponding air quality indicators.

**Box 7.1 ▷ Beijing: monitoring and forecasting to address air pollution**

Beijing has been growing at breakneck speed, becoming an important industrial hub that is also home to more than 20 million people. It is a city where poor air quality has become an unfortunate fact of everyday life. In 2015, the average annual concentration of $PM_{2.5}$ was just over 80 $\mu g/m^3$, with some southern parts of the city registering even higher concentrations because of the prevalent wind direction and other factors. This average concentration actually represents an improvement of 6.5% compared with 2014, although the days which were labelled as "heavy polluted" (which requires the daily concentration of one of the main pollutants measured by China's air quality index to exceed 200 $\mu g/m^3$) remained relatively stable at 46 days in 2015, compared with 45 days in 2014 (and down from 58 days in 2013).

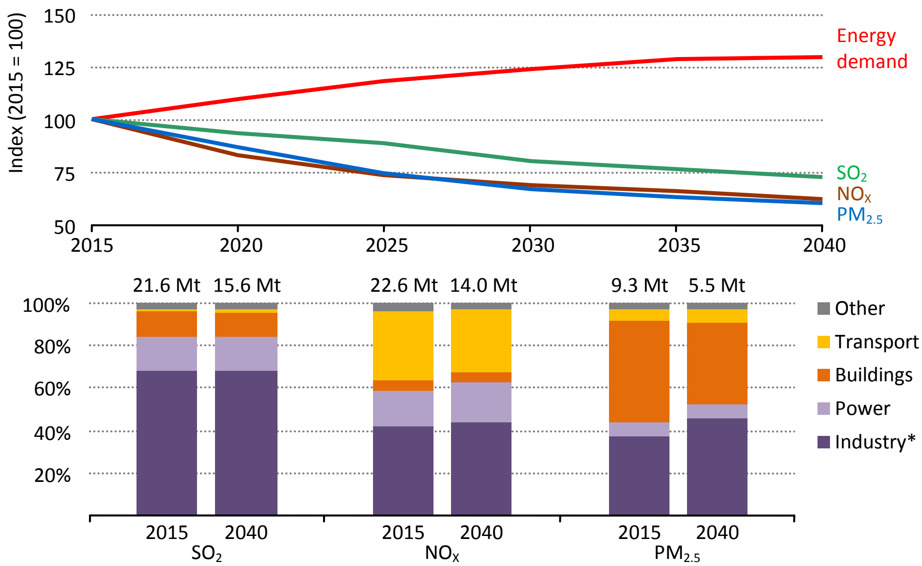
The availability of these data on air quality reflects a major effort by the municipal government to measure, monitor and forecast – an important pre-requisite for an effective policy response. Beijing has been actively researching air quality forecasting technologies since 1997 and was the first city in China to establish an environmental monitoring institution to produce air quality forecasts. Today, there are 35 air quality monitoring sites spread over the city, which contribute to the public release of information and assessments on the concentration levels of six major pollutants (including $PM_{2.5}$) and contribute to the formulation of the city's emergency responses. The city's air quality forecasting system is run by an Environmental Monitoring Centre under the Beijing Municipal Environmental Protection Bureau: the forecasting and alerting centre was established in 2014 and is run by a team of 12, of which three specialists have more than ten years' experience in analysis and forecasting. This operation is seen as a model for other cities, and the centre's news and alerts are widely followed and reported by newspapers, television, internet and mobile phone apps (Clean Air Asia, 2015).

## *The outlook for air quality to 2040: the New Policies Scenario*

In the New Policies Scenario, despite an increase of one-third in overall energy demand in support of a more than tripling of gross domestic product (GDP), air pollutant emissions from the energy sector in China in 2040 fall: $SO_2$ emissions are almost 30% below current levels in 2040, and $NO_X$ and $PM_{2.5}$ emissions around 40% lower. The policy push to improve China's energy intensity – as reflected in the COP21 climate pledge – leads to a 60% reduction in energy use per unit of GDP by 2040, constraining overall growth in energy demand (and hence growth in air pollutants as well). Efforts to further decarbonise the energy sector reduce the share of fossil fuels in power generation by 20 percentage points, to 57% in 2040. Coal use is affected most: after growing by almost 9% per year since 2000, total coal consumption growth levels off and then goes into a gradual decline. The share of coal in the overall energy mix falls below 50% by 2040, from around two-thirds today.

The average national ambient air quality target for $PM_{2.5}$ of 35 µg/m$^3$ is reached during the 2030s in the New Policies Scenario, but almost half of the population still lives in areas that are exposed to higher levels of pollution. Average life expectancy rises by nine months by 2040 due to cleaner air, relative to today, reducing the average loss of life expectancy due to air pollution to 16 months. This is not enough to reduce the level of premature deaths related to outdoor air pollution, which increase by more than 40% to 1.5 million in 2040 as demographic trends mean that the population becomes older (which increases the vulnerability to air pollution). A reduction of $PM_{2.5}$ emissions by more than 50% in the residential sector brings down premature deaths from household air pollution by more than 15% to 970 000 cases in 2040. Overall, the projections in the New Policies Scenario imply a significant improvement in air quality, but far from enough to resolve the problem.

**Figure 7.1 ▷ Emissions by air pollutant and by energy sector in China in the New Policies Scenario**




* Includes transformation (except power generation).

Sources: IEA; International Institute for Applied Systems Analysis (IIASA).

The reduction in emissions occurs across all pollutants (Figure 7.1). Energy-related $SO_2$ emissions are 6 Mt lower by 2040, relative to 2015. In the industry and transformation sector, the application of control technologies is accompanied by a decline in industrial process-related emissions and a large decrease in industrial coal use. In the power sector, air pollution policies are accompanied by a slowdown in coal consumption growth. Similar dynamics underpin a decline in $NO_X$ emissions from the power and industry sectors to 2040. In the transport sector (the main source of combustion-related $NO_X$ emissions), $NO_X$ emissions gradually decline as emissions standards become increasingly more stringent and make their way into the growing vehicle fleet. Total energy-related $NO_X$ emissions end up almost 8.6 Mt lower in 2040 than in 2015. $PM_{2.5}$ emissions also register a 40% decline over the same period, due to a strong decrease in emissions from the use of biomass in the residential sector, offset only in part by an increase of $PM_{2.5}$ emissions associated with biomass combustion processes in other sectors.

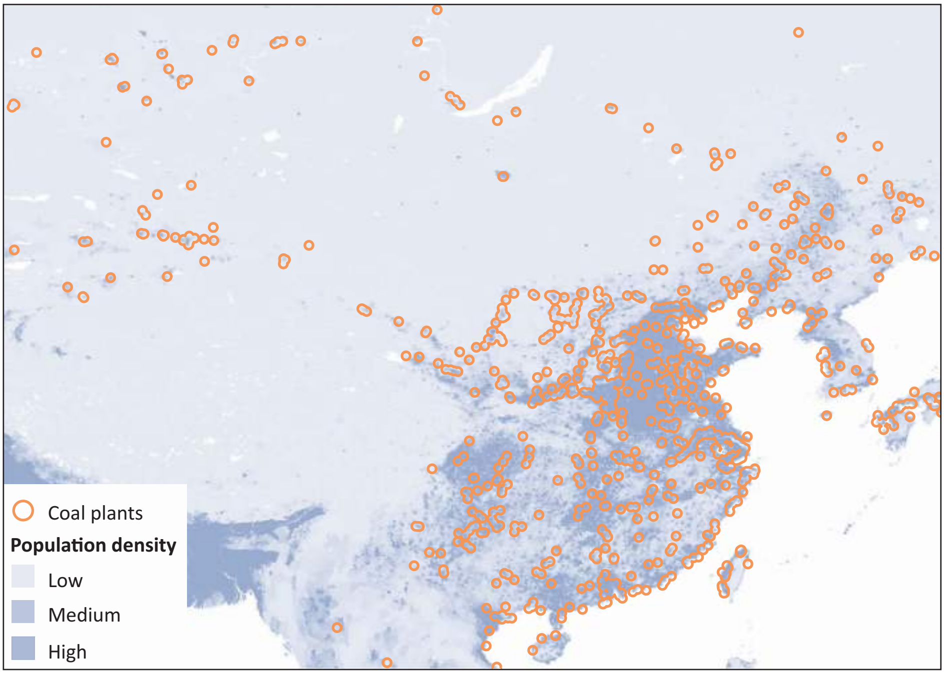
Overall, the industry and power sectors remain the largest contributors to energy-related $SO_2$ emissions through to 2040. The industry and transport sectors remain the largest source of $NO_X$ emissions due to continued rise in energy demand, while the industry and transformation sector (despite a decline in emissions) becomes the largest source of $PM_{2.5}$ emissions by around 2030, overtaking the buildings sector.

### *Outlook for the power sector*

The outlook for China's power sector is shaped by the overarching structural economic transformation that is anticipated in China over the period to 2040: the shift from an economy dominated by heavy industries towards a more service-oriented model. Power generation grew at over 11% per year in the period from 2000 to 2013, but growth has slowed markedly since. In the New Policies Scenario, electricity demand grows at a moderate 2.6% per year between today and 2040, accompanied by a profound diversification of the power generation mix away from coal. The share of coal in power generation drops from over three-quarters today to less than half in 2040, while renewables contribute one-third of power generation at the end of the *Outlook* period, up from one-fifth today.

In recent years, coal-fired power generation has been a major focus of policy efforts to tackle deteriorating air quality, not only because these plants are major emitters, but also because many of them are located in close proximity to densely populated urban areas in China's coastal provinces (Figure 7.2). With over two-thirds of China's coal-fired stations built over the last ten years, China has one of the world's most modern and efficient coal fleets. Yet, in the absence of systemic regulation, many plants were built without adequate control technologies, or, where equipment was installed, without adequate provision for monitoring performance: some plant operators chose to avoid the operational costs of running the control equipment. A new set of emissions standards was introduced in 2012, making Chinese coal plants subject to limits that are broadly comparable with those in Europe or the United States: for PM, the hourly limits are 30 $mg/m^3$; for $SO_x$, emissions, the flue-gas concentration for new plants may not exceed 100 $mg/m^3$ and for existing plants 200-400 $mg/m^3$, depending on the province; and for $NO_X$, the limits are 100 $mg/m^3$ for new and 200 $mg/m^3$ for existing plants. The need for existing plants to comply with these abated standards has triggered significant retrofitting investment in the Chinese coal-fired fleet (Figure 7.3). The initial focus was on plants located in the coastal provinces – these are now reported to be fully retrofitted. The current focus is on achieving compliance in the central and northern provinces, to be followed by plants in China's relatively sparsely populated west.

**Figure 7.2 ▷ Coal-fired power plants and population density in China, 2015**




This map is without prejudice to the status of or sovereignty over any territory, to the delimitation of international frontiers and boundaries and to the name of any territory, city or area.

Source: IEA analysis based on Platts World Electric Power Plants database and CoalSwarm.

In the New Policies Scenario, power generation in China almost doubles between today and 2040, but pollutant emissions fall over the same period: $SO_2$ by 30%, $NO_X$ by 35% and $PM_{2.5}$ by almost 40% (Figure 7.4). Implementation of the new, more stringent emissions standards for new and existing power plants is the main reason behind these declines, especially the retrofitting of existing plant (only around one-third of the coal fleet operating in 2040 is yet to be built). Policies to reduce pollution through emissions control – and the resulting declines in the emissions intensity of thermal power generation – explains around 70% of the decline in $SO_2$ and $PM_{2.5}$, and 85% in $NO_X$. Spurred by a fall in the PM intensity of coal-fired power, and reinforced by the diversification of the power mix, the overall $PM_{2.5}$ intensity of China's power generation falls by more than half by 2040. For similar reasons, the $SO_2$ and $NO_X$ intensities of power generation also decrease by around 50%.

Alongside the implementation of pollution controls and the diversification of the power mix, part of China's strategy aims at reducing human exposure to pollutants by locating emissions sources further away from densely populated areas. A good example is the establishment of coal-fired power plant clusters in northern and western China, areas of lower population density that send their electricity via high voltage direct current lines to the demand hubs in the coastal provinces. This practice serves to mitigate the health impacts of air pollutant emissions.

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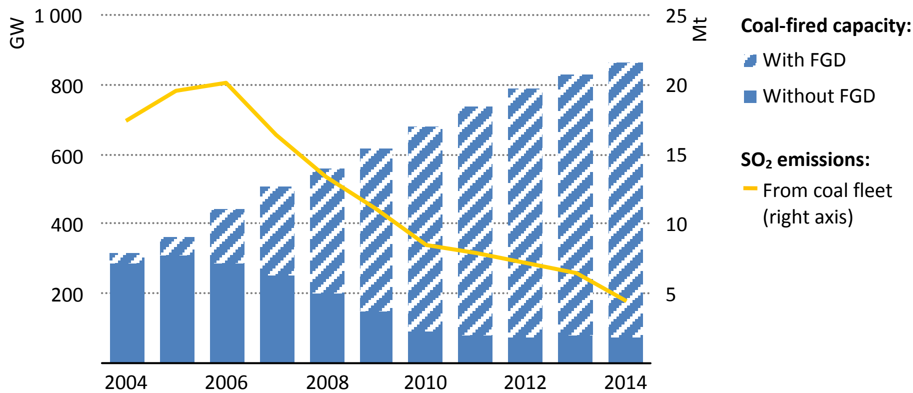
**Figure 7.3 ▷ Coal power capacity equipped with flue-gas desulfurisation and related $SO_2$ emissions in China**

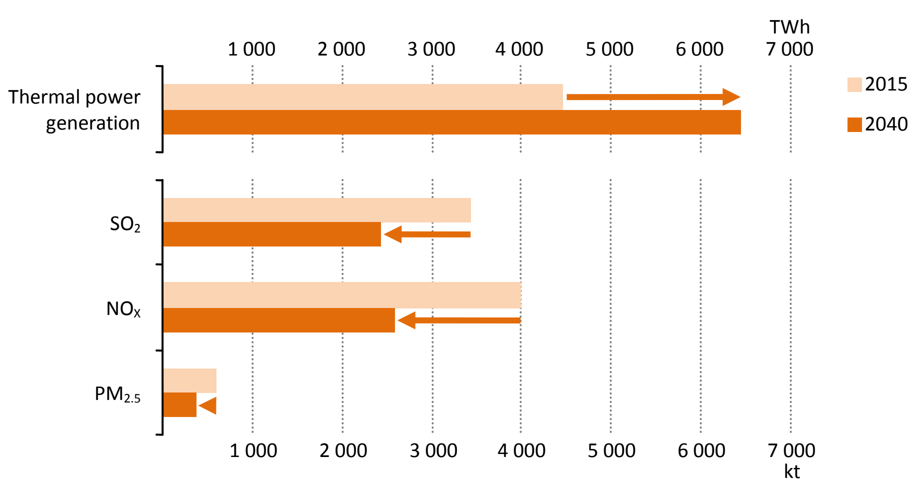



Note: FGD = flue-gas desulfurisation; GW = gigawatts.

Sources: IEA analysis; IIASA; Electric Power Planning & Engineering Institute; China Electricity Council.

An important variable in our projections, alongside the setting of stringent emissions limits, is the speed and consistency of their implementation. Although nationwide pollution control retrofitting is achievable within a few years, successful implementation also requires close monitoring and strict enforcement. China now pays a premium on power tariffs to generators who invest in ultra-low emission retrofits. This measure should speed-up installation of control technology and offers an incentive for over-achievement against the current emissions limits.

**Figure 7.4 ▷ Change in electricity generation and air pollutant emissions in China in the New Policies Scenario**




Note: TWh = terawatt-hour; kt = kilotonnes.

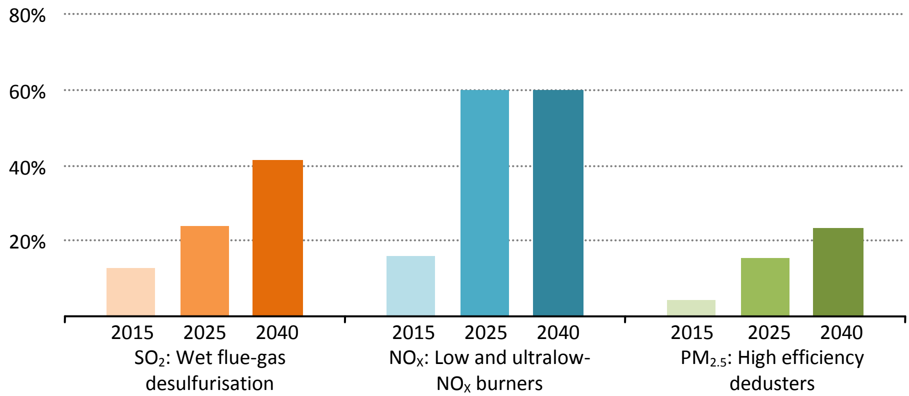
### *Outlook for the industry and transformation sector*

The industry and transformation sector is the largest consumer of energy in China, with more than two-thirds of its energy demand based on coal and oil. The sector is also by some distance the largest contributor to the emissions of air pollutants. It emits more $SO_2$ and $NO_X$ than any other sector, and is the second-largest contributor to $PM_{2.5}$ emissions, after the buildings sector. Given the size of the sector, pollutant emissions from Chinese industry make up around 40% of $SO_2$ and about one-third of $NO_X$ and $PM_{2.5}$ emissions attributable to the industry and transformation sector worldwide. There is no shortage of regulation for the industry and transformation sector in China, but there are more than 70 million well-scattered small- and medium-size enterprises in the country, making enforcement challenging. The 12th Five-Year Plan prioritised measures for industries that are highly energy and resource intensive, with the aim of eliminating outdated or inefficient production capacity in 21 key industries, including steel, cement, electrolytic aluminium and flat glass. The creation of new capacity in energy-intensive industries is strictly controlled, and where projects are newly built, modified or expanded, a similar or higher amount of outdated or excess production capacity must generally be eliminated.

The Action Plan for Air Pollution Prevention and Control sets stringent targets for its three key target regions: for example, in Beijing, 1 200 high-pollution enterprises are to be restructured and/or shut down by the end of 2017, while in Tianjin, total steel and cement production capacity within the administrative jurisdiction will be limited to 20 million tonnes (Mt) and 5 Mt, respectively. The Action Plan also requires clean production audits and clean production technology retrofits in key industries, such as steel, cement, chemical engineering, petrochemical and non-ferrous metal smelting, with the aim of reducing emissions intensity by more than 30% by 2017 compared with 2012. New dry-cement kilns are expected to use low-$NO_X$ combustion technology and the energy use per unit of added value in industry is to be reduced by approximately 20% by 2017.

Emissions control exists in the industry and transformation sector in China, but, although it is relatively widespread, the technologies used are often inefficient. For example, about two-thirds of coal-related $PM_{2.5}$ emissions in the industry and transformation sector are controlled today by basic and cheap electrostatic precipitator (ESP) devices. In-furnace limestone injection allows $SO_2$ emissions from about half of coal-consuming industries to be controlled, but with a removal efficiency of only about 50%. In the New Policies Scenario, more efficient technology makes significant inroads, based on existing and planned policies (Figure 7.5): dedusting technologies with higher efficiency (such as advanced ESP and fabric filters) allow for more efficient control of $PM_{2.5}$, while the increasing deployment of wet flue-gas desulfurisation devices, like wet scrubbing or sulfuric acid processes, comes with a removal efficiency of about 85%. For reducing $NO_X$ emissions, low-$NO_X$ burners are widely adopted, as they represent the least-cost option to control $NO_X$ emissions in the industry and transformation sector. The pace of diffusion of such technologies slows by around 2030 as the larger industrial facilities become fully equipped. The upfront costs are often too high for small- and medium-size enterprises, while smaller industries are only partially covered by regulation in the New Policies Scenario.

**Figure 7.5 ▷ Adoption rate of selected emissions control devices for coal combustion in the Chinese industry and transformation sector in the New Policies Scenario**



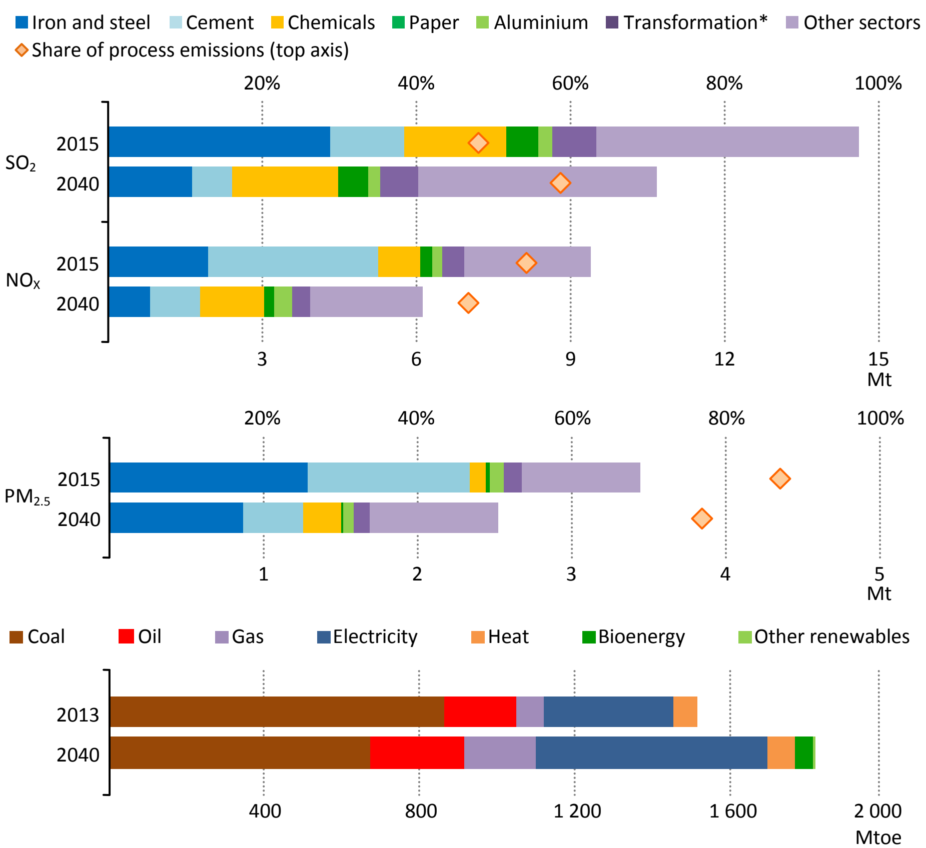

Note: Penetration rates are expressed as the share of total fuel consumption by sector covered by the control device.

Sources: IEA analysis; IIASA.

The policy efforts undertaken by China in the New Policies Scenario sharply reduce air pollutant emissions from the industry and transformation sector (Figure 7.6): over the period to 2040, $SO_2$ and $PM_{2.5}$ emissions fall by more than one-quarter below today's level, while $NO_X$ emissions decline by more than one-third. The sheer size of the sector means that these reductions account for a large share of total emissions abatement: pollutant emissions reductions in the Chinese industry and transformation sector by 2040 represent two-thirds of China's total $SO_2$ savings, almost 40% of $NO_X$ savings and one-quarter of total $PM_{2.5}$ emissions reductions. The total volumetric reduction of all pollutants is by far the highest in the world. For $SO_2$ and $PM_{2.5}$, the reductions are as large as the total amount emitted by the entire energy sector of the United States today. The iron and steel sector – the largest source of industrial air pollutant emissions today – accounts for a large part of the reductions in $SO_2$ emissions from the industry and transformation sector (emissions drop by 60%), while the cement industry is responsible for the majority of $NO_X$ emissions reductions (through a 70% drop in emissions); both sectors combined are essentially responsible for the entire decline in $PM_{2.5}$ emissions. While these sectors remain key emitters of air pollutants even by 2040, their overall share in air pollutant emissions diminishes over time as the economy matures further. By 2040, the chemicals sector becomes the predominant source of $SO_2$ and $NO_X$ emissions in China.

Alongside policy measures that target directly a reduction in air pollution, the trajectory of China's industrial emissions is also affected by two broader trends. The effort to implement industry performance standards and upgrade the technology used in major coal-consuming industries helps to reduce coal demand. In addition, the structural rebalancing of the Chinese economy away from heavy industries considerably decreases activity (and hence coal demand) in the iron and steel, and cement sectors, with knock-on effects on air pollutant emissions. Post-combustion control technologies and energy efficiency improvements contribute almost equally to $SO_2$ and $NO_X$ emissions reduction from the industry sector. Together, they more than compensate for the overall increase of industrial activity. The decrease of $PM_{2.5}$ emissions is almost entirely a result of post-combustion control measures.

**Figure 7.6 ▷ Air pollutant emissions and energy mix in the industry and transformation sector in China in the New Policies Scenario**




Notes: Mtoe = million tonnes of oil equivalent; kt = kilotonnes. * Transformation refers to fossil fuels (e.g. oil refining, oil and gas production, liquefied natural gas terminals), but excludes power and heat generation. The industry and transformation sector includes non-energy uses (mainly petrochemical feedstocks).

Sources: IEA; IIASA.

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### *Outlook for the transport sector*

The transport sector is not the largest source of air pollution in China today, although it emits almost as much $NO_X$ to the atmosphere as the industry and transformation sector. Nonetheless, action in this sector is critically important because of the high level of human exposure to transport-related pollutants, in particular $PM_{2.5}$: more than 80% of all passenger vehicle activity and almost 60% of all road freight activity today takes place in urban areas. Road transport contributes more than 20% of total PM emissions in Shanghai and Guangzhou, more than 30% in Beijing and more than 40% in Shenzhen.

In the past, policy makers have struggled to introduce measures fast enough to keep pace with the expansion in China's vehicle fleet. China's vehicle emissions control programme dates back to the early 1980s, but a modern nationwide control programme began only in the late 1990s. The effects of this are still felt today: it is estimated that about 6% of the vehicles in China do not comply with any emissions standard and give rise to more than 40% of road transport-related emissions of carbon monoxide, hydrocarbons (a sign of poor fuel combustion) and PM, as well as more than 30% of $NO_X$ emissions.

**Table 7.1 ▷ Emissions limits for selected air pollutants in road transport in China**

| Sector | Fuel | Standard | Implementation for all sales and registrations | PM limit | $NO_X$ limit | Sulfur limit | Unit |
|---|---|---|---|---|---|---|---|
| **Passenger cars** | Gasoline | China IV | 1 July 2011 | - | 0.08-0.11 | - | g/km |
| | | China 5 | 1 Jan. 2017 | 0.0045 | 0.06-0.082 | - | g/km |
| | Diesel | China IV | 1 July 2013 | 0.025-0.060 | 0.25-0.39 | - | g/km |
| | | China 5 | 1 Jan. 2018 | 0.0045 | 0.18-0.28 | - | g/km |
| **Two-wheelers** | Gasoline | China III | 1 July 2009 | - | 0.15 | - | g/km |
| **Three-wheelers** | Gasoline | China III | 1 July 2009 | - | 0.25 | - | g/km |
| **Heavy-duty vehicles** | Gasoline | China IV | 1 July 2014 | 0.02-0.03 | 3.5 | - | g/kWh |
| | Diesel | China IV | 1 July 2014 | 0.02-0.03 | 3.5 | - | g/kWh |
| | | China V | 1 July 2017 | 0.02-0.03 | 2.0 | - | g/kWh |
| **Fuel quality** | Gasoline | China IV | 31 Dec. 2013 | - | - | 50 | ppm |
| | | China V | 31 Dec. 2017 | - | - | 10 | ppm |
| | Diesel | China IV | 31 Dec. 2014 | - | - | 50 | ppm |
| | | China V | 31 Dec. 2017 | - | - | 10 | ppm |

Notes: g/km = grammes per kilometre; g/kWh = grammes per kilowatt hour; ppm = parts per million. Limit ranges reflect different vehicle sizes or engines.

Recent policy announcements have introduced much tougher controls on transport-related emissions in China. For fuel quality, the Action Plan for Air Pollution Prevention and Control mandates nationwide implementation of the China V standard by the end of 2017. This restricts sulfur concentrations to the same values as in Europe, Korea and Japan, the most stringent values in the world (Table 7.1). Regulation of other pollutants also follows the European example, both in terms of limit values and test cycles. For passenger vehicles, the current national standard is China IV for gasoline and diesel vehicles (the equivalent of Euro 4), but the Ministry of Environmental Protection issued the final version of the China 5 standard (which is nearly equivalent to Euro 5) for gasoline and diesel vehicles in 2013, with an implementation date of late-2017. The draft China 6 standards were issued in May 2016 and, once approved, are expected to be phased in starting from 2020, with the stringency of emissions increasing from the initial China 6a in 2020 to China 6b in 2023.[3] Tailpipe emissions from the immense production of two- and three-wheelers (China is the largest manufacturer of motorcycles in the world) are also regulated: China's current China III standards have been in place since mid-2009 and are based on Euro 3 standards for motorcycles, but with an added requirement of durability that requires motorcycles to comply with emissions limits for a certain period beyond the time of sale.

The important role of passenger transport in air pollution is further reflected in measures taken at city level: Beijing restricted new vehicle registration to 150 000 licence plates in 2015, of which 30 000 were reserved for so-called "new energy vehicles" (i.e. more efficient and alternative fuel vehicles). In 2014, only one out of 164 applicants received a licence plate in Beijing's number plate lottery. Shanghai auctioned only 100 000 licence plates in 2014 and 2015, with 5.6% of the applicants receiving a licence plate in 2014, at an associated registration cost of almost RMB 74 000 per vehicle (around Euro 10 500). Both cities have banned conventional scooters from the city and only allow the use of electric scooters. By end-2015, seven Chinese cities with more than 6% of China's population had implemented such caps on vehicle registration. In addition, 14 Chinese cities have regular driving restrictions and the Action Plan for Air Pollution Prevention and Control mandates the retirement by 2017 of all vehicles that fail to meet minimum pollution standards (yellow label vehicles) as well as promoting the use of public transport.

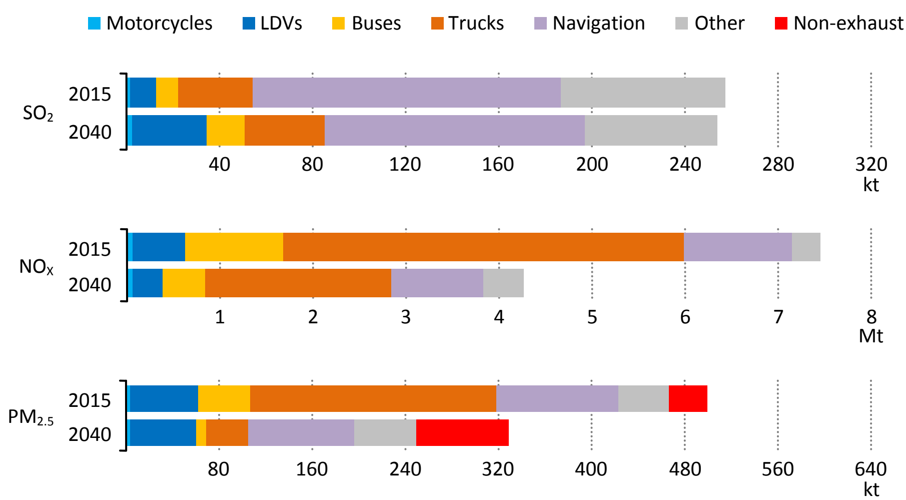
Rising per-capita income and strong demand for personal mobility and freight transport underpin the strong growth in transport activity in the New Policies Scenario: vehicle ownership rises from nearly 100 vehicles per 1 000 inhabitants today to 360 per 1 000 inhabitants in 2040, while freight activity rises by almost 3% per year on average, broadly tracking the growth of industrial activity. As a result, oil demand for transport increases from around 5 million barrels per day (mb/d) today to more than 9 mb/d in 2040, moderated only in part by increasing fuel efficiency and the uptake of alternative fuels (such as electricity, biofuels and natural gas).



[3] Due to the timing of its release, China 6 was not considered in the New Policies Scenario. The Clean Air Scenario presented in the remainder of this chapter, however, incorporates equivalent standards.

Against this backdrop, policies to regulate emissions play a vital role in containing transport-related emissions growth: $NO_X$ emissions fall to 4.2 Mt in 2040, more than 40% below today's level, with the pace of decline accelerating over time as vehicles with lower emissions increasingly make inroads into the total stock (Figure 7.7). Road transport, which accounts for 80% of total transport-related $NO_X$ emissions today, is the main determinant of this trend. The implementation of the China 5 standard for passenger cars brings down related emissions by around 45%; the introduction of the China 6 standard could bring down emissions further. The adoption of China V for heavy-duty vehicles (which further reduces $NO_X$ emissions limits, but not $PM_{2.5}$ limits) for all sales and registrations from 2017/2018 cuts $NO_X$ emissions from trucks (the main source of road transport $NO_X$ emissions) and buses by around 55%.

**Figure 7.7 ▻ Air pollutant emissions by transport type in China in the New Policies Scenario**




Sources: IEA; IIASA.

Transport-related emissions of $PM_{2.5}$ currently amount to only about 5% of all energy-related emissions in China, but this low share belies the fact that total transport emissions are high (about 60% higher than in the United States), and disproportionately occur in densely populated urban regions of the country. Policy efforts in the New Policies Scenario lead to a reduction in total $PM_{2.5}$ emissions by one-third, from 500 kt per year in 2015 to less than 330 kt in 2040, despite a three-fold growth of road vehicle-kilometres travelled and a doubling of transport energy use. Despite this marked progress, $PM_{2.5}$ emissions from transport are still about 7% higher nationwide in China than they are currently in the United States, with an important impact on human health. While the emissions standards successfully reduce exhaust emissions, the strong rise in overall vehicle-kilometres increases the share of non-exhaust emissions in total $PM_{2.5}$ emissions, which rise from 7% today to almost 25% by 2040. In addition, $SO_2$ emitted from the combustion of final transport fuels makes up only a small share of total energy-related $SO_2$ emissions. Efforts to strengthen fuel quality standards help contain the rise in $SO_2$ emissions, which peak at around 315 kt by around 2030 and then start to decline, despite a continued rise in oil demand.

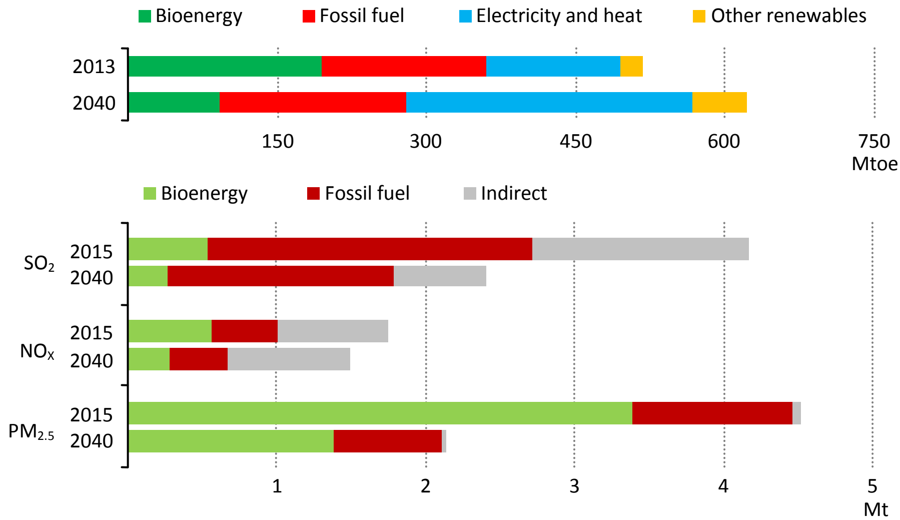
### *Outlook for the buildings sector*

Almost half of the Chinese population continues to rely on the use of solid fuels for cooking and heating today, mostly in rural areas; around two-thirds of these people use solid biomass, while the others use coal. Household air pollution in China is linked to around 1.2 million premature death cases in 2015.[4] The Chinese government has long put great emphasis on alleviating this problem: already by the end of the 1990s, the National Improved Stove Program had delivered around 180 million improved stoves to households around the country, targeting a reduction in biomass use (and in land degradation and deforestation). China's Ministry of Health launched another programme in the 1990s to promote "improved kitchens" in selected regions of the country, and most cities started to introduce or improve policies to promote the use of cleaner energy for cooking and heating during the 9th Five-Year Plan, encouraging households to switch from coal to either electricity or gas. These initiatives successfully reduced the use of solid biomass in the households, but coal consumption in the residential sector has been on the rise again, as urbanisation, higher incomes and changing lifestyles increase demand for space heating. Looking to future trends, additional initiatives (notably the China Clean Stove Initiative launched by the Ministry of Agriculture) help to tackle this issue and the number of people relying on traditional biomass for cooking decreases by two-thirds from today's 450 million. Nonetheless, around 170 million people are projected still to rely on the traditional use of biomass in China in 2040.

The reduction in biomass (and, to a lesser extent, coal) use for cooking and heating enables the residential sector to cut direct $PM_{2.5}$ emissions by more than half, and to decrease direct $NO_X$ and $SO_2$ emissions by one-third each (Figure 7.8). The reduction in $PM_{2.5}$ emissions plays an important role in reducing health impacts: the number of premature deaths associated with household air pollution falls by around 15% to around 1 million cases per year by 2040. Among broader trends in the residential sector, a continued focus on energy efficiency reduces electricity demand growth to around 3.5% per year on average, one-quarter of the level observed over the last decade, so limiting the sector's role in power-related emissions. In addition, upgrades to central heating systems in more than 30 cities by 2017 are expected to result in lower direct combustion of fuels in dwellings, reducing health impacts. Some cities aim at full-scale central heating upgrades in their industrial zones (Quzhou, Taizhou [Zhejiang Province], Dongguan and Yinchuan) while others have set high coverage targets in residential areas (Harbin, Shijiazhuang, Jiangmen and Handan).

[4] China has indoor air quality standards for households, limiting the concentration levels of particulate matter to 150 μg/$m^3$, but most households exceed this limit.

**Figure 7.8 ▷ Energy demand in buildings and related pollutant emissions by fuel in China in the New Policies Scenario**



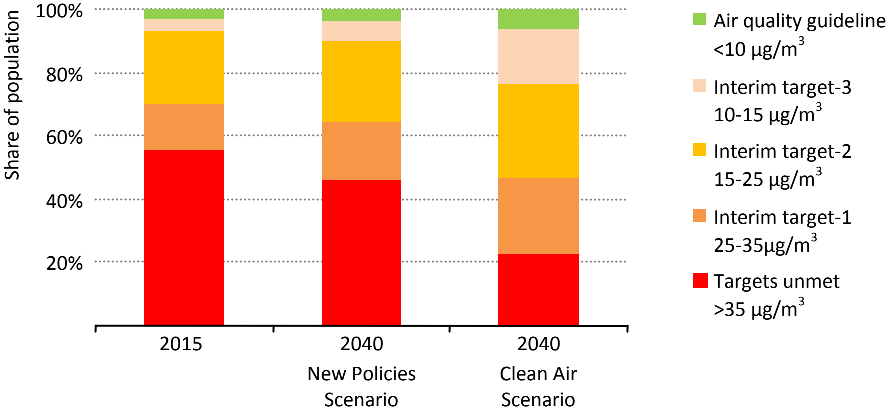

Sources: IEA; IIASA.

## *Improving the outlook for air quality to 2040: the Clean Air Scenario*

With a further strengthening of policy efforts, China has scope to realise additional improvements in air quality beyond those already anticipated in the New Policies Scenario. In the Clean Air Scenario, the national air quality target of 35 µg/m$^3$ is reached during the 2020s, much earlier than under existing and planned regulation in the New Policies Scenario. The number of people in China exposed to air quality that exceeds the WHO interim target-1 of 35 µg/m$^3$ in 2040 is significantly reduced to less than one-quarter of the population, compared with 46% in the New Policies Scenario (Figure 7.9).

This reduction in the concentration of air pollutant emissions brings significant health benefits. Life expectancy increases by six months by 2040 in the Clean Air Scenario, relative to the level achieved in the New Policies Scenario; this is 15 months more than today (Figure 7.10). The number of people dying prematurely due to outdoor pollution increases from around 1 million people today to around 1.5 million in 2040 in the New Policies Scenario as the ageing population of China means that an increasing number of people become vulnerable to the impacts of air pollution. The number of premature deaths associated with household air pollution falls to just below 1 million in 2040 in the New Policies Scenario. In the Clean Air Scenario, the impact of air pollution on human health is significantly reduced: premature deaths associated with outdoor air pollution fall to around 1 million cases by 2040, more than one-quarter below the level in the New Policies Scenario; those connected to household air pollution are reduced to around 560 000 in 2040.

**Figure 7.9 ▷ Population in China exposed to different $PM_{2.5}$ concentration levels according to WHO targets, by scenario**

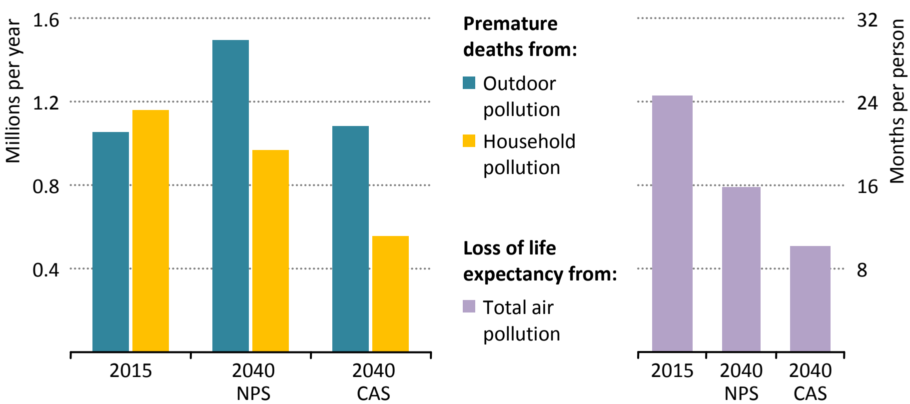



Source: IIASA.

In the Clean Air Scenario, emissions of the main air pollutants are reduced across all parts of the energy sector (Figure 7.11). $PM_{2.5}$ emissions fall to 2.2 Mt in 2040, an additional 60% gain, compared with the level achieved in the New Policies Scenario. Around 85% of the reduction in $PM_{2.5}$ emissions in the Clean Air Scenario is achieved within the next ten years, highlighting the rapid return available from stringent policy action. About half of the additional savings in 2040, relative to the New Policies Scenario, come from the residential sector, where the use of traditional cookstoves diminishes as people get access to cleaner alternatives. In the Clean Air Scenario, the urban population achieves full access to clean cooking alternatives (such as liquefied petroleum gas [LPG], natural gas and electricity) by

7

**Figure 7.10 ▷ Premature death cases and loss of life expectancy in China by scenario**

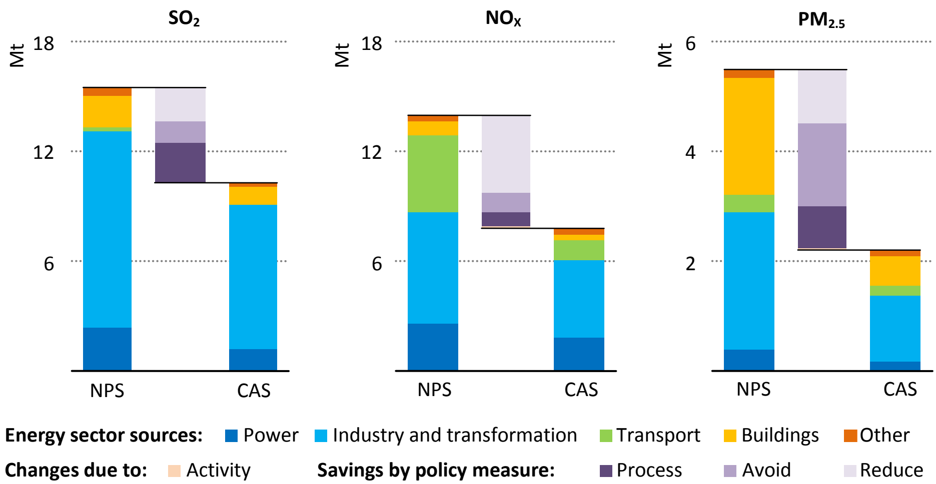



Note: NPS = New Policies Scenario; CAS = Clean Air Scenario.

Source: IIASA.

around 2020. On the back of strong policy support in the Clean Air Scenario, the rural population follows suit by the mid-2020s, mainly via alternatives such as LPG, solar-based stoves and improved and advanced cookstoves using processed biomass, such as briquettes and pellets, or fuelwood and charcoal in more efficient stoves equipped with chimneys (Spotlight in Chapter 3).

**Figure 7.11 ▷ Pollutant emissions savings by measure in China in the Clean Air Scenario relative to the New Policies Scenario, 2040**



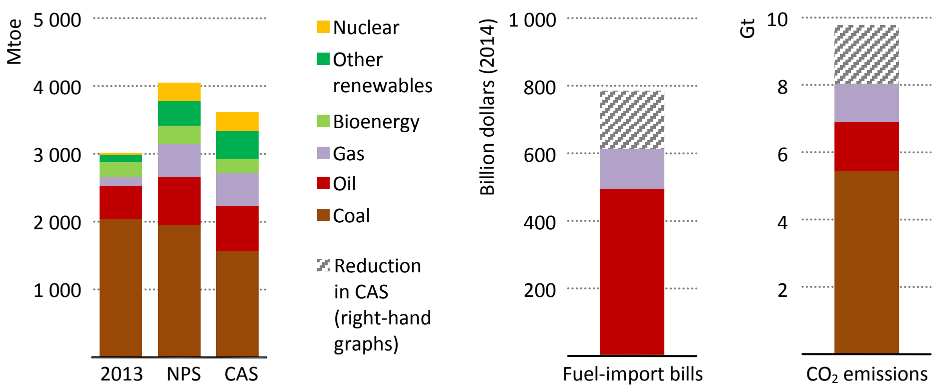

Sources: IEA; IIASA.

Around 40% of the savings in $PM_{2.5}$ emissions in 2040 in the Clean Air Scenario, relative to the New Policies Scenario, come from the industry and transformation sector. The largest savings are from reducing process-related emissions in the iron and steel sub-sector. The contribution of transport to reducing overall $PM_{2.5}$ emissions, at 5%, is relatively small, but the health impact of improvement in this sector is far greater. By 2040, transport-related $PM_{2.5}$ emissions are cut by half, relative to the New Policies Scenario. $PM_{2.5}$ emitted from heavy-duty vehicles is cut to near-zero by 2040, due to more stringent standards; but non-exhaust emissions from road vehicles remain significant even in 2040. In urban areas, emissions standards contribute almost half of the $PM_{2.5}$ savings from personal motorisation, relative to the New Policies Scenario, while strategies to avoid or shift traffic to mass transportation modes contribute a further one-third, fuel switching another 15% and improved fuel efficiency the remaining 5%.

Despite the already significant decline of $NO_X$ emissions in the New Policies Scenario, an additional 6.2 Mt are saved in the Clean Air Scenario by 2040, cutting $NO_X$ emissions by almost 45%. At around 50%, the largest share in these reductions comes from the transport sector, with enhanced emissions standards for heavy-duty vehicles playing a pivotal role. Total savings in urban areas are mostly related to passenger transport and are derived from emissions standards, the shift away from road transport to other modes and fuel switching to natural gas buses and electric urban delivery. The industry and transformation sector contribute around one-third of total $NO_X$ emissions reductions relative to the New Policies Scenario, due mainly to post-combustion exhaust gas treatment (in particular in the refining and chemicals sectors) and policies to reduce process emissions, although increased energy efficiency also contributes. The power sector, where emissions fall to 1.8 Mt in 2040 (750 kt below the level in the New Policies Scenario), contributes another 12% to total $NO_X$ reductions. This is largely due to the switch from inefficient coal-fired power stations to low-carbon alternatives, given the already strong regulatory efforts to reduce tailpipe emissions in the New Policies Scenario. In the Clean Air Scenario, the share of low-carbon fuels (excluding biomass) in the power mix increases from around 22% in 2013 to 49% in 2040, while the share of coal-fired power generation falls from 76% in 2013 to 39% in 2040.

China's $SO_2$ emissions fall by another 5.2 Mt in 2040 in the Clean Air Scenario, one-third below the level reached in the New Policies Scenario. The main source lies in the industry and transformation sector, the largest emitter of $SO_2$ emissions in China today, where there is a dramatic fall in process-related emissions e.g. from the cement, refining and pulp and paper industries. The power sector is another key contributor, thanks to policies promoting renewables and the phase-out of inefficient coal-fired power plants and measures to further stimulate the uptake of post-combustion control technologies to desulfurise the flue-gas stream.

**Figure 7.12 ▷ Energy demand and energy sector key indicators in China by scenario, 2040**




Note: NPS = New Policies Scenario; CAS = Clean Air Scenario.

The Clean Air Scenario brings important co-benefits. Demand for all fossil fuels is lower in 2040, relative to the New Policies Scenario, with coal demand dropping by 19%, oil demand by 10% and natural gas demand by 2%, resulting in lower import bills for fossil fuels (Figure 7.12). The power sector is responsible for 90% of the reduction in coal use, compared with the New Policies Scenario, while the increase in vehicle fuel economy, a modal shift that takes some passenger and freight traffic off the roads, and policies to promote fuel switching in urban areas are responsible for around 95% of oil demand reductions. Lower natural gas demand is due primarily to lower gas use in the power sector, but this is partially offset by increased gas use for buses in urban areas and in the residential sector. As a result of these trends, China's $CO_2$ emissions in 2040 are reduced by 1.7 gigatonnes, or 17%, compared with the New Policies Scenario.

# India

## Highlights

- Eleven of the world's 20 most polluted cities are in India and poor air quality is already a major public health issue: around 590 000 premature deaths were attributable to outdoor air pollution in 2015 and about 1 million premature deaths to household air pollution. Average life expectancy in India today is reduced by 23 months because of air pollution. Demographic trends, rising incomes, urbanisation and industrialisation are all driving up energy consumption and worsening air pollution.
- Existing and planned policies in India help contain pollutant emissions growth in the New Policies Scenario: $SO_2$ and $NO_X$ emissions each grow by about 10% to 2040, and $PM_{2.5}$ emissions by 7%, despite strong economic growth. The New Environment Protection Amendment Rules are particularly effective in cutting power sector pollutant emissions and the new Bharat VI standard brings down $NO_X$ and $PM_{2.5}$ emissions in transport. But these achievements are more than offset by strong growth in emissions from the industry and transformation sector. The net result is that air quality remains an important policy concern through to 2040. Although the average loss of life expectancy declines to 16 months, the number of people dying prematurely from outdoor air pollution grows to over 900 000. The number of premature deaths associated with household air pollution drops to around 800 000 as the use of cleaner cookstoves expands.
- The Clean Air Scenario demonstrates the positive impact that timely and more stringent air pollution regulations can have on public health in a country that has yet to build the bulk of its energy and industrial infrastructure. Achieving universal access to clean cooking facilities, imposing emissions standards on heavy-duty vehicles, more stringent fuel-quality standards and limits on emissions from the industry and transformation sector, all contribute to a significant drop in emissions by 2040: $SO_2$ emissions are lower by more than 70% compared with the New Policies Scenario, $NO_X$ emissions are down by more than half and $PM_{2.5}$ emissions are cut by almost 80%. By 2040, the average loss of life expectancy drops to eight months and the number of premature deaths attributable to air pollution to around 560 000 (outdoor pollution) and 360 000 (household air pollution). In the Clean Air Scenario, almost 10% of the population in 2040 live in areas meeting the World Health Organization air quality guideline, compared with less than 1% today.

## *The energy and air quality context*

India is in the midst of a profound transformation of its economy and its place in global energy affairs. As China's growth slows and becomes less energy-intensive, India assumes the role of prime motor of global energy demand. With over one-sixth of the world's population today but only 6% of global energy use, the scope for a rapid expansion in India's energy consumption is clear and new policies have been introduced – on the both supply and demand sides – to provide for this. Rising levels of access to modern energy, incomes, urbanisation and industrialisation (e.g. via the "Make in India" initiative) are the forces that underpin India's energy outlook. But there is a major risk that these same forces may also lead to a worsening of India's already bad air quality, especially given the importance in India's energy mix of coal (44% of total energy demand), biomass (24%) and oil (23%) and today's relatively small shares of natural gas (6%), renewables (2%) and nuclear (1%).

India is very densely populated, with some 420 inhabitants per $km^2$ (12 times the population density of the United States) and has more than 45 cities with a population exceeding one million. In many of them – including Delhi, Mumbai, Chennai and Kolkata – air quality is already a serious problem: of the 20 most polluted cities in the world, according to the WHO, 11 are in India (WHO, forthcoming) (Box 8.1). India is still in the early stages of its economic development, with policy makers facing a number of economic and environmental challenges, and trade-offs. Nonetheless, air pollution is progressing up the list of policy priorities. It has been identified as the fifth most important cause of mortality (Atkinson R., et al., 2011). In many parts of India, air pollution has become a potent issue of public concern, especially among India's growing urban middle classes.

Since the mid-1980s, ambient air quality is being monitored across the country under the National Air Monitoring Programme, which was initiated by the Central Pollution Control Board (CPCB). Currently there are more than 580 air quality monitoring stations in service. They cover some 245 cities (including the above-mentioned 45 one million plus cities) in 28 states and five union territories. Particulate matter (PM) is currently the main concern as concentrations exceed the standards (60 $\mu g/m^3$ for $PM_{10}$) in many of the monitoring locations.[1] Nitrogen oxides ($NO_X$) are becoming increasingly problematic with measurements indicating concentrations that approach or exceed the standards (40 micrometres per cubic metre [$\mu g/m^3$]) in a growing number of locations. Sulfur dioxide ($SO_2$) concentrations are generally below the set limits (50 $\mu g/m^3$) in the measurement locations, primarily due to the combustion of coal with low-sulfur content.

As elsewhere, air pollution comes from a number of energy-related sources including vehicle tailpipes, thermal power stations, back-up generators, brick kilns, industrial activity

[1] Size is an important factor in determining the health impacts of PM: "coarse particles" are between 2.5 and 10 micrometres (μm) in diameter and "fine particles" are smaller than 2.5 μm.

and biomass burning for cooking and heating. In India, non-energy related air pollution from road dust, waste and agricultural burning and construction activity also plays an important role. The residential sector – especially through the traditional use of biomass – is the main contributor to $PM_{2.5}$ emissions, accounting for nearly two-thirds of India's total. This traditional use of biomass for cooking and heating remains the mainstay of rural energy supply: around two-thirds of the Indian population today uses solid fuels as their primary fuel for cooking. The adverse consequences fall predominately on women and children, who suffer the worst health effects of the smoky indoor environment (see Chapter 3 Spotlight).

$NO_X$ emissions primarily arise in the transport sector, which contributes 40% to the total, followed by the power sector (around 30%) and the industry and transformation sector (around 20%). Most of the $NO_X$ emissions in transport come from road transport, mainly from heavy-duty vehicles (HDVs) such as trucks and buses. Mass transport modes, such as buses and rail, are important sources of mobility in India, although there is a trend towards greater individual motorisation (as in other emerging economies and many industrialised countries).

The power sector is the source of more than half of $SO_2$ emissions from the energy sector. Coal is the core fuel of the Indian power system, accounting for almost three-quarters of the power supply. Indian coal is relatively low in sulfur, but has high-ash content – three-quarters of current coal production has ash content of 30% or more, with some of the highest ash coals approaching 50%. Imported coal, especially coal from Indonesia has more modest ash levels and is low in sulfur too. The composition of domestic coal compounds India's problem with PM emissions as, if not adequately controlled for, high-ash coals result in elevated dust emissions. In 2015, India formulated a set of emission standards for $SO_2$, PM and $NO_X$ for large combustion plants, supplanting the previous standards that primarily targeted PM.

Despite the former absence of emissions standards for $SO_2$ and $NO_X$, a number of plants have installed control technologies for these pollutants but this equipment is often of sub-optimal quality or operated inefficiently. Regulation of PM emissions promoted the installation of particulate control technology in many coal-fired power stations: we estimate that over 85% of the coal plants in India use some sort of control device, most commonly electrostatic precipitators (ESP). But these are often absent from smaller industrial power and heat generation units. State-of-the-art ESPs can achieve dust removal efficiencies of 99%, but reaching such high levels requires a sound configuration of the control device with the plant's operational characteristics and the coal type. Introducing strict monitoring of plant emissions is a necessary step in the face of widespread lack of compliance with pollution control regulations.

**Box 8.1 ⊳** **Delhi: addressing a multitude of pollutant sources through energy and air quality policies**[2]

Delhi, India's capital and home to more than 16 million inhabitants, has been plagued by poor air quality for more than a decade. Ambient concentrations of respirable $PM_{2.5}$ have been more than ten-times in excess of the WHO air quality guideline value (see Chapter 1). This has earned Delhi the title of the world's most polluted city.

Although the transport sector is often the focus of media attention, air pollution in Delhi comes from a wide range of sources. In response to the problem, several key measures have been implemented for more than a decade. These include:

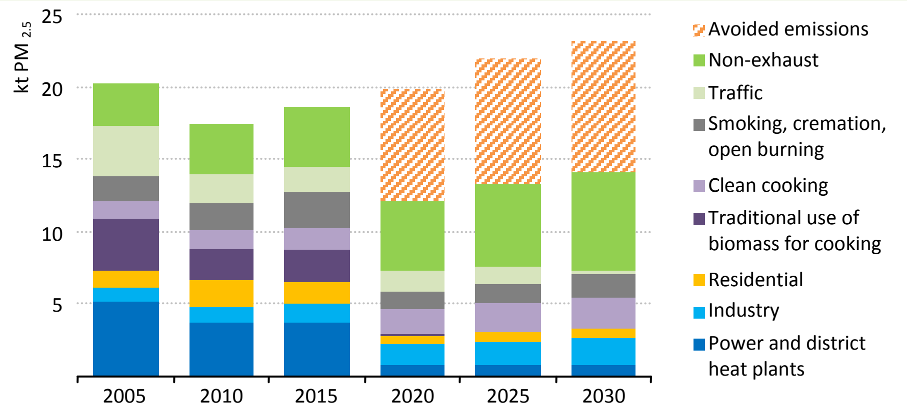
- Highly polluting industries, such as cellulose production, cement manufacturing, production of fertiliser and inorganic chemicals, paper, rubber and wood industries and brick kilns, were required to relocate outside Delhi.
- All public transport buses were converted from diesel to compressed natural gas, as well as many three-wheelers and taxis. In addition, national emissions standards were adopted earlier than elsewhere for vehicles registered in Delhi.
- Some coal-fired power plants were converted to natural gas.
- Open burning of waste was prohibited in Delhi.
- Most recently, the Government of India has imposed a partial circulation ban on private cars, allowing their operation only every second day, based on licence plate number.

Although these measures have been effective in relation to particular sources of pollution, their beneficial effects have quickly been offset as a result of the total growth of population and economic activity. In any case, local measures alone will not be sufficient to achieve low PM concentrations in the city, as primary and secondary particles are imported from outside the region: imposing emission controls upwind can actually be the most cost-effective way of tackling pollution. Significant air pollution abatement in Delhi depends upon a comprehensive approach including tackling all the major sources, and due consideration of their geographic origin and dispersal patterns.

Traditional use of biomass for cooking and two coal-fired power plants (Badarpur and Rajghat) are the two main sources of $PM_{2.5}$ emissions in Delhi. Without action to tackle these emissions, among others, PM emissions in Delhi are expected to increase by 25% over the next 15 years under current legislation (Figure 8.1) Emissions could fall by 35% over the next 15 years, if effective measures to reduce emissions from the power sector and traditional open cooking were taken and proved successful.

[2] The analysis is part of ongoing research conducted by A. Bhanarkar et al. from the National Environmental Engineering Research Institute NEERI and P.Purohit et al. from IIASA.

**Figure 8.1 ▷ Reducing $PM_{2.5}$ emissions from the power sector and the traditional use of biomass for cooking in Delhi**




Note: kt = kilotonnes.

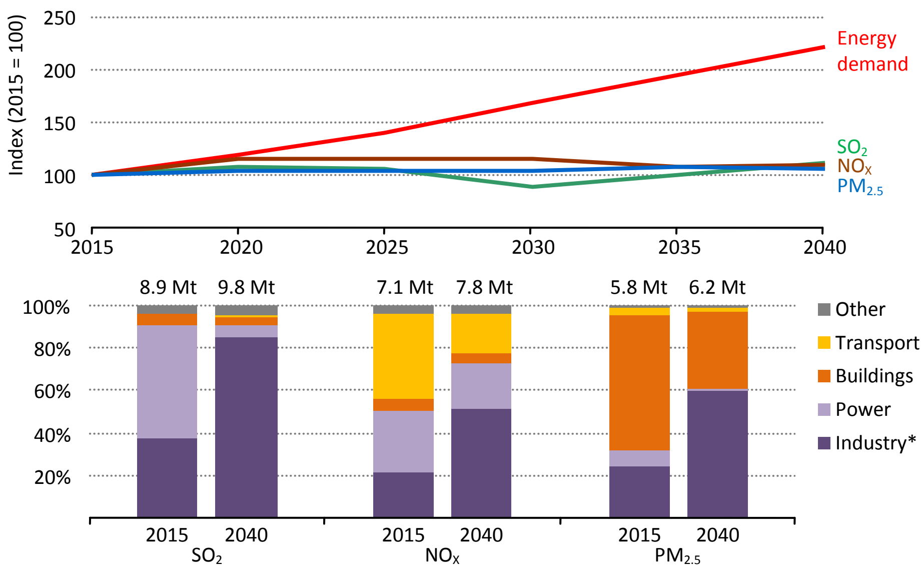
## *The outlook for air quality to 2040: the New Policies Scenario*

In our projections, India's energy consumption more than doubles to 2040 – growing in absolute terms by more than any other country – as the Indian economy expands more than five-fold. Such an expansion will lift millions of people out of poverty and help progress to universal access to electricity, bring higher incomes and improved quality of life to many millions. Mobilising the investment required to meet India's burgeoning energy needs will be a major challenge; and achieving this growth while keeping the environmental footprint of energy production and use in check, will be a very demanding task.

India is expected to become the most populous country in the world by the mid-2020s. The resulting increase in population density – to an average of 540 inhabitants/km$^2$ in 2040 – would put India's population density on a par with that of the Netherlands today. An additional 315 million people are expected to be added to the urban population by 2040, with associated increased demand for housing and for the energy-intensive products – steel, cement, glass – required for new infrastructure. We estimate that three-quarters of India's housing stock in 2040 has yet to be built – a major challenge, yet also an opportunity to build in best available efficiency (especially for cooling). Among the issues to be tackled is adequate dust suppression, without which severe non-energy related PM emissions from construction activity would compound the energy-related strains on air quality. On the transport side, a wealthier population demands greater mobility and an additional 255 million passenger cars are added to India's vehicle stock over the period to 2040 in the New Policies Scenario.

Policy action to curb the growth of air pollutant emissions is essential. Absent the policy efforts anticipated in the New Policies Scenario, $SO_2$ and $PM_{2.5}$ emissions would roughly double by 2040 and $NO_X$ emissions would grow almost 2.5 times. New power sector regulation is the main factor that limits $SO_2$ emissions growth to around 10% to 2040 relative to today, while continued efforts to promote access to clean cooking facilities among poorer households are necessary to moderate the rise in $PM_{2.5}$ to around 7%. $NO_X$ emissions growth is contained to 10% in 2040 by new standards for passenger cars in the transport sector (Figure 8.2).

**Figure 8.2 ▷ Emissions by air pollutant and by energy sector in India in the New Policies Scenario**




* Includes transformation (except power generation).

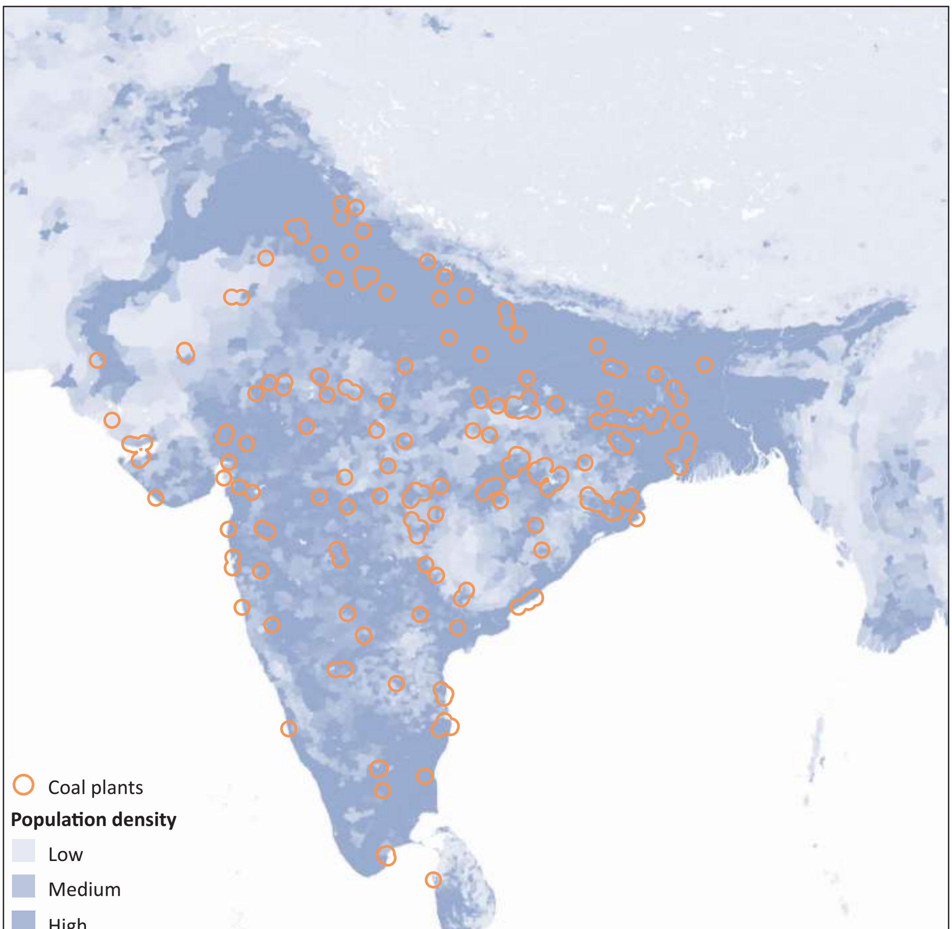
Sources: IEA; International Institute for Applied Systems Analysis (IIASA).

The implications of our outlook for public health remain severe. Although measures are taken to bring down emissions intensities across all sectors, the absolute growth in emissions – especially $PM_{2.5}$ – coupled with strong population growth means the number of premature deaths attributable to outdoor air pollution will grow significantly. A fall is anticipated in premature deaths associated with household air pollution (from 1 million per year today to some 800 000 in 2040). The average loss of life expectancy from air pollution falls from 23 months today to 16 months in 2040.

*Outlook for the power sector*

Power generation in India more than triples over the *Outlook* period and despite a rapid expansion of solar photovoltaics (PV) and wind power (underpinned by ambitious government targets), coal remains the mainstay of the power system in the New Policies Scenario. With nearly 1 500 terawatt-hours (TWh) of additional power generated from coal in 2040, coal exhibits much stronger absolute growth than any other source of power generation in India. As power plants are often located near cities, towns and villages (Figure 8.3), the potential impact on health is significant. While around a quarter of the population lives in close proximity to a coal plant, less than 5% live near a plant that is not fitted with dust control equipment and this situation is expected to improve.

**Figure 8.3 ▷ Coal-fired power plants and population density on the Indian sub-continent, 2015**




This map is without prejudice to the status of or sovereignty over any territory, to the delimitation of international frontiers and boundaries and to the name of any territory, city or area.

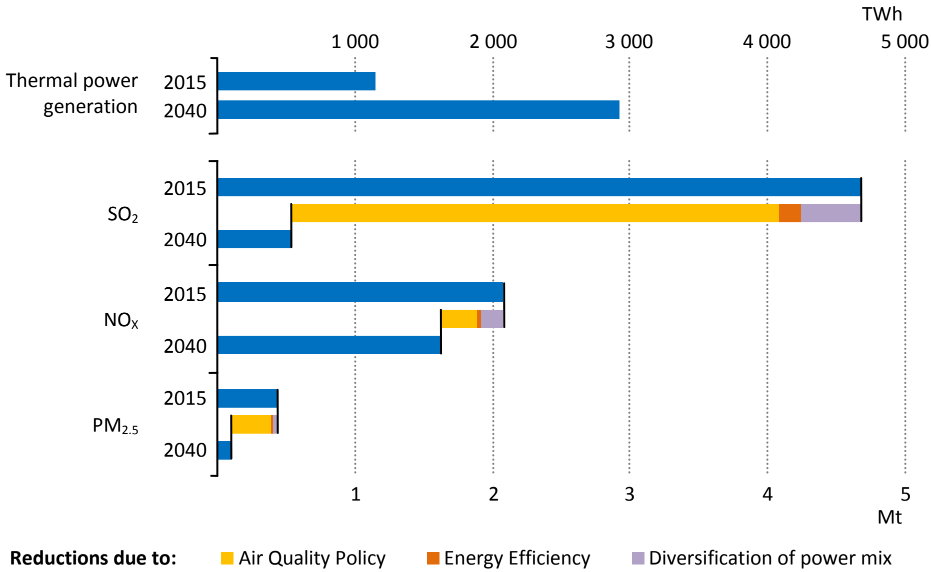
Source: IEA analysis based on Platts World Electric Power Plants database and CoalSwarm.

In December 2015, the Environment Protection Amendment Rules (EPAR) strengthened the emissions standards for new and existing plants. The limit for PM from new power plants is 30 $mg/m^3$, while the limit for existing plants is 50 $mg/m^3$ or 100 $mg/m^3$ depending on when the plant was built. The EPAR also put new limits on $SO_2$ and $NO_X$ emissions from coal-fired power plants, which are comparable in to those in place in the Europe Union and the United States. Even though the coal types used in India are usually quite low in sulfur content, the new rules will require considerable retrofit investment in scrubbers and other control technologies. Full compliance with the new standards is to be achieved by end-2017.

There is considerable risk of delays and non-compliance in the application of the EPAR. Nonetheless, timely implementation of the rules along with improvements in generation efficiency and the diversification of the power mix can deliver a reduction in $SO_2$ emissions from the power sector by almost 90% over the period to 2040 (from 4.7 Mt to some 0.5 Mt) and in PM emissions by three-quarters. (Power mix diversification is foreseen in current and planned policies with rapid growth in non-biomass renewables and nuclear generation.) $NO_X$ emissions are more than 20% lower by 2040, as a strong decrease in emissions from coal plants is partially offset by increases from gas-fired plants and biomass combustion. Implementation of EPAR requires the bulk of the currently installed 174 gigawatts (GW) of coal-fired capacity to be retrofitted with modern control technology, while the 305 GW that are projected to be built over the *Outlook* period come with a full set of state-of-the-art technologies for $NO_X$, $SO_2$ and PM control. Some coal plants can comply with the $SO_2$ regulation of EPAR by burning low-sulfur domestic coal or importing low-sulfur coal, e.g. from Indonesia. Increased coal washing, underpinned by a requirement that coal which is transported more than 500 kilometres (km) must have an ash content below 34%, helps to reduce fly ash – or particulate matter – from power generation. Of the total reductions, stronger regulation via EPAR is responsible for some 85% of the achieved $SO_2$ and $NO_X$ reductions and almost 90% of the fall in $PM_{2.5}$ emissions (Figure 8.4). Power sector diversification – or fuel switching – contributes significantly to the reduction of $NO_X$ (11%), $SO_2$ (10%) and $PM_{2.5}$ (8%). The adoption of more efficient generation technologies explains the remainder.

The standards set by EPAR are stringent and achievable. Yet they will not be delivered without effective compliance that needs to be closely monitored at the plant level with penalties for non-compliance. The cumulative investments required in control technology of around $145 billion are large, but the value of the social and public health benefits obtained in terms of improved air quality is much greater. The real challenge lies in finding ways to enable the generators investing in control technology to recoup the additional cost without which they are unlikely to be able to finance the investment. This is a big hurdle in India, where prices for power are heavily regulated and full cost recovery is not always guaranteed (IEA, 2015).

**Figure 8.4 ▷ Change in electricity generation and air pollutant emissions in India in the New Policies Scenario**




Sources: IEA; IIASA.

### *Outlook for the industry and transformation sector*

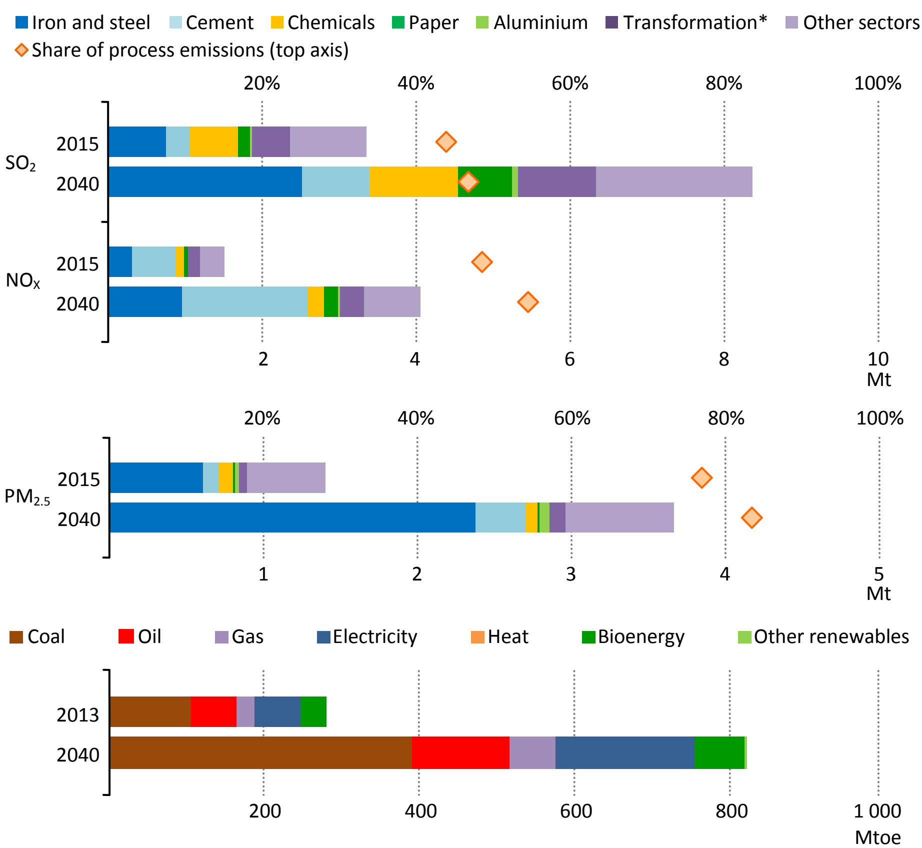
With the "Make in India" initiative, the government is seeking to rebalance the composition of economic activity towards industry-led growth. This can bring multiple benefits, but will also place additional demands on the energy sector (a unit of gross domestic product derived from industry typically uses at least ten-times as much energy as one created in the services sector) with direct consequences for air quality. Industry today gives rise to one-third of total energy-related $SO_2$ emissions in the country, nearly one-quarter of $PM_{2.5}$ emissions and around one-fifth of $NO_X$ emissions.

India's CPCB is gradually establishing emission standards for key industrial sectors: for example, the cement and steel sub-sectors have standards for PM, $NO_X$ and $SO_2$ emissions, while other sub-sectors (e.g. aluminium, large paper production facilities and small boilers) currently only have PM emission limits. $SO_2$ emissions are often tackled by the imposition of minimum stack height requirements and standards depending on the age or size of the installations. However, in some cases, controls are applied to reflect the greater health risks near populated area. Other policy efforts will help curb pollutant emissions growth, notably efforts to increase industrial energy efficiency via the Perform, Achieve and Trade scheme, an innovative market-based trading programme for efficiency certificates that is now being extended to energy transformation sectors (including refineries).

8

The gradual implementation of tighter emissions standards for industry is expected to improve the emissions intensity of key industrial sectors in the New Policies Scenario. However, in most cases, regulation in India today is considerably weaker than in other countries. For instance, PM emission limits for most iron and steel processes (e.g. blast furnaces, sintering plants and basic oxygen furnaces) are set three-times higher in India than in China (150 micrograms per cubic metre [mg/m$^3$] compared with 50 mg/m$^3$) and 7.5 times higher than in Germany (20 mg/m$^3$) (World Steel Association, 2014). The environmental performance of industry in India nonetheless is projected to fail to meet the best international emission standards in 2040.

**Figure 8.5 ▷ Air pollutant emissions and energy mix in the industry and transformation sector in India in the New Policies Scenario**




Notes: Mtoe = million tonnes of oil equivalent; kt = kilotonnes. * Transformation refers to fossil fuels (e.g. oil refining, oil and gas production, liquefied natural gas terminals), but excludes power and heat generation. The industry and transformation sector includes non-energy uses (mainly petrochemical feedstocks).

Sources: IEA; IIASA.

As a result, despite policy efforts to improve emissions intensities, the sheer growth in industrial output means a large absolute increase in pollutant emissions in the New Policies Scenario. By 2040, $SO_2$, $NO_X$ and $PM_{2.5}$ emissions from the industry and transformation sector are all about two-and-a-half times higher than in 2015 (Figure 8.5). Three energy-intensive sectors (steel, cement, chemical and petrochemical sectors) give rise to the vast majority of emissions for each pollutant today and remain their dominant source by 2040. The steel sector alone gives rise to 45% of total $PM_{2.5}$ emissions from the industry and transformation sector today and this share increases to about two-thirds by 2040 as crude steel production increases by a factor of 4.5, compared with 2015 levels. Despite the low-sulfur content of Indian coal, $SO_2$ emissions also increase dramatically, especially from the iron and steel sub-sector. As in many Southeast Asian countries, high $SO_2$ and $PM_{2.5}$ emission levels from brick kilns are and will remain an important health hazard in cities, due to the kilns' proximity to where people live and breathe, even though their share in total industry-related emissions decreases (Box 8.2).

**Box 8.2 ▻ Brick kilns in India**

About 90% of the world's brick production is concentrated in China and South Asia (including India, Pakistan, Bangladesh and Nepal). After China, India is the second-largest brick producer in the world, with an estimated production of 250 billion bricks per year. The brick industry is a large energy consumer (almost 15% of total industrial energy demand) and a significant source of air pollutants: 11% of industrial $SO_2$ emissions and about 17% of industrial $PM_{2.5}$ emissions. The industry employs more than 10 million workers in around 140 000 brick kilns around the country (Maithel, 2013), with a large concentration in the Indo-Gangetic Plain in the north, where more than half of the Indian population lives.

The structure of the brick industry in India is very different from that in developed countries. There are many small plants and heavy reliance on traditional production methods (including fixed chimney bull trench kilns and brick clamps), resulting not only in large quantities of $SO_2$ emissions but also the emission of black carbon (a particularly damaging sub-category of $PM_{2.5}$, both from a health and a climate change perspective). Partly because of the incomplete burning of biomass and coal in the brick industry, the Indo-Gangetic Plain is a major global source for black carbon. The large reliance on manual labour in the brick industry, its close proximity to urban areas and the concentration of production in only three to four months of the year amplifies the adverse health impacts.

The Indian authorities started to tackle emissions from the brick industry in 1996 by setting emissions standards, but achieving compliance is a major challenge. In this very dispersed and fragmented sector improving operating practices, including internal fuel-firing (making use of fly ash from coal-fired power plants) and adopting more modern brick technologies, such as zig-zag firing or variable shaft brick kilns, can cut PM emissions by up to 50% (Shakti foundation 2012). Producing hollow instead of solid bricks in modern tunnel kilns can significantly reduce emissions levels.

*Outlook for the transport sector*

Passenger vehicle ownership in India has nearly tripled over the last decade, bringing with it a strong increase in tailpipe and non-exhaust emissions and thus more damage to human health: around three-quarters of total passenger vehicle-kilometres in India today are driven in urban areas. The CPCB set the first emission standards in the mid-1980s for gasoline and diesel vehicles. The current nationwide regulatory standard for light- and heavy-duty vehicles is Bharat Stage III, comparable to Euro 3 for light-duty vehicles (LDVs) and Euro III for HDVs.

Many of India's most populous cities have adopted more stringent emissions standards, in advance of their adoption nationwide, putting in place Bharat IV (analogous to Euro 4) standards in 2010 (Table 8.1). The government has announced its intention to make Bharat IV standards universal for LDVs and HDVs across the country by 2017. In February 2016, the government further issued a "draft notification" to move to Bharat VI nationwide for LDVs and HDVs alike by April 2020[3], essentially skipping Bharat V. Implementing Bharat VI will limit gasoline and diesel fuels to 10 parts per million (ppm) of sulfur, bringing India into line with the global leaders in fuel sulfur standards.

Initiatives to reduce air pollution from road transport in India stem from various sources. In addition to policy initiatives taken at different levels of government, the Indian Supreme Court rulings on the situation in Delhi over the years have led to the retirement of commercial vehicles older than 15 years, the conversion of all commercial passenger vehicles (including buses, taxis and three-wheelers) to compressed natural gas (CNG) and a temporary ban on the sale of new diesel vehicles with engines above a certain size. These measures, often reinforced – as in the case of CNG – by supportive national and municipal policies, have diminished emissions intensity, but this benefit is more than offset by ongoing strong demand growth for mobility and so transport energy use: Delhi remains among the most heavily polluted cities in the world. The National Electric Mobility Mission Plan 2020 aims to achieve sales of 6-7 million hybrid and electric vehicles per year by 2020, a market dominated by two-wheelers.

Co-ordinated urban planning and investment in public transport, as envisaged in the Smart Cities Mission, offers a promising avenue to curb transport-related air pollution. The development of Delhi's metro rail system (following earlier systems in Kolkata and Chennai), is one such example, the adoption of which is being considered by the authorities in many of India's other large cities, such as Lucknow, the capital city of Uttar Pradesh. Another option is the development of systems for rapid transit by bus. Such systems have been implemented in eight Indian cities, accommodating more than 400 000 passengers per day along bus corridors of a combined length of almost 170 kilometres. Some of these

[3] For heavy-duty vehicles, Bharat VI implies the adoption of the more stringent world harmonised stationary cycle (WHSC) and world harmonised transient cycle (WHTC) test cycles, off-cycle emissions testing and in-service conformity testing and the issuance of specifications for portable emissions measurements systems testing at type approval.

initiatives, as in Ahmedabad, have proved successful, although the experience in some other cities shows that these achievements are far from easy.

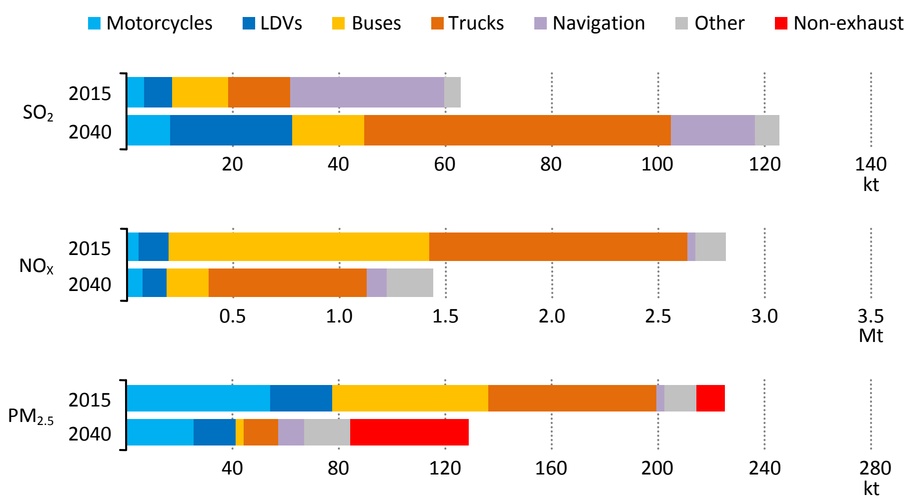
**Table 8.1 ▹ Emissions limits for selected air pollutants in road transport in India**

| Target | Fuel | Standard | Implementation for all sales and registrations | PM limit | $NO_X$ limit | Sulfur limit | Unit |
|---|---|---|---|---|---|---|---|
| **Passenger light-duty vehicles** | Gasoline | Bharat III | 2010 | - | 0.15-0.21 | - | g/km |
| | | Bharat IV | 2017 | - | 0.08-0.11 | - | g/km |
| | | Bharat VI | 2020 | 0.0045 | 0.06-0.082 | - | g/km |
| | Diesel | Bharat III | 2010 | 0.05-0.1 | 0.50-0.78 | - | g/km |
| | | Bharat IV | 2017 | 0.025-0.06 | 0.25-0.39 | - | g/km |
| | | Bharat VI | 2020 | 0.025-0.06 | 0.08-0.125 | - | g/km |
| **Two-wheelers** | Gasoline | Bharat III | 2010 | - | 1.0 | - | g/km |
| | | Bharat IV | 2017 | - | 0.20-0.39 | - | g/km |
| | | Bharat VI | 2020 | 0.045 | 0.06 | - | g/km |
| | Diesel | Bharat III | 2010 | 0.05 | 0.5 | - | g/km |
| | | Bharat IV | 2017 | - | 0.20-0.39 | - | g/km |
| | | Bharat VI | 2020 | 0.045 | 0.09 | - | g/km |
| **Three-wheelers** | Gasoline | Bharat III | 2010 | - | 1.3 | - | g/km |
| | | Bharat IV | 2017 | - | 0.2 | - | g/km |
| | | Bharat VI | 2020 | - | 0.085 | - | g/km |
| | Diesel | Bharat III | 2010 | 0.05 | 0.5 | - | g/km |
| | | Bharat IV | 2017 | 0.0425 | - | - | g/km |
| | | Bharat VI | 2020 | 0.025 | 0.1 | - | g/km |
| **Heavy-duty vehicles** | | Bharat III | 2010 | 0.16-0.22 | 3.5 | - | g/km |
| | | Bharat IV | 2017 | 0.03 | 3.5 | - | g/km |
| | | Bharat VI | 2020 in selected cities | 0.01 | 0.46 | - | g/km |
| **Fuel quality** | Gasoline | Bharat III | 2010 | - | - | 150 | ppm |
| | | Bharat IV | 2017 | - | - | 50 | ppm |
| | | Bharat VI | 2020 | - | - | 10 | ppm |
| | Diesel | Bharat III | 2010 | - | - | 350 | ppm |
| | | Bharat IV | 2017 | - | - | 50 | ppm |
| | | Bharat VI | 2020 | - | - | 10 | ppm |

Notes: g/km = grammes per kilometre. Limit ranges reflect different vehicle sizes or engines. Earlier implementation of the Bharat IV standard occurs only in selected regions.

In the New Policies Scenario, passenger car ownership grows from less than 20 vehicles per 1 000 inhabitants today to 175 cars per 1 000 people in 2040, and overall road passenger vehicle activity increases more than six-times. Despite fuel-economy improvements in the LDV and HDV fleets, transport oil demand rises from 1.5 million barrels per day (mb/d) today to more than 5 mb/d in 2040 (and, as in other regions, the uptake of alternative fuels remains limited). The projected adoption of Bharat VI does constrain the growth in air pollutant emissions from transport (Figure 8.6). Transport currently accounts for about 40% of energy-related $NO_X$ emissions in India, but as emissions decline by 50% to 1.4 Mt in 2040, the share drops to less than a fifth. The decline is underpinned by increasing stringency of standards for HDVs with a key role for buses. India remains heavily reliant on road freight in the New Policies Scenario despite the intention to move part of this load to new dedicated rail freight corridors. But with gradual introduction of Bharat VI starting in selected cities, emissions from freight trucking drop by 40% in the period to 2040, despite burgeoning industrial output.

**Figure 8.6 ▷ Air pollutant emissions by transport type in India in the New Policies Scenario**




Sources: IEA; IIASA.

Transport plays a relatively minor role (less than 5%) in India's energy-related emissions of $PM_{2.5}$, but the level of PM emissions by trucks, buses and two-stroke motorcycles is higher than in many other countries. Successful efforts to control exhaust emissions from buses (and a move away from two-stroke motorcycles) are projected to put total transport-related $PM_{2.5}$ emissions on a declining trend over the next ten to fifteen years, but then emissions flatten, as the passenger vehicle fleet grows and offsets some of the declines.

Non-exhaust emissions also contribute to $PM_{2.5}$ emissions growth. Currently they are responsible for only 5% of transport-related $PM_{2.5}$ emissions, while the increase in vehicle activity pushes their share to some 35% by 2040. Emissions from transport fuels contribute less than 1% of India's total energy-related $SO_2$ emissions today. In the *Outlook*, the majority of the projected growth in energy-related $SO_2$ emissions is from road freight vehicles, even taking account of the planned tightening of the relevant fuel-quality standards.

### *Outlook for the buildings sector*

Solid fuels are the primary source for cooking for about two-thirds of the people in India. This reliance is changing in urban areas where the use of solid biomass for cooking is on the decline. Only one-quarter of urban households use solid biomass for cooking today, down from a 50% share 25 years ago. Yet, reliance remains high in rural areas at about 85%. The adverse consequences of cooking with solid fuels predominately affect women and children, who are the most at risk from the health impacts of a smoky indoor environment. The government's PaHal scheme seeks to ameliorate this by promoting liquefied petroleum gas (LPG) as a cleaner alternative. The PaHal scheme entitles qualified households to buy 12 cylinders of LPG per year each. The purchase attracts a direct subsidy payment to the user's bank account (making this one of the world's largest cash transfer programmes for social purposes). Efforts have also been made to reduce household air pollution by encouraging a switch to more efficient biomass cookstoves and by promoting biogas as a cooking fuel, but these have yet to achieve results on the anticipated scale. A recently launched programme, called UJJWALA, aims to provide free LPG for domestic cooking needs to women living below the poverty line in rural areas. Some 50 million households below the poverty line are expected to be eligible for the programme.

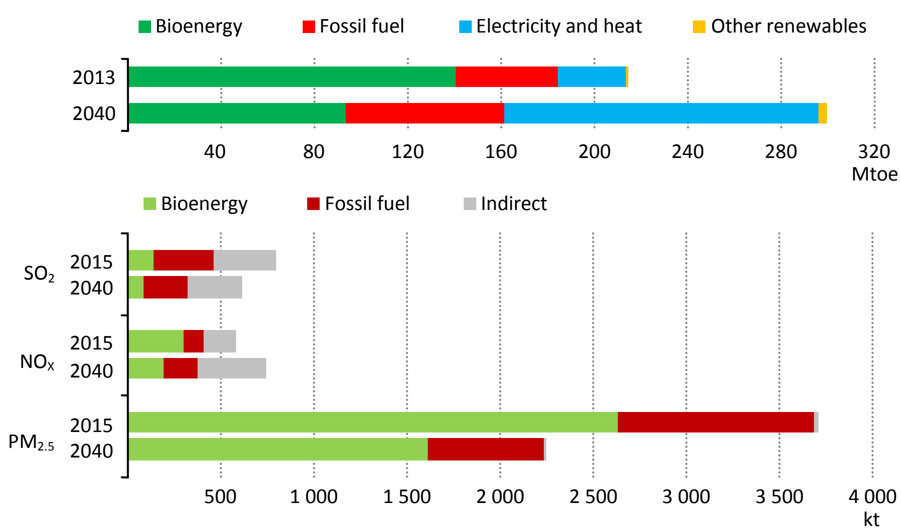
Cooking is not the only domestic activity in India that contributes to household air pollution. Around 240 million people remain without access to electricity (some 20% of the population) and many millions more suffer from unreliable supply, especially during demand peaks in the evenings.[4] Kerosene lamps are widely used for lighting (biomass, torches, candles and solar lamps are used by only around 1% of the population). Kerosene lamps are used on a regular basis by 30% of Indian households (around 80 million). Smoke from kerosene contains a high level of PM, especially black carbon (see Chapter 1, Box 1.2).

PM emitted by combustion activities in the buildings sector represents almost two-thirds of total energy-related PM emissions in India today (the sector accounts for only a small share of total $NO_X$ and sulfur oxides emissions). The way that this evolves in the projections is shaped by the major progress that India is expected to make in household electrification, achieving universal access to electricity by 2040. This achievement, combined with reliable electricity supply, enables kerosene use for lighting to be phased out, significantly reducing the health impacts of household fuel combustion by 2040.

[4] Noteworthy initiatives for increasing access to electricity or clean off-grid lighting solutions are the Remote Village Electrification Programme to provide clean lighting, the Global Off-Grid Lighting Association (GOGLA) initiative and the Lighting Asia/India Consumer Awareness Campaign.

In the New Policies Scenario, the number of people without access to clean cooking facilities is projected to decline from around 840 million today to 480 million by 2040, all living in rural areas. All urban households switch from solid biomass and kerosene as cooking fuels by 2040, instead using LPG and, in some instances, piped natural gas and electricity. These improvements cut $PM_{2.5}$ emissions from the buildings sector by 40% in 2040, compared with today (Figure 8.7). $NO_X$ emissions from the sector decrease slightly because of reduced use of solid biomass, although emissions from the consumption of oil products in residential and commercial buildings see a rise. $SO_2$ emissions also fall due to a decrease in use of solid biomass and the phase-out of kerosene lamps. Electricity demand in the buildings sector increases almost five-fold to 2040: the indirect emissions of $SO_2$ and PM from the power sector associated with this electricity consumption fall (following the implementation of EPAR), but $NO_X$ emissions more than double.

**Figure 8.7 ▷ Energy demand in buildings and related pollutant emissions by fuel in India in the New Policies Scenario**

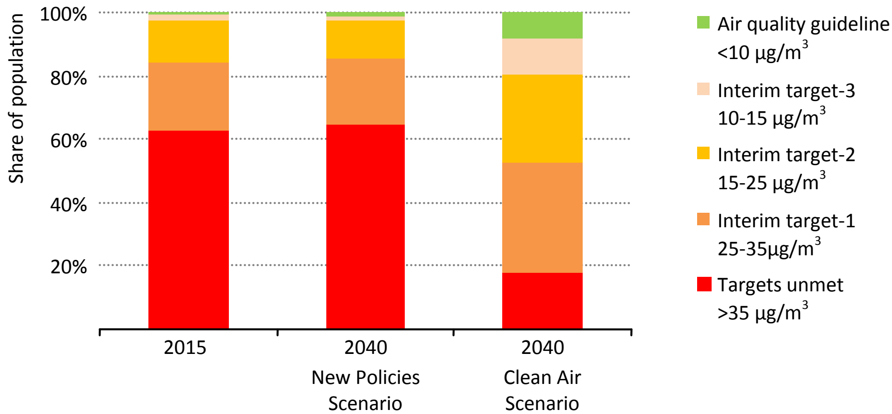



Sources: IEA; IIASA.

## *Improving the outlook for air quality to 2040: the Clean Air Scenario*

The New Policies Scenario sees India take important steps to tackle the issues of air pollution, but much more could be done. By 2040, the Clean Air Scenario still sees two-thirds of India's population living with air pollution levels that exceed the WHO interim target-1 (Figure 8.8). Implementation of the policies proposed in the Clean Air Scenario would cut average nationwide $PM_{2.5}$ emissions by 80% below the level in the New Policies Scenario. As a result, the share of the population living with air pollution above the WHO interim target-1 would fall to less than 20%.

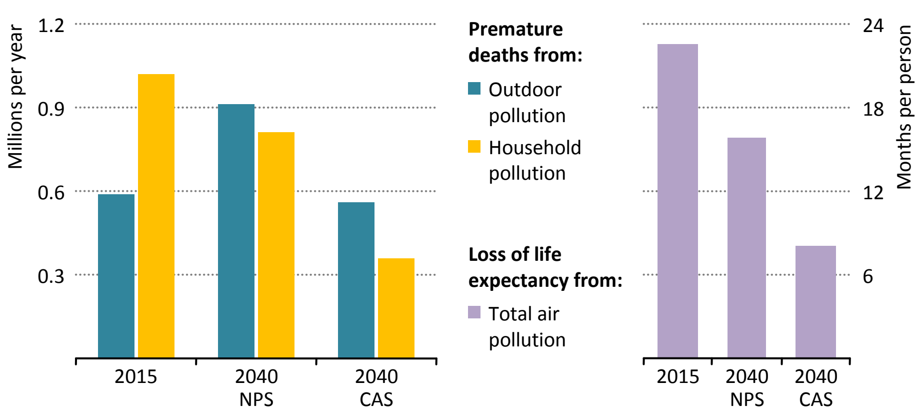
**Figure 8.8 ▷ Population in India exposed to different $PM_{2.5}$ concentration levels according to WHO targets by scenario**




Source: IIASA.

The Clean Air Scenario brings about a marked improvement in public health: on average, by 2040, people live eight months longer than in the New Policies Scenario and 15 months longer than today (Figure 8.9). Premature deaths associated with outdoor air pollution are cut by 40%, relative to the New Policies Scenario, to around 560 000 cases in 2040. The number of people exposed to indoor $PM_{2.5}$ emissions from the traditional use of biomass for cooking falls considerably as India achieves universal access to clean cooking facilities by 2040, diminishing premature deaths associated with household air pollution to around 360 000 cases in 2040.

**Figure 8.9 ▷ Premature death cases and loss of life expectancy in India by scenario**



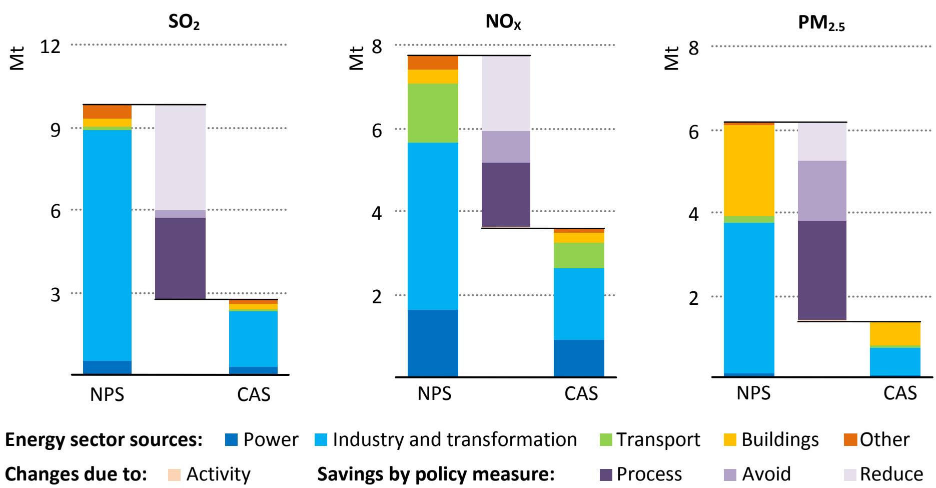

Note: NPS = New Policies Scenario; CAS = Clean Air Scenario.

Source: IIASA.

8

In the Clean Air Scenario, total energy-related $PM_{2.5}$ emissions drop by almost 80% relative to the New Policies Scenario, to reach 1.4 Mt in 2040 (Figure 8.10). Although all sectors contribute, the buildings and industry sectors combined account for some 90% of the reduction, spurred by the introduction of modern fuels and more efficient cookstoves in rural households and a halving of industrial $PM_{2.5}$ emissions. In industry, the main reductions are achieved in iron and steel manufacturing, underlining the huge impact that timely implementation of stringent standards can have in a country that is yet to build a large part of its energy and industrial infrastructure.

**Figure 8.10 ▷ Pollutant emissions savings by measure in India in the Clean Air Scenario relative to the New Policies Scenario, 2040**



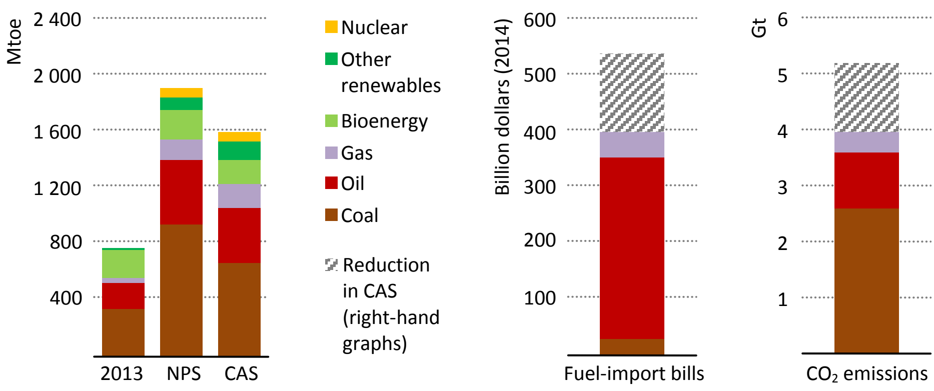

Sources: IEA; IIASA.

The power and transport sectors make, in absolute terms, a comparably small contribution to India's $PM_{2.5}$ emissions reductions in the Clean Air Scenario. Yet, given the country's high population density and the close proximity of power plants to where people live, plus the strongly growing traffic volumes, the drop in $PM_{2.5}$ emissions from the power and transport sectors has a disproportionately positive effect on public health. Power sector $PM_{2.5}$ emissions are cut by half in 2040 in the Clean Air Scenario relative to the New Policies Scenario, due to further diversification of the power mix and strengthened emissions standards. The share of coal in power generation halves from 73% today to 37% in 2040. In the transport sector, $PM_{2.5}$ emissions are down by almost 50% in 2040 relative to the New Policies Scenario, with the bulk of the additional reduction coming from two- and three-wheelers as the promotion of electric two-wheelers brings their share in the fleet to more than 85% in 2040, compared with less than 1% today.

The Clean Air Scenario sees $NO_X$ emissions cut by half to 3.6 Mt in 2040 relative to the level in the New Policies Scenario. More than 50% of this reduction comes from the industry and transformation sector, in particular from reducing process-related emissions in the cement industry. Industry emissions still increase, albeit moderately, as there is limited potential to switch to cleaner fuels and the typically smaller size of industrial boilers (compared with power stations) reduces the effectiveness of $NO_X$ control. Stringent standards, applied to larger facilities, thus remain the main policy option to contain $NO_X$ emissions growth in the industry and transformation sector. The transport sector is the second-largest contributor to the savings, in large part through further reductions from road freight vehicles and buses. $NO_X$ emissions from the power sector also fall and, by 2040, are some 45% lower than in the New Policies Scenario, with most of the reduction coming from accelerated deployment of renewables and more stringent regulation. $NO_X$ control technology typically achieves lower removal efficiencies than $SO_2$ or PM control equipment. Hence, a shift away from combustion-based power generation to renewables such as wind, solar or hydropower can often achieve a considerable reduction of $NO_X$ emissions.

Total $SO_2$ emissions fall to 2.7 Mt in 2040 in the Clean Air Scenario, a drop of 70% relative to the New Policies Scenario. Industry contributes 80% of the reduction, reflecting the lack of regulatory efforts to-date. Emissions are cut across all industries, with the largest scope in the sectors that grow fastest such as iron and steel, and cement. Power generation, the main source of $SO_2$ emissions today, accounts for only a minor share of the reduction, relative to the New Policies Scenario, given the sharp drop under EPAR rules already achieved in the New Policies Scenario.

**Figure 8.11 ▷ Energy demand and energy sector key indicators in India by scenario, 2040**




Note: NPS = New Policies Scenario; CAS = Clean Air Scenario.

The improvement in air quality, in the Clean Air Scenario delivers complementary benefits. The increase in end-use efficiency and diversification of the power sector away from coal means that annual $CO_2$ emissions in 2040 are some 1.2 gigatonnes lower than in the New Policies Scenario (Figure 8.11). In the Clean Air Scenario, oil imports are 13% lower than in the New Policies Scenario and coal imports are halved while gas imports are 22% higher.

The annual oil import bill drops by some $110 billion and the coal import bill by $25 billion in 2040 relative to the New Policies Scenario, while the increase in natural gas imports is offset by a lower gas price in the Clean Air Scenario, delivering an unchanged import bill.

# Southeast Asia

## Highlights

- Air pollution is a pressing concern in many countries in the Southeast Asia region. Its sources are multiple and varied. Nevertheless, the energy sector plays a key role. Although air quality standards often are in place, enforcement is weak. Reliance on traditional use of bioenergy for cooking in some countries is a major contributor to air pollution. In 2015, Indonesia experienced around 70 000 premature deaths associated with outdoor pollution and 140 000 associated with household air pollution.
- Energy demand rises at a rapid pace to almost 1 100 Mtoe in 2040 in the New Policies Scenario, 80% more than today's level. The absence of stringent air quality policies and strong growth in coal demand mean that emissions rise: $SO_2$ and $NO_X$ emissions each grow by some 45% through to 2040. $PM_{2.5}$ emissions fall by 13%, as the share of people without access to clean cooking devices falls from 45% today to 30% by 2040. Yet 225 million people in the region still rely on the traditional use of biomass for cooking by 2040 and the associated health impacts remain severe: the number of premature deaths in Indonesia associated with outdoor air pollution rises to almost 120 000 in 2040 and premature deaths related to household air pollution decline only modestly to 120 000.
- There is particular scope for the measures in the Clean Air Scenario to be effective in Southeast Asia. Emissions of $SO_2$ and $NO_X$ are some 75% lower in 2040 compared with the New Policies Scenario while emissions of $PM_{2.5}$ are 85% lower. Universal access to clean cooking devices is reached by 2035 and universal access to electricity by 2030. The results are very beneficial for human health: premature death cases in Indonesia from outdoor air pollution drop to 19 000 in 2040 and from household air pollution to around 45 000. By 2040, more than 80% of the Indonesian population enjoys air quality levels that comply with the WHO guidelines for $PM_{2.5}$ (from over 40% today).

## *The energy and air quality context*

The circumstances of the ten countries that belong to the Association of Southeast Asian Nations are diverse in economic, political and energy terms, but all share a common characteristic – rapid growth. The region's economy has doubled in size since 2000, while the population has grown by around 20% and the share of people living in urban areas increased from less than 40% in 2000 to over 45% today. This rapid growth in the economy and population has been accompanied by a strong rise in energy demand, which has grown by around 55% since 2000. In this period, energy demand growth was met by coal and natural gas (both at around 30%), oil (27%) and bioenergy (10%), although renewables such as hydropower, solar and wind have been making inroads.[1] Yet, despite the formidable growth in supply, close to 20% of the population still has no access to electricity and around 45% have no access to clean cookstoves, relying instead, on the use of fuelwood and charcoal for cooking. The combination of rapid economic and energy demand growth, with increasing urbanisation and reliance on the traditional use of biomass presents a serious threat in terms of air pollution. Air quality standards are in place in several countries in the region (Table 9.1). However, while some of the standards comply with the World Health Organization (WHO) interim targets, enforcement action is limited and concentration limits are frequently exceeded.

**Table 9.1 ▷ Selected ambient air quality standards in Southeast Asia** (μg/m³)

| Country | $PM_{2.5}$ | | $SO_2$ | | $NO_2$ | |
|---|---|---|---|---|---|---|
| | 24 hour | Annual | 24 hour | Annual | 24 hour | Annual |
| Brunei Darussalam | - | 15 | - | - | - | - |
| Cambodia | - | - | 300 | 100 | 100 | - |
| Indonesia | 65 | 15 | 365 | 60 | 150 | 100 |
| Lao PDR | - | - | 300 | 100 | - | - |
| Malaysia* | - | 35 | 105 | - | - | - |
| Myanmar | - | - | - | - | - | - |
| Philippines** | 50 | 25 | 180 | 80 | 150 | - |
| Singapore | 37.5 (25) | 12 (10) | 50 (20) | 15 | - | 40 |
| Thailand | 50 | 25 | 300 | 100 | - | 57 |
| Viet Nam | 50 | 25 | 125 | 50 | - | 40 |

Notes: PDR = People's Democratic Republic; targets for 2020, values in brackets are long-term targets; *interim target for 2015; **$PM_{2.5}$ represents revised standards in 2016.

Source: Clean Air Asia ( 2016).

Combustion of coal for power generation and industrial processes are the largest sources of energy-related $SO_2$ emissions in Southeast Asia today, together accounting for around three-quarters of the total 3.9 million tonnes (Mt) of sulfur dioxide ($SO_2$) emissions. Almost half of the $SO_2$ emissions from coal-fired power generation occur in Indonesia alone – roughly matching its share of the regional coal-fired power generation fleet. Energy-related nitrogen oxides ($NO_X$) emissions were 5.7 Mt in Southeast Asia in 2015, of which around two-thirds were the result of oil combustion, primarily in the transport sector. The number of private cars in the region more than doubled from around 10 million in 2000 to more than 20 million today, reflecting income growth, although two- and three-wheelers and public buses remain important sources of mobility and, hence, urban $NO_X$ emissions (Box 9.1). Fine particulate matter ($PM_{2.5}$) emissions from the energy sector in Southeast

[1] For an in-depth analysis of energy developments, challenges and opportunities in the region, see *World Energy Outlook-2015 Special Report: Southeast Asia Energy Outlook*, available as a free download at: *www.worldenergyoutlook.org/southeastasiaenergyoutlook*.

Asia are very high, at almost 3 Mt in 2015, mostly generated in the residential sector. More than 90% of the emissions from households arise from the use of fuelwood and charcoal for cooking and heating: around 275 million people, 45% of the regional population of the region, of which around 98 million are in Indonesia, still have no access to clean cookstoves. The consequent human and environmental burden of air pollution in the region is considerable.

**Box 9.1 ▹ Shifting from motorcycles to public transport: Jakarta**

Jakarta, the capital of Indonesia, is grappling with significant levels of air pollution: in 2013, the annual average concentration of $SO_2$ monitored across the metropolitan area reached 68 µg/m$^3$, and $NO_2$ 38 µg/m$^3$ (BPLHD, 2013). Annual $PM_{10}$ concentrations have consistently been above the WHO guidelines since 2005, reaching 73 µg/m$^3$ (24-hour mean) in 2012 (Firdaus R., 2013). The impact is severe: an analysis by the Indonesian Ministry of Environment estimated the annual costs of health impacts in Jakarta in 2010 at $535 million (Safrudin A., et al., 2013).

Road traffic is a significant source of air pollution in Jakarta. The city has experienced a rapid increase in the number of registered passenger cars and motorcycles, growing by 12% per year in the period 2009-2014. Today, there are more than 3 million cars and 13 million motorcycles on the road, contributing to traffic congestion and air pollution. Another important factor is some 30 000 public buses: many are very old, produced prior to any emissions standards, with very high emission levels. High purchase taxes on public buses (16-20% versus 6-10% for private cars) are one factor holding back fleet renewal.

In the short term, further reducing fuel sulfur levels, upgrading the truck and bus fleets, and implementing and aggressively enforcing fuel quality and tailpipe emissions standards can mitigate negative public health effects in Jakarta (Chambliss and Bandivadekar, 2014). Much of such action will rest with the national government. The local government is taking additional measures to combat traffic-related air pollution. Encouraging fuel switching to low-emissions vehicles is one such measure, including to electric vehicles and natural gas fuelled two- and three-wheelers, buses and trucks. Another is efforts to promote the shift to alternative modes of transport after decades of underinvestment in public transit, an important part of the future mitigation strategy for a city with an urban form that is notoriously unconducive to walking and cycling. TransJakarta, the city’s bus rapid transit system, began operations in 2004, and additional corridors were added in 2014-2015. A metro system is currently being built. The Sustainable Urban Transport Program Indonesia (NAMA SUTRI) is implementing a €14 million project from 2014-2018 to co-fund transport demand management projects including walking and cycling and “park and ride” infrastructure in selected Indonesian cities. Such projects are of vital importance. Ultimately, Jakarta’s air pollution problems will require breaking the monopoly of motorcycles and cars.

*Cambodia* does not have a national air quality policy in place, but the government imposed air pollution controls in 2000 with standards for ambient air quality and emissions limits for stationary and mobile sources. The general air quality situation is challenging. Ambient concentrations of PM are very high, in particular in urban areas: Cambodia's capital, Phnom Penh, is one of the most heavily polluted cities in the world. The Office of Air Quality, Noise and Vibration Management is in charge of managing and monitoring urban air quality. Air quality monitoring systems, however, are generally limited (although international donors are working to support solutions) and overall environmental pollution has become a major challenge to World Heritage sites, such as the Angkor Archaeological Park. Today, Cambodia's energy sector relies on the use of bioenergy (almost 70%) and oil (nearly 30%), with the residential sector being responsible for two-thirds of total bioenergy use, primarily for cooking. Cambodia's COP21 climate pledge refers to a number of energy sector priorities, which could have a significant impact on reducing air pollution, for example through the promotion of mass public transport, energy efficiency for buildings and more efficient cookstoves and expanding the use of renewables.

*Indonesia* is the largest economy in the region, representing 40% of the region's economy and population, and 36% of its primary energy demand. National ambient air quality standards meet the WHO interim target-1 for PM emissions, but not for $SO_2$ and $NO_X$. National government regulations for air pollution control specify ambient air quality standards and emissions standards for industrial activities and motor vehicles. Provincial governments can set additional standards that are more stringent. Energy-related air pollution is a significant problem in Indonesia, arising especially from transport and power generation, and while an air quality monitoring system exists, enforcement of regulations is often insufficient and the availability of real-time data limited. A major contribution to the air pollution problem in Indonesia comes from outside the energy sector: the open burning of waste and forest fires, often from the illegal clearance of land for agricultural purposes, is a significant source of air pollution. The effects cross into neighbouring countries and generate controversy at the highest political levels.

Indonesia's energy demand today relies heavily on the combustion of oil, meeting 36% of total energy demand, bioenergy (26%) and coal (15%). Indonesia is among the few countries in the region that made explicit reference to the energy sector in its climate pledge at COP21, with an increase of "new and renewable energy" to 23% in 2025 featuring as part of its ambitious mitigation strategy.

The national ambient air quality standards in *Malaysia* generally comply with the WHO interim targets and the environmental air quality (clean air) regulations, which date back to the late 1970s, are frequently reviewed. With its history of air quality management, Malaysia has well-developed monitoring systems and the Environmental Strategic Plan for 2011-2020 has a requirement to maintain good air quality. Today Malaysia's energy demand is largely satisfied by natural gas (43%), oil (35%) and coal (17%) with additional minor contributions from bioenergy and hydropower. Malaysia made an unconditional pledge at COP21 to reduce its greenhouse-gas emissions intensity by 35% by 2030 from

2005 levels. Its main features are the 2014 Roadmap of Emissions Intensity Reduction towards a reduction of carbon dioxide ($CO_2$) emissions intensity by 40% in 2030 relative to 2005 and its 2010 Renewable Energy Policy and Action Plan.

The Clean Air Act of 1999 is the foundation of air quality policy in the *Philippines*, and which sets outs implementing rules. National ambient air quality standards today meet WHO interim targets or guidelines in all cases except for $SO_2$. Progress has been sustained in recent years. Even so, and despite 44 air quality monitoring systems being in place, implementation and enforcement of the Clean Air Act remains challenging, with emissions from transport and the burning of waste being the most serious problems. Energy use in the Philippines today is relatively diversified: the main sources are oil (30%), coal (24%), (non-biomass) renewables (20%), bioenergy (18%, half of which is used for cooking and heating in the residential sector) and natural gas (7%). No explicit energy sector targets were expressed in the climate pledge of the Philippines at COP21, which instead opted for a 70% reduction of greenhouse-gas emissions by 2030 relative to a business-as-usual scenario.

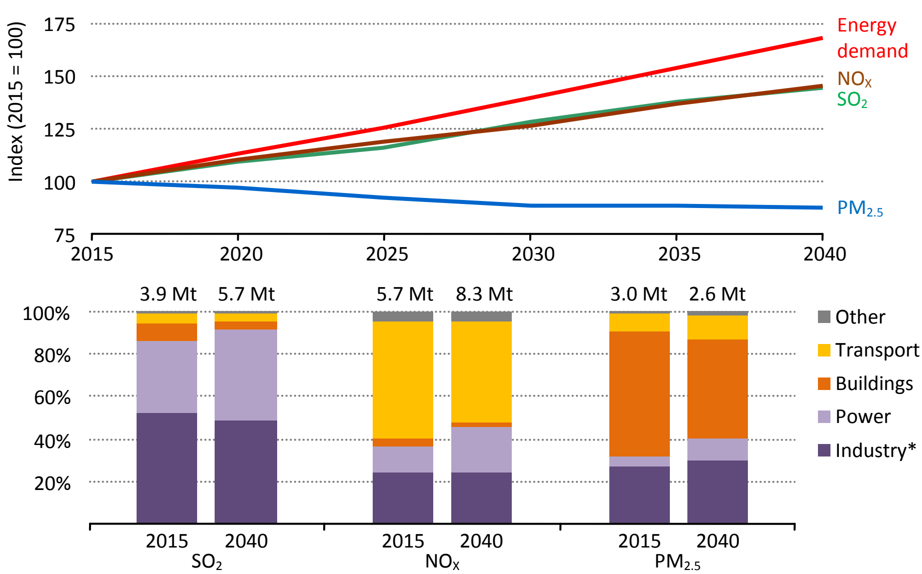
*Thailand* is actively addressing air pollution and has air quality standards in place that partly meet WHO interim targets. There is legislation in place specific to several mobile and stationary sources, and 53 air quality monitoring stations provide relevant data. Bangkok, long known as one of the most polluted cities in the world, has made significant improvements in air quality by reducing emissions from transport (achieved through the introduction of vehicle and fuel-emissions standards, switching to natural gas use for public buses and supporting public transport). Yet, air quality remains a major policy concern for Thailand given its continued strong growth in demand for energy and mobility, and continuing problems with the enforcement of regulations. Energy use in Thailand today largely derives from oil (40%), natural gas (28%), coal (13%) and bioenergy (19%), all of which contribute in varying degrees to air pollution. In its climate pledge at COP21, Thailand referred to three key energy policy pillars: the Power Development Plan, the Alternative Energy Development Plan and the Energy Efficiency Plan. These plans provide for the attainment of a 20% share of renewables in power generation and 30% in total final energy use by 2036, plus a 30% reduction in energy intensity in the same year from the 2010 level.

*Viet Nam* has adopted ambient air quality standards that meet WHO interim targets or meet recommended standards. However, enforcement is weak: in practice, 98% of the population is exposed to $PM_{2.5}$ levels exceeding those in the ultimate WHO guidelines, with traffic being the main source. Viet Nam is planning to develop a new law on Clean Air. Three-quarters of energy use in Viet Nam today is satisfied (in almost equal parts) by coal, oil and bioenergy, while natural gas (14%) and hydro (8%) account for much of the remainder. Among the measures to support its climate pledge are energy efficiency policies, changes to the fuel mix in the industry and transport sectors, and the promotion of new and renewable sources in energy production and use.

## *The outlook for air quality to 2040: the New Policies Scenario*

In the New Policies Scenario, energy demand in Southeast Asia grows at a rapid pace to almost 1 100 million tonnes of oil equivalent (Mtoe) in 2040, 80% over the level reached in 2013. At 2.2%, annual growth in energy demand exceeds the global average, although it is lower than in recent years due to slower economic and population growth, a switch away from the traditional use of biomass and energy efficiency improvements. While all fuels contribute to meet energy demand growth, coal is the largest contributor, driven by strong growth in the power sector, where coal overtakes natural gas to become the dominant fuel. The share of coal in total power generation is projected to increase by 17 percentage points, to almost 50%, by 2040, despite efforts to decarbonise the power sector and to increase the use of renewables, as expressed in some of the region's climate pledges. In the New Policies Scenario, Indonesia alone accounts for almost 40% of total energy demand growth and 45% of the increase in coal use, as coal-fired power generation provides two-thirds of total electricity generation, up from about half today. The share of the population relying on the use of fuelwood and charcoal for cooking in the buildings sector falls from 45% today to 30% in 2040; but there are still 225 million people relying on the traditional use of bioenergy for cooking by 2040.

**Figure 9.1 ▷ Emissions by air pollutant and by energy sector in Southeast Asia in the New Policies Scenario**




* Includes transformation (except power generation).

Sources: IEA; International Institute for Applied Systems Analysis (IIASA).

The projected robust rise in energy demand entails strong growth in $SO_2$ and $NO_X$ emissions. $SO_2$ emissions grow by 45% over current levels, to 5.7 Mt in 2040, driven by rising coal use in power generation, which accounts for two-thirds of total $SO_2$ emissions growth (Figure 9.1). As a result, the levels of $SO_2$ emissions from the power sector match $SO_2$ emissions from the industry and transformation sector by around 2040. $NO_X$ emissions rise by almost 50%, to 8.3 Mt in 2040, with two-thirds of the total growth attributable to increased coal use in the power sector and rising oil use in transport (where car ownership rises from around 35 cars per 1 000 inhabitants today to more than 80 per 1 000 inhabitants in 2040). Although $NO_X$ emissions from the industry and power sectors grow faster, the transport sector remains by far the largest source of $NO_X$ emissions in 2040, contributing almost half of the total. Driven by lower use of traditional fuelwood and charcoal for cooking, emissions of $PM_{2.5}$ decline slowly to around 2.6 Mt in 2040, 13% below current levels. Yet, households remain the largest source of $PM_{2.5}$ emissions and a key contributor to human health problems.

### *Outlook for the power sector*

Southeast Asian countries all have different power systems, but they share a prospect of very strong electricity demand growth over the *Outlook* period. The region as a whole is projected to see its power demand almost triple, reaching close to 2 000 terawatt-hours (TWh) in 2040. Natural gas is the dominant fuel in power generation in Southeast Asia today, accounting for a 45% share. Yet, abundant low-cost coal reserves in the region – especially in Indonesia and Viet Nam – combined with strong economic growth and electrification, lead to a surge in coal demand, making it the number one source for power generation around 2020. By 2040, every other megawatt-hour is generated from coal.

Although all major coal-consuming countries in the region have emissions regulations in place, the standards vary in stringency. For instance, new plants in Thailand typically have to meet $SO_2$ levels of 180 milligrams per cubic metre ($mg/m^3$), (roughly comparable with regulations in the European Union and the United States), a result of the lessons learned from severe $SO_2$ pollution episodes caused by lignite-fired power plants during the 1990s. $SO_2$ emission standards in Indonesia and Viet Nam are less stringent (750 $mg/m^3$ and 500 $mg/m^3$ for existing and new plants respectively), but the problem of $SO_2$ emissions is somewhat mitigated by the prevalence of very low sulfur coal in Indonesia, which is increasingly exported to power plants across the region. PM and $NO_X$ emissions are also regulated in all major coal-consuming countries but, again, their stringency varies. Generally, the limits for new power plants are much more ambitious than for existing plants. For example, Malaysia and Indonesia set a $PM_{2.5}$ limit of 50 $mg/m^3$ and 100 $mg/m^3$ for new plants respectively, while Viet Nam requires new plants to comply with a limit of 200 $mg/m^3$.

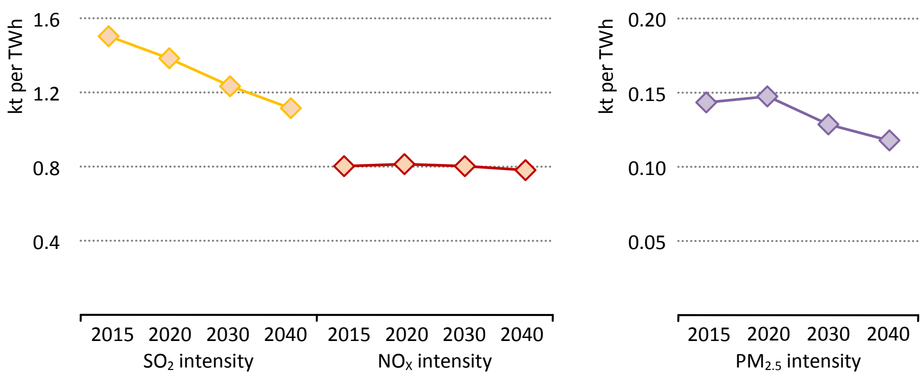
**Box 9.2 ▷ The role of clean coal technologies in mitigating air pollution in Southeast Asia**

In the New Policies Scenario, Southeast Asia increasingly relies on coal-fired power generation over the period to 2040. Around 145 gigawatts (GW) of new coal-fired capacity are built in the region. Applying best available technologies is therefore critical to containing air pollutant emissions growth. Ultra-supercritical technology (with efficiencies typically between 40% and 44%) is gradually making inroads to the coal-fired power generation sector around the world. With 130 GW, China has the largest ultra-supercritical plant fleet, followed by 16 GW in Japan and 8.5 GW in the European Union. Japan has been a key developer of high-efficiency coal-fired technology: its Isogo ultra-supercritical plant came online as early as 2002 (followed by a second unit in 2009). Isogo is an example of Japan's policy to use coal as cleanly and as efficiently as possible. The plant is located in Yokohama near Tokyo (one of Japan's most densely populated metropolitan areas) and is equipped with flue-gas desulfurisation and a multi-pollutant control system that removes $NO_X$, dust and mercury. Emissions of $PM_{2.5}$, $SO_2$ and $NO_X$ are extremely low at 1 mg/$m^3$, 6 mg/$m^3$, and 20 mg/$m^3$ respectively, while achieving an efficiency of 42%.

Malaysia is the first country in Southeast Asia to adopt ultra-supercritical power generation technology. Manjung unit 4, located near Lumut about 200 km north of Kuala Lumpur, went online in 2015 and achieves an efficiency of 40%. The plant is equipped with a seawater flue-gas desulfurisation system (FGD) that removes up to 90% of the $SO_2$, bringing $SO_2$ emissions to 200 mg/$m^3$, well below the country's regulatory standard of 500 mg/$m^3$. A combination of over-fire air and other measures to tackle $NO_X$ formation reduce the plants $NO_X$ emissions to 500 mg/$m^3$ – fully consistent with national regulations. Manjung 4 uses a fabric filter system to control particulate emissions, bringing the plant's $PM_{2.5}$ emissions below the standard of 50 mg/$m^3$. Thailand is soon to follow suit, with an ultra-supercritical lignite unit at its Mae Moh plant scheduled to go online in 2018. The plant will be equipped with an FGD system that removes up to 98% of the $SO_2$ and electrostatic precipitators that remove 99.9% of the particulate matter. There is significant potential to introduce more efficient coal-fired power plants in Southeast Asia (IEA, 2015). However, deployment faces various challenges, including lack of financial resources and building the operational capacity to achieve the stated efficiency potential.

Air pollutant emissions from power generation in Southeast Asia increase significantly over the *Outlook* period: $SO_2$ emissions nearly double, $PM_{2.5}$ emissions double and $NO_X$ emissions grow 2.5 times. These trends are primarily caused by the strong rise in power generation and the shift to increased use of coal. They occur despite governments in Southeast Asia setting more stringent standards for new coal plants and pushing for the construction of efficient supercritical and ultra-supercritical plants (Box 9.2). Even so, since three-quarters of the coal fleet operating in 2040 has yet to be built, setting challenging emissions standards promptly is of the utmost importance and has a profound impact. The emissions intensity of $SO_2$ and $PM_{2.5}$ (expressed as kilotonnes [kt] of pollutant per TWh) decreases markedly over time as the share of renewables increases and new plants comply with more stringent limits (Figure 9.2). For $NO_X$, regulations on new plants are projected to be insufficiently stringent to lead to a decline in intensity, highlighting the scope to raise ambitions in light of the strong growth in gas and coal-fired power generation.

**Figure 9.2 ▷ Emissions intensity in the power sector by pollutant in Southeast Asia in the New Policies Scenario**

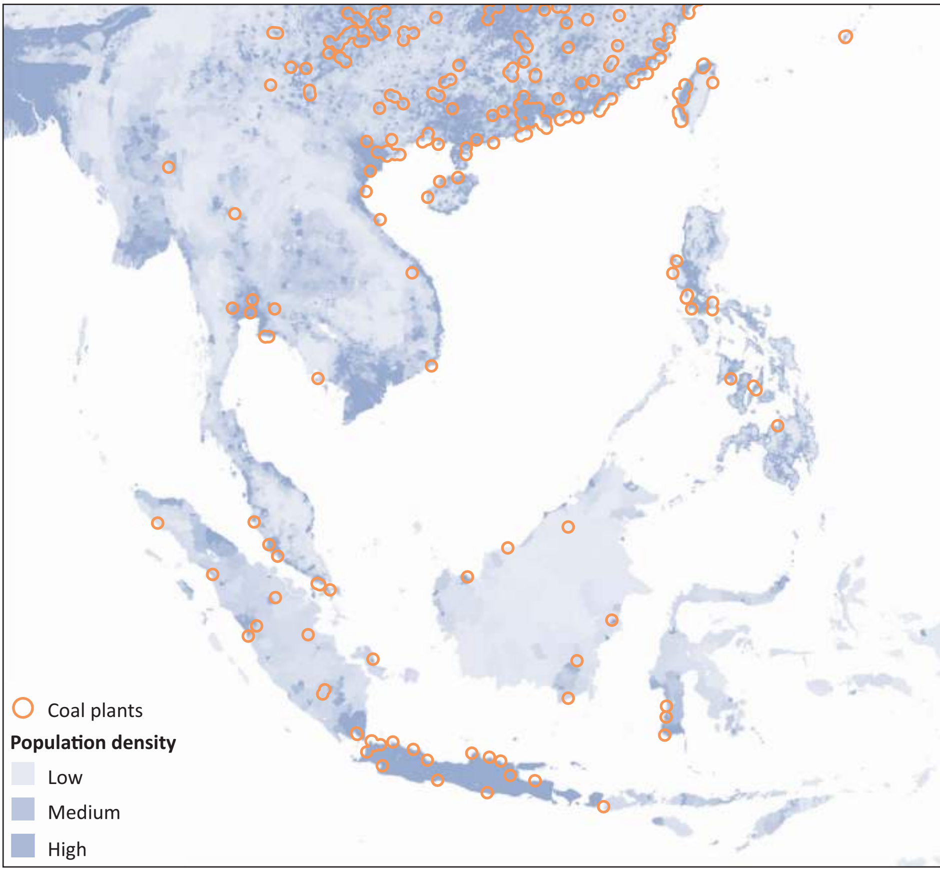



Sources: IEA; IIASA.

The large absolute increases in projected pollutant emissions, despite the efforts to address power sector air pollution by setting more ambitious standards for new plants, gives cause for serious concern – especially in relation to densely populated areas, such as Java and northern Viet Nam, where clusters of coal plants are located (Figure 9.3). In the long term, there is scope for improving air quality further by lowering emission levels for future new-builds and providing sufficient incentives to retrofit existing plants with effective control technology.

9

**Figure 9.3 ▷ Coal-fired power plants and population density in Southeast Asia, 2015**




This map is without prejudice to the status of or sovereignty over any territory, to the delimitation of international frontiers and boundaries and to the name of any territory, city or area.

Source: IEA analysis based on Platts World Electric Power Plants database and CoalSwarm.

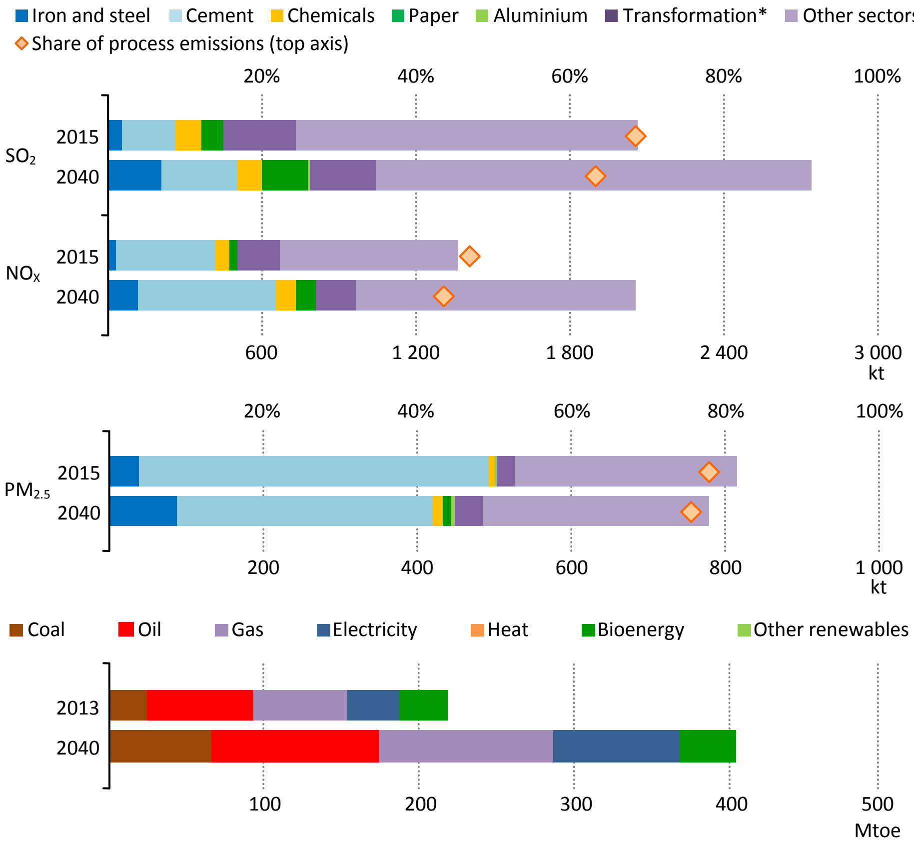
### *Outlook for the industry and transformation sector*

Indonesia, Thailand and Viet Nam together are responsible for a large part of the air pollutant emissions from the industry and transformation sector in Southeast Asia, mainly due to their economic weight (about 60% of the region's gross domestic product in 2014), as reflected in their relatively high level of industrialisation. In Southeast Asia, emissions related to industrial activity have risen considerably and today contribute one-quarter of energy-related $NO_X$ (1.4 Mt) and $PM_{2.5}$ emissions (0.8 Mt) and more than half of $SO_2$ emissions (2.1 Mt). Most countries in Southeast Asia have already introduced legislation to contain further growth of air pollutant emissions in the industry and transformation sector, mostly using emission standards. In *Indonesia*, standards were first introduced in 1988 and were successively replaced in 1995 and 2008. For industrial boilers, they cover PM, $SO_2$ and $NO_X$. *Viet Nam* first regulated emissions in 1995 and set their most recent emissions standards in 2009. Unlike most countries, Viet Nam sets emissions standards based on the size and location of the industrial facilities. In *Thailand*, emissions standards for industrial plants were released in 2006 and cover all main pollutants from combustion and process-related industrial activities. There are additional specific regulations for refineries, cement plants, steel processes and chemicals production. The *Philippines* established emissions limits in 2000, distinguishing fuel burning equipment from other industrial stationary sources. Different limits apply, depending on the proximity of the emission source to an urban area. *Malaysia* established emission standards for the industry and transformation sector as early as 1978, covering both existing and new facilities. The standards impose specific dust limits for some industries (e.g. asphalt concrete and cement plants, manufacture of nitric acid or sulfuric acid). In Singapore, emissions from industries are one of the key contributing sources of air pollution. Air emission standards are laid down in the Environmental Protection and Management (Air Impurities) Regulations, which was introduced in 2001 to replace previous regulations that had been in force since the 1970s. In 2015, standards for industrial emissions were tightened over a range of pollutants, including $NO_X$, $SO_2$ and PM, as part of continued efforts to improve air quality and safeguard public health. $SO_2$ emissions are also controlled by the imposition of sulfur content limits for fuels.

Along with the setting of emissions standards, many countries in the region actively aim to increase industrial energy efficiency. Examples are the National Energy Conservation Master Plan in Indonesia, the Minimum Energy Performance Standards in Viet Nam and the 20-Year Energy Efficiency Development Plan in Thailand. Together, these policies limit the increase of pollution from industrial activities, relative to past trends, but they do not fully compensate for the growing industrial activity in the region, especially as reflected in $NO_X$ and $SO_2$ emissions (Figure 9.4). In the New Policies Scenario, industry-related $SO_2$ emissions increase by one-third and $NO_X$ emissions by half in 2040. In the industry and transformation sector, emissions related to construction activity to support economic growth increase the most: the steel and cement sectors together account for more than one-third of the increase of $SO_2$ and $NO_X$ emissions through 2040, although the pulp and paper industry is also an important contributor, in particular to the increase of $SO_2$ emissions. Indonesia accounts for more than 40% of the region's increase of $SO_2$ and $NO_X$ emissions, given its weight in industrial activity in the region. Emissions from the Indonesian iron and steel sub-sector alone quadruple by 2040 for all three pollutants. $PM_{2.5}$ emissions seem set to be much better controlled in Southeast Asia, owing to new air quality measures. This includes the cement sector, where $PM_{2.5}$ emissions fall towards 2040 in the New Policies Scenario.

Containing further emissions growth from industrial activities in Southeast Asia is a particular challenge in relation to small- and medium-industries, which are often uncontrolled, and from brick kilns surrounding urban areas, which feature among the key priorities for health improvement in the most populated Asian regions.

**Figure 9.4 ▷ Air pollutant emissions and energy mix in the industry and transformation sector in Southeast Asia in the New Policies Scenario**




Notes: Mtoe = million tonnes of oil equivalent; kt = kilotonnes. * Transformation refers to fossil fuels (e.g. oil refining, oil and gas production, liquefied natural gas terminals), but excludes power and heat generation. The industry and transformation sector includes non-energy uses (mainly petrochemical feedstocks).

Sources: IEA; IIASA.

### *Outlook for the transport sector*

The transport policies of the ten Southeast Asian countries vary widely: Cambodia, Lao PDR and Myanmar, for example, do not impose any vehicle emission standards, while in Singapore, tailpipe emissions regulations date back to the 1980s and are currently at Euro 4 standard for light-duty gasoline vehicles, Euro 5 standard for light-duty diesel vehicles and Euro V for heavy-duty vehicles (HDVs) (Table 9.2). Singapore also has an efficient public transport network and a transport master plan aiming to increase the mode share of public transport to 75% by 2030. Viet Nam has several major public transport projects underway, including a metro rail project in Hanoi planned for 2018. Five of the ten countries have emission standards equivalent to Euro 4 or better planned by 2016. However, only three countries regulate heavy-duty vehicle (HDV) tailpipe emissions (which are responsible for more than two-fifths of transport-related $NO_X$ emissions) and only Singapore HDV standards reach Euro V. Fuel quality is poor in several countries, with sulfur limits up to 3 500 ppm. In Thailand, although Euro 4 standards have been in place for light-duty vehicles (LDVs) and Euro IV for heavy-duty diesel vehicles since 2012, traffic is a significant source of pollution in urban areas.

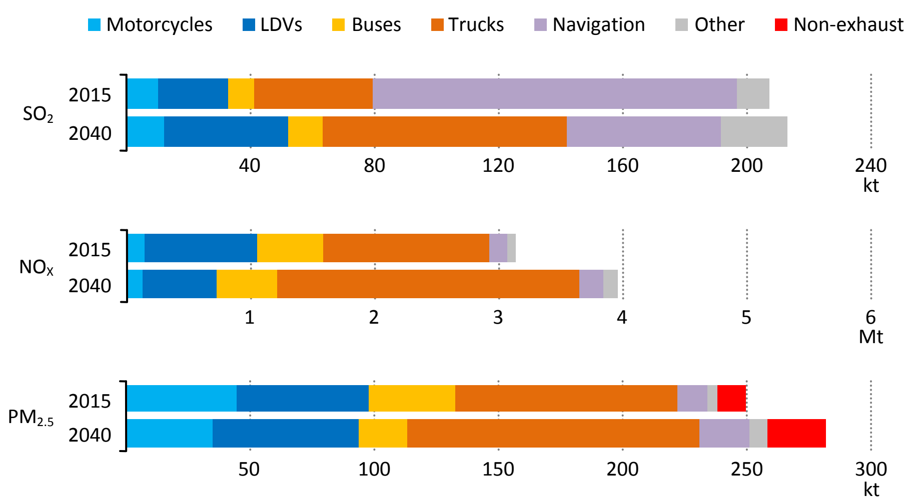
**Table 9.2 ▷ Emissions limits for selected air pollutants in road transport in Southeast Asia**

| Country | Tailpipe emissions standards | | | Fuel-quality standards for sulfur | |
|---|---|---|---|---|---|
| | Light-duty vehicles | Motorcycles | Heavy-duty vehicles | Gasoline | Diesel |
| Brunei Darussalam | Diesel – Euro 1<br>Gasoline – Euro 2<br>Moving to Euro 4 in 2016 | | | 1 000 ppm | 500 ppm |
| Cambodia | | | | 1 000 ppm; Commonly available less than 50 ppm | 1 500 ppm; Commonly available less than 500 ppm |
| Lao PDR | | | | 500 ppm | 2 500 ppm |
| Myanmar | | | | No limit; leaded fuel available | 2 000 ppm |
| Singapore | Euro 4 – gasoline<br>Euro 5 – diesel<br>Euro 6 for both by 2018 | Euro 3 | Euro V, moving to Euro VI from 2018 | 10 ppm | 10 ppm |
| Indonesia | Euro 2 – planned move to Euro 4 in near future | | Euro II | 500 ppm | 3 500 ppm |
| Malaysia | Euro 2 from 2001 – planned move to Euro 4 in the near future | Planned Euro 3 for 2016 | | 500 ppm | 500 ppm |
| Philippines | Euro 2<br>Euro 4 in 2016 | | | 50 ppm | 50 ppm |
| Thailand | Euro 4: current standards limit CO and hydrocarbons of gasoline-fuelled vehicles and black smoke for diesel vehicles | | Euro IV: current standards limit black smoke emissions | 50 ppm | 50 ppm |
| Viet Nam | Euro 2<br>Euro 4 planned for 2017, and Euro 5 for 2022 | Euro 2<br>Euro 3 planned for 2017 | | 500 ppm; 50 ppm planned for 2018 | 500 ppm; 50 ppm planned for 2018 |

Sources: Clean Air Asia (2011) and UNEP (2015).

Transport is a key contributor to air pollution in Southeast Asia: the sector produced 3.1 Mt of $NO_X$ emissions in 2015, more than half of all energy-related $NO_X$ emissions in the region, all of which come from oil and the vast majority (around 95%) from road transport (Figure 9.5). Aviation, navigation and rail only account for some 5% of the emissions of $NO_X$ from the transport sector. While the intensity of average transport $NO_X$ emissions falls by over a quarter in the New Policies Scenario by 2040, reflecting the introduction of more stringent standards, absolute $NO_X$ emissions grow by 0.8 Mt, reflecting increased demand for transport services: road oil demand grows from 2.1 million barrels per day (mb/d) today to 3.2 mb/d in 2040. Responsible for almost half of road $NO_X$ emissions in 2015, a near doubling of the emissions from trucks pushes their share to three-fifths of transport emissions by 2040. The main reason is the projected strong increase in road freight activity with energy demand nearly doubling, while emissions intensity falls by only 9% based on the regulations for trucks. By contrast, the average emissions intensity of LDVs falls by 65%, resulting in $NO_X$ emissions declining by one-third, despite a strong increase in energy demand. Buses currently account for 14% of transport-related $NO_X$ emissions, but as energy demand increases only modestly, emissions fall by 8% by 2040.

**Figure 9.5 ▷ Air pollutant emissions by transport type in Southeast Asia in the New Policies Scenario**




Sources: IEA; IIASA.

At 250 kt, transport contributes 8% of energy-related $PM_{2.5}$ emissions in Southeast Asia today. As in other regions, most of this (almost 40%) comes from trucks, but emissions from two- and three-wheelers are also important, due to their key role in satisfying demand for mobility in the region. The resulting emissions (which account for almost 20% of the total) are concentrated in urban areas, with important repercussions for human health. Buses contribute another 15% of transport-related $PM_{2.5}$ emissions. Non-exhaust emissions, at 5% of transport-related $PM_{2.5}$ emissions, play only a minor role today, but are projected to increase at a faster pace than other sources since they are entirely uncontrolled and efforts to shift between transport modes are not sufficient to curb growth. In the New Policies Scenario, transport-related $PM_{2.5}$ emissions grow by 13% to 280 kt in 2040. At 37%, the largest contribution to this comes from non-exhaust emissions.

Transport is responsible for only 5% of $SO_2$ emissions, some 55% of which come from navigation. Emissions from ships are a considerable problem for the many ports in the region. Emissions from shipping drop by around 60% by 2040 in the New Policies Scenario reflecting improvements in fuel quality. The decline is partially offset by a rise in emissions from trucks, which currently account for 18% of transport $SO_2$ emissions but double their share by 2040, reflecting a higher level of truck activity.

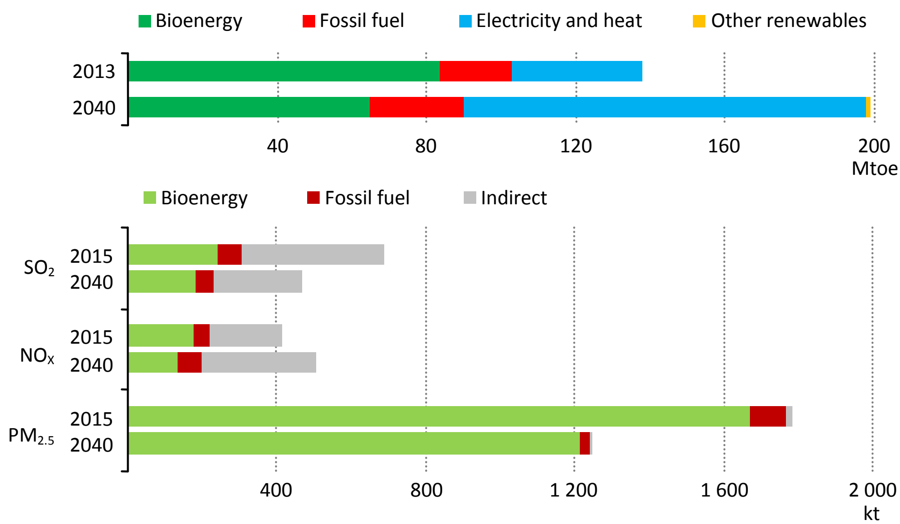
### *Outlook for the buildings sector*

Almost three-quarters of the energy consumed by Southeast Asian households is solid biomass. This high reliance on solid fuels, coupled with the low technical sophistication of the stoves used, leads to high levels of PM emissions in these countries, thus domestic use accounting for more than half of the total $PM_{2.5}$ emitted in Southeast Asia today. This daunting figure should not disguise the impressive improvements that have been made over the last 25 years: three-quarters of the population relied on solid fuels at the beginning of the 1990s and today this share is 45% (276 million people). Related efforts sought to encourage switching away from kerosene (used for both cooking and lighting), which, although its emissions intensity is lower than solid biomass, involves the risk of burns, fires and intoxication as well as household air pollution. In the period 2007 to 2011, Indonesia's Kerosene to LPG Conversion Program supported the switch of more than one-third of Indonesian households to liquefied petroleum gas (LPG), while the proportion of kerosene users declined by two-thirds (World Bank, 2013). However, the programme failed to reach the poorest people in rural areas, where 65% of the population still relies on solid fuels for cooking.

The picture is brighter in relation to access to electricity in all Southeast Asian countries. Five countries (Brunei Darussalam, Malaysia, Singapore, Thailand and Viet Nam) have achieved universal electricity access or are very close to reaching this target. However, access is still particularly low in Cambodia and Myanmar, where around two-thirds of the population have no household electricity. Such households rely on kerosene lamps for lighting, which are inefficient and release high levels of hazardous emissions, such as black carbon. Electrification programmes using innovative business models have achieved some success in a number of Southeast Asian countries. For example, in Myanmar, a fee-for-service model allows the poorest to pay for a very small amount of electricity without incurring capital cost for a connection. In Cambodia, a Rural Electrification Fund has been created with the goal of providing electricity access to 70% of the population by 2030.

In the New Policies Scenario, universal electricity access in Southeast Asia is almost fully achieved by 2040, lowering kerosene consumption in favour of electricity. Emissions from households decrease for each of the three main pollutants (Figure 9.6). The reduction is largest for $PM_{2.5}$, supported by the switch from the traditional use of solid biomass to more modern and efficient forms of energy in households, even though emissions remain sizeable by 2040. Although electricity demand in buildings more than triples by 2040, indirect $SO_2$ and $PM_{2.5}$ emissions related to electricity production decrease. Growth in electricity demand to serve expanding end-uses such as space cooling and appliances is moderated by energy efficiency programmes.

**Figure 9.6 ▷ Energy demand in buildings and related pollutant emissions by fuel in Southeast Asia in the New Policies Scenario**



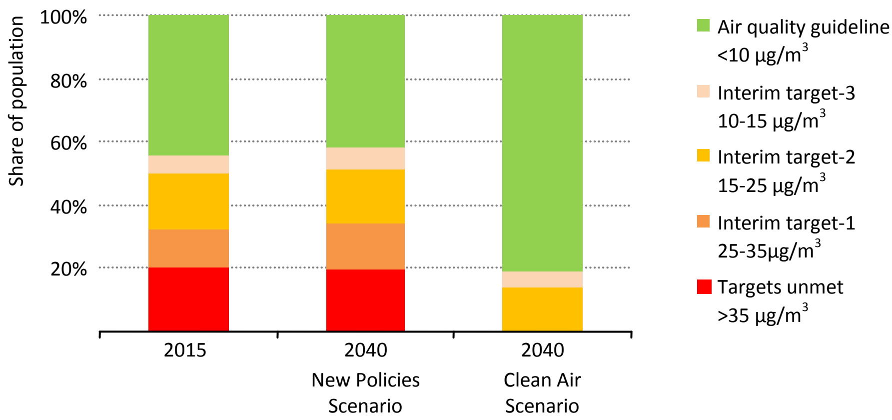

Sources: IEA; IIASA.

## *Improving the outlook for air quality to 2040: the Clean Air Scenario*

As seen in the New Policies Scenario, Southeast Asia makes progress in containing the adverse effects of growing fossil fuel use on air quality, yet existing and planned policies are not sufficient to achieve a complete reversal of pollutant emission trends. For example, in Indonesia, the region's largest generator of coal-fired power, even though the average loss of life expectancy attributable to air pollution falls from 16 to 12 months in the period to 2040, the share of the population exposed to air pollution levels that exceed the WHO interim target-1 (35 $\mu g/m^3$) broadly remains at today's level of 20% (Figure 9.7).

In the Clean Air Scenario, timely implementation of wider and more stringent air quality policies and judicious energy sector planning help to achieve deep cuts in emissions, despite the region's rapid economic development and increased coal use. In the case of Indonesia, the share of the population exposed to an air pollution level that exceeds the WHO interim target-1 drops to zero by 2040, while more than 80% of the population enjoy air quality compatible with the WHO guideline of 10 $\mu g/m^3$. The average loss of life expectancy attributable to air pollution falls to three months in 2040.

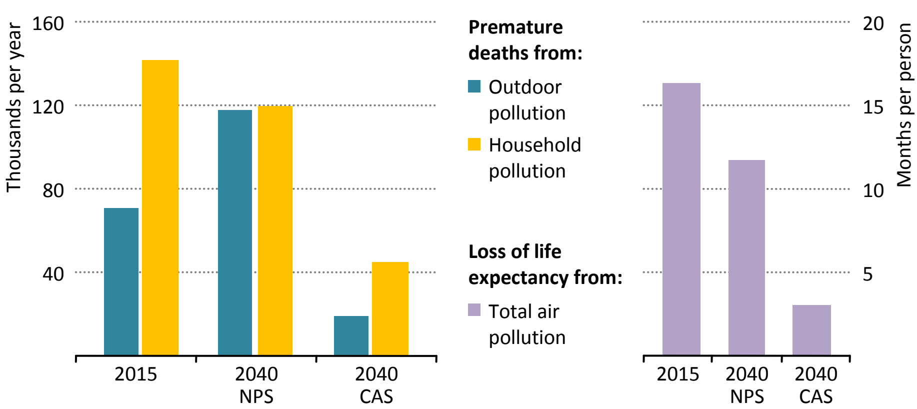
**Figure 9.7 ▷ Population in Indonesia exposed to different $PM_{2.5}$ concentration levels according to WHO targets by scenario**




Source: IIASA.

Southeast Asia's $PM_{2.5}$ emissions in 2040 drop by 85% relative to the New Policies Scenario, to around 0.4 Mt. By far the biggest contribution comes from households, where universal access to electricity is achieved by 2030 and full access to clean cooking facilities by the mid-2030s, resulting in a 90% fall in $PM_{2.5}$ emissions to 140 kt in 2040. These improvements have major implications for household air pollution: in Indonesia, for example, cases of premature deaths attributable to household air pollution drop from around 140 000 today to about 45 000 in 2040, compared with 120 000 in the New Policies Scenario (Figure 9.8).

**Figure 9.8 ▷ Premature death cases and loss of life expectancy in Indonesia by scenario**

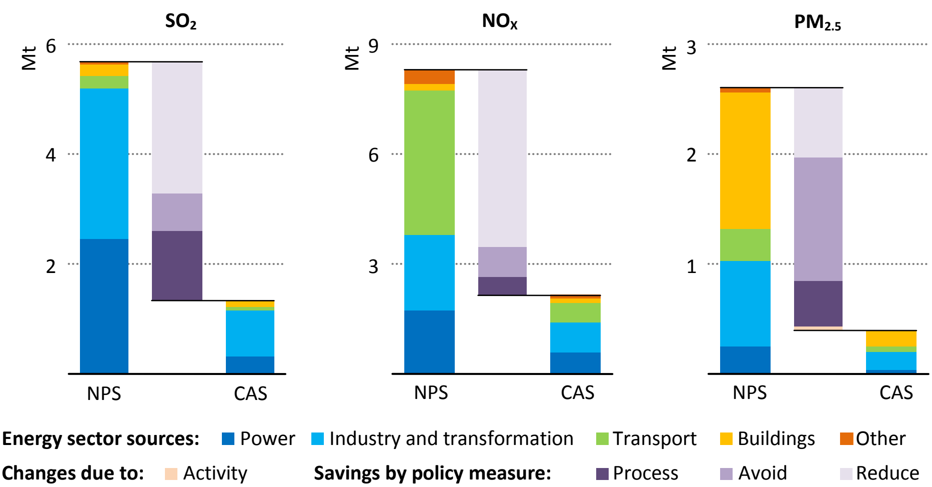



Note: NPS = New Policies Scenario; CAS = Clean Air Scenario.

Source: IIASA.

Industry, power generation and the transport sector each achieve $PM_{2.5}$ reductions of more than 80% in 2040 relative to the New Policies Scenario (Figure 9.9). A reduction of process emissions from heavy industries is the main source, in particular from iron and steel, and cement manufacturing. Yet by 2040, the industry and transformation sector is the region's largest $PM_{2.5}$ emitter, reflecting the more dramatic reduction in the residential sector, and accounts for around 40% of energy-related $PM_{2.5}$ emissions. The power sector is a relatively minor contributor to Southeast Asia's $PM_{2.5}$ emissions today. But as much of the region's coal-fired capacity is installed in densely populated areas, as in Java and northern Viet Nam, and its emissions have important public health implications; $PM_{2.5}$ emissions reduction is an important contributor to health benefits in the Clean Air Scenario. Similarly, exposure to traffic-related $PM_{2.5}$ is acute in cities and hence, urban emissions reductions bring significant health benefits. Much of the reduction in $PM_{2.5}$ emissions can be achieved by banning motorcycles with two-stroke engines or offering replacement programmes, such as with electric two-wheelers.

**Figure 9.9 ▷ Pollutant emissions savings by measure in Southeast Asia in the Clean Air Scenario relative to the New Policies Scenario, 2040**




Note: NPS = New Policies Scenario; CAS = Clean Air Scenario.

Sources: IEA; IIASA.

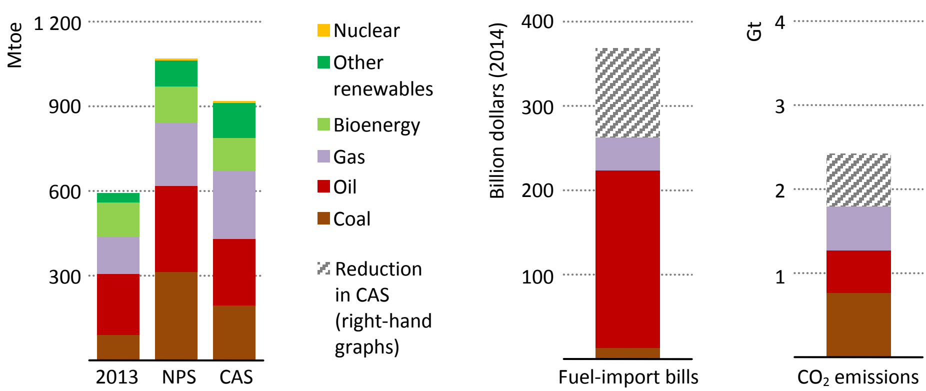
In the Clean Air Scenario, $SO_2$ emissions decline by two-thirds, from almost 4 Mt today to 1.3 Mt in 2040, three-quarters lower than in the New Policies Scenario (in which emissions keep growing). The industry and transformation sector cuts $SO_2$ emissions by 1.9 Mt relative to the New Policies Scenario, while power sector emissions fall by 2.1 Mt. The decline of $SO_2$ emissions from power plants is driven by a concerted effort of combustion control regulation and diversification of the power generation mix. In contrast to the New Policies Scenario, coal becomes the number one fuel for power generation only temporarily in the Clean Air Scenario, losing out to gas and renewables in the longer term. Southeast

Asia's electricity mix becomes more diversified, with gas accounting for 34% followed by renewables and coal each accounting for 32% of power generation by 2040. The strong reduction in $SO_2$ emissions from power plants is a testament to the effectiveness of applying vigorous regulatory standards, primarily to some 105 GW of coal plant yet to be built (three-quarters of the coal fleet in 2040).

Southeast Asian $NO_X$ emissions decline to 2.2 Mt by 2040, one-quarter of the level in the New Policies Scenario. By far, the transport sector is currently the largest emitter of $NO_X$, accounting for 55% of the total. However, a 90% drop in emissions (relative to the New Policies Scenario) is achieved in the Clean Air Scenario, primarily through stricter emissions standards for HDVs (trucks and buses) and this reduces the sector's share in total $NO_X$ emissions to just over one-quarter in 2040. Industrial $NO_X$ emissions fall by 60% relative to the New Policies Scenario, predominantly as a result of regulatory action and efficiency improvements. While $PM_{2.5}$ and $SO_2$ emissions are related to solid and liquid fuels, $NO_X$ emissions from gas-fired power generation can also be significant, yet NOx emissions from gas plants are 10% lower in 2040 than in the New Policies Scenario while total power sector NOx emissions are two-thirds lower (mainly due to more stringent emissions regulation).

Emissions from the growing number of gas-fired power plants partially offset the decline of $NO_X$ emissions achieved in coal-fired power generation, limiting the drop in $NO_X$ emissions from the sector, relative to the New Policies Scenario, to two-thirds.

**Figure 9.10 ▷ Energy demand and energy sector key indicators in Southeast Asia by scenario, 2040**




Notes: NPS = New Policies Scenario; CAS = Clean Air Scenario. Excludes export revenues.

While the policy measures assumed in the Clean Air Scenario are primarily targeted at improving air quality, there are associated co-benefits for other policy objectives. Boosting end-use efficiency, increasing renewables deployment and reducing the role for coal in power generation play a big part in cutting $CO_2$ emissions by 0.6 Gt in 2040 relative to the New Policies Scenario (Figure 9.10). Fossil fuel-import bills are $105 billion lower compared to the New Policies Scenario. In 2040, some $95 billion less is spent on oil imports in the

Clean Air Scenario, mainly due to higher efficiency in the transport sector, which reduces oil imports. Expenditure for coal imports is $12 billion lower in 2040, while fuel switching implies an increase in imports of natural gas which pushes up the gas import bill by some $4 billion relative to the New Policies Scenario.

# Africa

## Highlights

- Africa faces multiple developmental and environmental challenges, which are rooted in poverty and the source of a grave health burden on the population. Air pollution from the energy sector is increasingly a leading risk factor. Household air pollution, closely linked to a lack of access to modern energy services, causes around half a million premature deaths annually in sub-Saharan Africa, where four-fifths of the population rely on the traditional use of solid biomass for cooking, and candles and kerosene lamps are extensively used for indoor lighting. Cities are becoming increasingly choked with vehicles which are unregulated by emission standards, by the use of back-up generators to mitigate the often absent or unreliable electricity supply, and the widespread burning of waste.
- The outlook to 2040 for Africa in the New Policies Scenario is mixed. Even though there is a general absence of current policy measures to mitigate the adverse effects of air quality associated with the projected 75% rise in energy demand, which means that $PM_{2.5}$ emissions in Africa grow by almost a fifth by 2040, improvements in access to modern energy cause the annual number of premature deaths attributable to household pollution to decrease by 110 000. The share of the population relying on traditional cooking methods falls from 68% today to one-third by 2040, and the share of people without electricity access falls from 57% to 25%, bringing power to over one billion more people. Power generation is projected to almost triple over the period, with renewables (excluding biomass) providing one-third of generation by 2040, twice today's share. Despite some improvements, however, strong population growth leaves 655 million people still without access to clean cooking, and half a billion people without electricity access, and as a result over 360 000 premature deaths are still attributable to household air pollution in 2040.
- In the Clean Air Scenario, $PM_{2.5}$ emissions fall by more than 80% in 2040 relative to the New Policies Scenario, largely as a result of achieving universal access to energy. $SO_2$ is more than halved and $NO_X$ falls by three quarters relative to the New Policies Scenario because emission standards in transport, industry and power generation are introduced. This means that by 2040, 220 000 deaths are prevented annually from household air pollution compared with the New Policies Scenario. Overall primary energy demand decreases by one-quarter compared with the New Policies Scenario: energy is used more efficiently and the consumption of all fossil fuels is reduced, and as a result, $CO_2$ emissions in 2040 fall from 1.8 Gt in the New Policies Scenario to 1.5 Gt in 2040.

## *The energy and air quality context*

Parts of Africa are experiencing relatively strong economic growth. The economic output of sub-Saharan Africa has doubled since 2000, but remains below that of Germany, despite the population being more than ten-times larger. Across the continent as a whole, gross domestic product per capita has increased by more than one-quarter over the past decade. The population of the continent is rapidly growing and urbanising. Africa is expected to be home to around 22% of the global population by 2040, compared with 10% in 1971 and 16% today. Africa is today the world's most rural continent (with only around 40% of the population living in urban areas), but it is one of the fastest-urbanizing world regions – more than half of the population is expected to live in urban areas by 2040.

Energy demand in Africa has risen by half since 2000 though per-capita energy demand remains low at about one-third of the global average. The energy mix is dominated by biomass, which accounts for almost half of energy demand across Africa and has a share as high as three-quarters of the total in sub-Saharan Africa (excluding South Africa). Only one-third of the population of the continent has access to modern cooking fuels – a low level matched only in India – with biomass used extensively as a cooking fuel. Electricity access is also the lowest in the world: around 635 million people, 57% of the population, do not have access to electricity today. Per-capita electricity consumption in Africa is one-fifth of the global average, with wide variations by country: while almost all North Africans have access to electricity, only one-third has access in sub-Saharan Africa, and this falls to just 17% when looking at the rural population. Nigeria alone has 96 million people without access to electricity. Those who do have access to electricity experience frequent blackouts – Nigeria experiences on average 33 power outages every month and rationing due to inadequate supply and ageing infrastructure (World Bank, 2016). Demand outstrips electricity supply, resulting in the cost of electricity generation being significantly higher in many African countries than in other world regions (AfDB, 2013). Industrial activities are also compromised as a result of high prices. The many positive efforts to provide electricity access across the continent have not been sufficient to decrease the number of people without access to electricity; Africa is the only world region where the number of people without access to electricity has actually increased since 2000, despite a significant decrease in numbers in North African countries and some sub-Saharan countries, including South Africa, Gabon, Botswana and Ghana.

Fossil fuels dominate the production of electricity, accounting for more than 80% of total power supply. South Africa, which generates almost 60% of all the power generated in sub-Saharan Africa, derives 94% of its power from coal. South Africa also accounts for around 25% of total oil consumption in sub-Saharan Africa and Nigeria for more than 20%, meaning that the remaining 40-plus countries collectively consume less oil than the Netherlands. While there has been increasing international focus on delivering universal clean energy access, such as through the African Development Bank's New Deal on Energy for Africa, it is clear from the UN SE4All tracking that progress falls substantially short of what is required to attain clean energy access by 2030 (IEA and World Bank, 2015).

These characteristics – rising energy consumption, concentrating urban populations and persistent lack of energy access – have contributed to ever-increasing air pollution, household as well as outdoor. Around half a million premature deaths can be attributed to household air pollution in Africa today, a health problem which is closely related to the lack of access to modern forms of energy. The traditional use of biomass for cooking causes severe emissions of particulate matter ($PM_{2.5}$), as does the use of candles and kerosene for lighting. Kerosene, used by many households that do not have access to reliable electricity or alternative solutions, is the primary lighting fuel in around half of African countries and is also a grave source of fires and casualties in households (World Health Organisation, 2016); programmes such as SolarAid, GOGLA and Lighting Africa are promoting the use of solar lamps to help phase out the use of these lighting fuels.

Indeed, 7.5 million tonnes (Mt) of $PM_{2.5}$ are emitted annually in Africa today, of which almost three-quarters is from the burning of biomass indoors. Damage to air quality from these sources affects mostly the poorest population of Africa: while there is almost no dependence on the traditional use of solid biomass for cooking in North Africa, only one-fifth of sub-Saharan Africans have access to modern cooking fuels, leaving 755 million people to cook with solid biomass, typically with inefficient stoves in poorly ventilated spaces without chimneys. In more than four-fifths of sub-Saharan countries, more than half of the population relies on solid biomass for cooking, and in half of these, the share is above 90%. Several countries have implemented programmes to promote the use of cleaner and more efficient cookstoves, the prime objective being to reduce the health effects of pollution from indoor smoke. Kenya aims to eliminate kerosene use in households by 2022 and improved biomass cookstoves are already relatively available in urban areas. Kenya has also passed a law that requires new buildings to be fitted with solar water heating systems. Strong policies in Senegal have supported a switch to liquified petroleum gas (LPG) and less than 30% of the urban population now use solid biomass. Other countries, including Ghana and Cameroon, have also made commitments to increase the share of LPG for cooking and are developing related policy measures. It has to be acknowledged, however, that in general rising incomes alone have not been sufficient to result in increasing access to clean cooking fuels and concentrating populations will likely exacerbate this urgent problem (see Chapter 3 Spotlight), and moreover, many improved biomass cookstoves on the market today, though a great improvement on traditional cooking, still produce enough $PM_{2.5}$ to be considered a health hazard.

Deaths in Africa attributed to outdoor pollution, at more than 210 000 per year in 2012 (WHO, 2016a, forthcoming), are less than half of those attributable to household air pollution. As a result of limited economic activity, concentrations of outdoor pollution is low in most areas relative to other world regions, but the emissions intensity of new economic activity is high. Today the major sources of outdoor air pollution include old and unregulated vehicles, smoke from indoor and outdoor cooking with biomass, the unregulated burning of wood and waste (including the burning of toxic materials, such as electronics), dust from dirt roads, and coal-fired power generation, particularly in South

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Africa. The use of back-up diesel generators (including an unknown but large number of small generators in and around residences/apartments) to supplement inadequate grid-based electricity supply is also a cause of noxious emissions (IEA, 2014) Measuring overall outdoor pollution is a major challenge: air quality monitoring does not exist in most African countries. For those cities in Africa that are monitored, the annual mean $PM_{10}$ and $PM_{2.5}$ emissions exceeded the World Health Organization (WHO) Air Quality Guidelines levels in almost all cases (WHO, 2016b). A satellite study suggests that between 2010 and 2012, 32% of West Africans and 28% of the North African and Middle Eastern populations are exposed to levels of $PM_{2.5}$ exceeding the WHO interim target-1 of 35 $\mu g/m^3$, compared with none of the population of high-income countries (Donkelaaer van, et al., 2015).

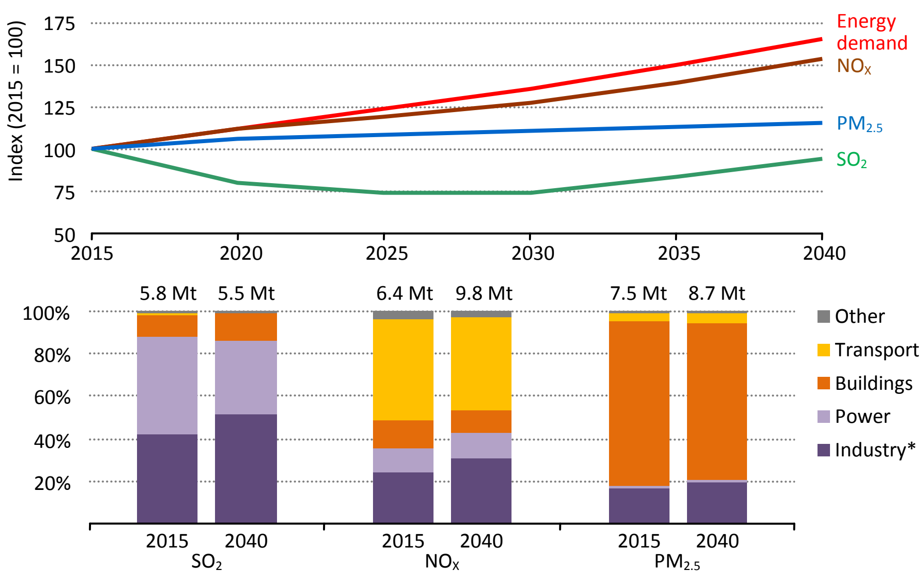
Nitrogen oxides ($NO_X$) emissions in Africa were around 6.4 Mt in 2015, around half from vehicle tailpipe emissions and a quarter from industry. Sulfur dioxide ($SO_2$) emissions were 5.8 Mt in 2015, 42% from the industry and transformation sectors and 45% from power generation, largely as a result of coal combustion in South Africa. Some efforts have been made across the continent to reduce $PM_{2.5}$ emissions mainly through incentivising the use of modern cooking fuels, such as LPG and natural gas, though pollutant emissions have risen, as has the number of people without access to clean cooking. However, South Africa, through the National Environmental Management Air Quality Act of 2004, is one of the only African countries comprehensively regulating air quality and setting emissions standards, imposing limits on new and existing power plants and industrial installations. Effectively securing compliance remains an issue in South Africa (as in many parts of the world).

Transport is a major contributor to outdoor air pollution in Africa. An old and growing vehicle fleet, poor fuel quality and rapid unplanned urban growth all contribute to increasingly choked cities. Proper urban planning as well as improving public transport systems could reduce the number of vehicles on the road. Improving fuel quality, particularly removing sulfur, is a necessary step towards the use of improved vehicle technologies that reduce tailpipe pollution. Leaded gasoline was largely phased out in the 2000s, but fuel quality remains variable. Despite some regulation, the sulfur content of diesel remains very high in many countries: in Egypt, diesel sulfur content is up to 7 000 ppm, over 700 times the level in Europe. Only a small number of African refineries have the capacity to produce low-sulfur fuels and, even though the value of the health benefits derived from upgrading refineries may far outweigh the costs, sufficient incentive for investment is lacking. Low quality fuels not only contribute to tailpipe emissions, but prevent the adoption of higher vehicle exhaust emissions standards. Such standards are implemented to a very limited extent: only Nigeria and South Africa have emissions standards reaching the level of Euro 2 (introduced in Europe in 1996) or beyond. Many countries ban or place tariffs on the import of older vehicles to discourage the dumping of outdated and inefficient vehicles, but their low price remains an attraction. The age and lack of maintenance of vehicles, weak enforcement of laws in place and variable fuel quality often means that the gap between test-standards (where they exist) and real-world operation can be particularly large.

## *The outlook for air quality to 2040: the New Policies Scenario*

The outlook to 2040 for air pollution in Africa in the New Policies Scenario is mixed: to serve the growing population, which almost doubles, and economy, which grows almost 3.5 times by 2040, energy demand grows strongly, projected to be 75% higher in 2040 than today. The energy demand growth combined with a persistent deficit in clean cooking and electricity access, despite some progress, and the relative absence of air pollution regulation in current policies add up to a 20% growth in $PM_{2.5}$ emissions and a 50% growth in $NO_X$ (Figure 10.1). $PM_{2.5}$, while growing in absolute terms, falls by a third when measured on a per-capita basis. Particular emphasis is given over the next two-and-a-half decades to providing modern energy services to lift the constraint on economic growth that is due to the lack of access to electricity and unreliable supply. In the New Policies Scenario, electrification spreads from 43% of the population today to 75% in 2040, granting over a billion more people access to electricity compared with today. This will require an almost trebling of power generation, with renewables (excluding biomass) projected to account for one-third of generation by 2040, twice today's share.

**Figure 10.1 ▹ Emissions by pollutant and by energy sector in Africa in the New Policies Scenario**




* Includes transformation (except power generation).

Sources: IEA; International Institute for Applied Systems Analysis (IIASA).

Access to clean cooking (including the use of improved biomass cookstoves and alternative fuels like LPG) also improves, with the proportion of the population relying on the traditional use of biomass for cooking falling from 68% today to one-third in 2040. Despite such gains, population growth implies that the number of people without access does not fall to the same extent; 655 million people still rely on the traditional use of biomass for cooking in 2040, a modest decline below today's level, while an additional 220 million people use biomass for cooking in improved cookstoves. As a consequence, although bioenergy's share of primary energy demand declines from about half today to more than one-third by 2040, the absolute amount of bioenergy in the mix grows by one-third, with the two-thirds still being used for cooking in 2040, compared with three-quarters today.

The level of biomass used in cooking has implications for $PM_{2.5}$ emissions. Though some of the biomass used in the future is consumed in improved cookstoves, it remains a very significant source of $PM_{2.5}$ emissions, which increase by around 15% by 2040 in the New Policies Scenario. This is driven by increased biomass use in households (50% of the growth), mainly for cooking. Around 40% of increased $PM_{2.5}$ emissions are from the industry and transformation sector, as emissions from the sector are practically unregulated in current or announced policies across most of the continent (except South Africa). Sub-Saharan Africa is almost entirely responsible for this increase in $PM_{2.5}$ emissions.

$NO_X$ emissions are projected to increase by over 50%, from 6.4 Mt to 9.8 Mt by 2040. The transport sector is the major emitter of $NO_X$, responsible for almost half of emissions today. Very strong growth in freight activity adds 1.2 Mt of $NO_X$ emissions by 2040, an increase of two-thirds. Industry and power generation combined contribute 36% of $NO_X$ emissions today, and drive almost 60% of the increase in $NO_X$ emissions by 2040. South Africa, in contrast with the rest of the continent, sees $NO_X$ emissions decline, as stronger transport and power generation regulations offset the rise in $NO_X$ emissions in industry. $NO_X$ emissions in the rest of sub-Saharan Africa more than double, mainly from the transport and industry sectors. North Africa sees $NO_X$ emissions grow by a quarter, mainly from industrial activity.

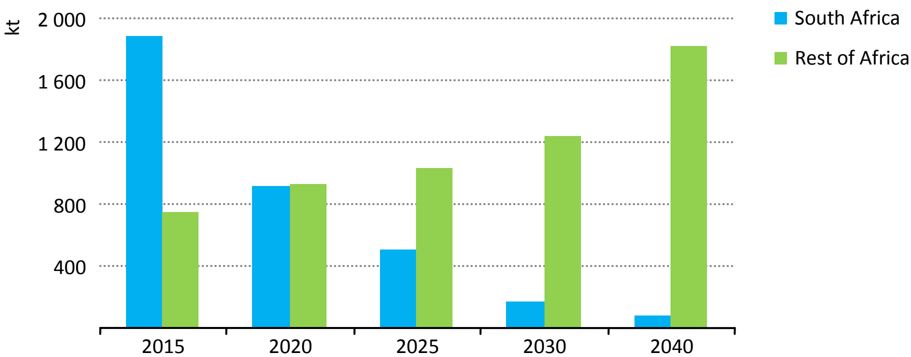
Contrary to $NO_X$ and $PM_{2.5}$, $SO_2$ emissions are set to fall by a quarter in the period to 2030, largely as a result of the strong decline in emissions from the South African power sector, which offsets strong growth from power generation and industry sectors in other parts of Africa. $SO_2$ emissions are then projected to rise back to almost today's levels, as power generation and industrial activities overtake emissions savings. Growth in electricity demand is met mostly by natural gas and renewables, neither of which emits $SO_2$. Emissions of $SO_2$ by the buildings sector, responsible for 10% of $SO_2$ emissions in 2015, increase by around 20% over the *Outlook* period.

### *Outlook for the power sector*

Across the continent, electricity demand is set to triple in the period to 2040 with natural gas remaining the number one power generation source by 2040. Renewables grow very strongly, with their share in electricity generation projected to almost overtake natural gas as the main source of electricity. Power sector trends in Africa differ significantly by country, reflecting different stages of economic development, natural resource endowments, institutional frameworks, demographic trends and prospects for economic growth. Sub-Saharan Africa has excellent hydro power resources, but geothermal, wind and solar photovoltaics (PV) also contribute substantially to future power supply. Today, South Africa accounts for around 90% of the continent's coal-fired power.

The dominance of coal in South Africa's power mix led to the adoption of regulations for pollutant emissions from power generation in the mid-2000s. They took effect in 2010, with a first phase and interim target for 2015. The second phase requires all plants (existing and new) to comply with a $PM_{2.5}$ emissions limit of 50 milligrams per cubic metre ($mg/m^3$) by 2020; the limits for $NO_X$ are 750 $mg/m^3$ and for $SO_2$ 500 $mg/m^3$, and represent a significant tightening from the level of the interim target. These emissions standards are expected to trigger considerable retrofitting investments over the coming years in some 35 gigawatts (GW) of existing plants and the installation of new control technology in close to 10 GW of plants under construction.

**Figure 10.2 ▷ $SO_2$ emissions from the power sector in Africa in the New Policies Scenario**




Note: kt = kilotonnes.

Sources: IEA; IIASA.

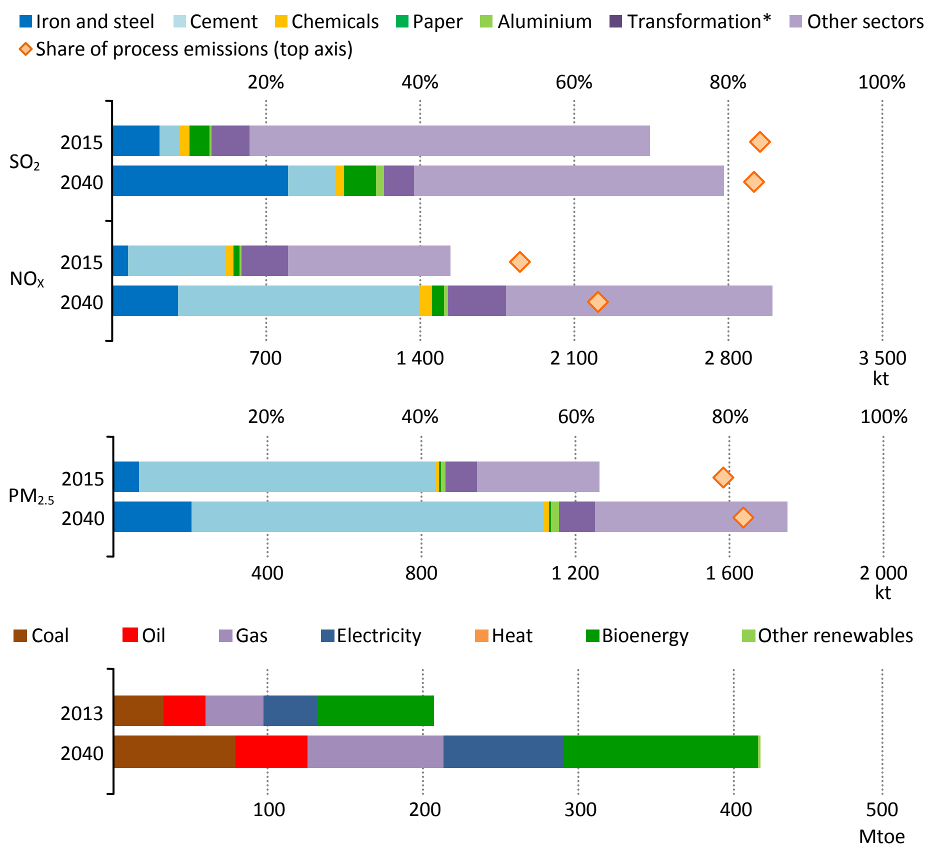
Action to conform with these emissions standards results in a 50% drop in $SO_2$ emissions from South Africa's power generation sector already by 2020 and by 2040 $SO_2$ emissions from coal-fired plants almost disappear (Figure 10.2). $NO_X$ and $PM_{2.5}$ emissions in the South African power sector fall by close to 40% and 80% respectively by 2040, also primarily a result of the implementation of emissions standards for coal-fired power plants. A number of other African countries which lack emissions regulations – mostly in the southern and eastern parts of the continent – expand coal-fired power generation in the New Policies Scenario, which leads to a strong increase in pollutant emissions. $PM_{2.5}$ emissions from power generation outside South Africa are negligible when averaged over the African continent. However, as with $SO_2$, the expansion of coal-fired power generation without air quality regulations in place leads to high concentration of local $PM_{2.5}$.

Reflecting these divergent trends across the continent, the decrease in $SO_2$ emissions in South Africa is diminished by increases from uncontrolled coal plants elsewhere (Figure 10.2). In addition, significant amounts of $SO_2$ emissions in Africa arise from oil-fired plants and diesel generators. Oil is responsible for over one-fifth of the $SO_2$ emissions from power generation in Africa and the share increases to one-quarter in 2040. Power generation from natural gas currently accounts for one-fifth of the $NO_X$ emissions from the power sector in Africa. However, the increasing output of gas in power generation, combined with the assumed lack of $NO_X$ regulation in countries with large natural gas-fired power generation results in a strong increase in $NO_X$ emissions. By 2040, over 40% of the $NO_X$ emissions from power generation stem from gas-fired plants.

### *Outlook for the industry and transformation sector*

In South Africa, regulations have significant impacts for emission trends in the industry and transformation sector: $SO_2$ emissions fall by almost 40% to some 480 kilotonnes (kt) and $PM_{2.5}$ emissions fall by 4% to around 120 kt by 2040. Reductions in combustion-related $NO_X$ emissions, however, are offset by growth in process-related emissions. Overall, industry and transformation sector-related $NO_X$ emissions rise by around 25% by 2040.

**Figure 10.3 ▷ Air pollutant emissions and energy mix in the industry and transformation sector in Africa in the New Policies Scenario**




Notes: Mtoe = million tonnes of oil equivalent; kt = kilotonnes. * Transformation refers to fossil fuels (e.g. oil refining, oil and gas production, liquefied natural gas terminals), but excludes power and heat generation. The industry and transformation sector includes non-energy uses (mainly petrochemical feedstocks).

Sources: IEA; IIASA.

The African continent as a whole, however, does not reflect the trends in South Africa. Largely unregulated, emissions of major pollutants by the industry and transformation sector in the rest of Africa all rise over the period to 2040 (Figure 10.3). Although the decline in South Africa reduces total $SO_2$ emissions of Africa over the next ten years or so, a strong rise in other parts of Africa leads to a reversal of this trend by around 2030 and $SO_2$ emissions rise by 14% to 2.8 Mt in 2040, driven particularly by the steel sector. $PM_{2.5}$ emissions grow by around 40% to 1.7 Mt in 2040 compared with today, largely as a result of process-related emissions. Growth is strongest in $NO_X$ emissions, which double over the projection period. Growth in $PM_{2.5}$ and $NO_X$ emissions is mostly driven by sectors related to construction activities, such as the steel and cement sub-sectors, which together account for about 60% of additional emissions. Emissions from the cement sector, which already represent around 60% of total $PM_{2.5}$ emissions from the entire African industry and transformation sector today, are, and will remain, a challenge.

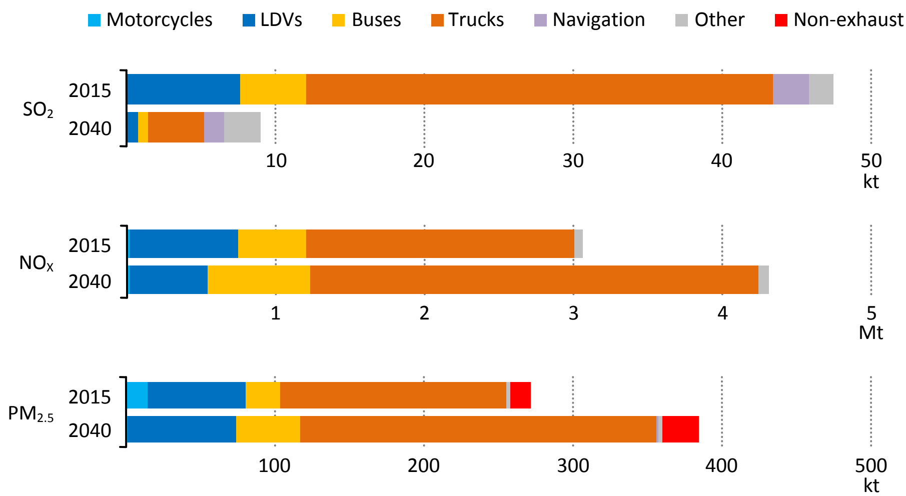
### *Outlook for the transport sector*

South Africa and Nigeria are the only countries in Africa that enforce vehicle standards today. South Africa has Euro 2 standards for light-duty vehicles (LDVs) and Euro II standards for heavy-duty vehicles (HDVs) and engines, but plans to move to Euro 5 (LDVs) by 2017 and to Euro V (HDVs) before 2020. Nigeria imposes Euro 2 standards on LDVs. While the rest of the continent has no tailpipe emission standards in place, various countries as noted above place age and/or total mileage restrictions on vehicle imports or impose additional import taxes on old vehicles. Permissible fuel sulfur concentrations in automotive gasoline and diesel vary widely and although many African nations set target dates to reduce sulfur concentration in diesel fuel to 50 ppm in the period 2008-2015, few reached this target. Poor road quality and congestion within cities both contribute to further damage to air quality.

Oil use in transport is a major source of air pollution in Africa. In the New Policies Scenario, the demand for transport increases rapidly to keep pace with growth in the population and the economy. Transport oil consumption rises by around 70%, with demand for road freight growing particularly strongly. There are direct, adverse consequences for air pollution. $NO_X$ emissions are the most significant pollutant from transport today, contributing 3 Mt, or half of all energy-related $NO_X$ emissions in Africa. Trucks account for the majority of these emissions at almost 60% - a share which increases to 70% by 2040 as $NO_X$ emissions from trucks rise by two-thirds (Figure 10.4). Around 90% of truck emissions arise from diesel. While the intensity of $NO_X$ emissions for LDVs, including commercial vehicles, falls by over half by 2040, the emissions intensity for trucks falls by only 3%. The emissions intensity of transport as a whole falls by only 13%, insufficient to offset the increase in activity. In the absence of emissions regulations, pollution from buses increases by more than half by 2040. Of the different regions, South Africa, which is responsible for 15% of total African transport-related emissions, achieves a net reduction in emissions as regulations successfully offset activity growth, particularly by light-commercial vehicles. Sub-Saharan Africa is responsible for a 1 Mt increase in the continent's transport-related emissions.

Emissions by the transport sector of $PM_{2.5}$ and $SO_2$, 4% and 1% of total emissions respectively, are of lesser concern. Planned fuel-quality standards help reduce $SO_2$ further, by four-fifths by 2040. However $PM_{2.5}$ emissions from transport increase by two-fifths by 2040, mainly from trucks.

**Figure 10.4 ▷ Air pollutant emissions by transport type in Africa in the New Policies Scenario**



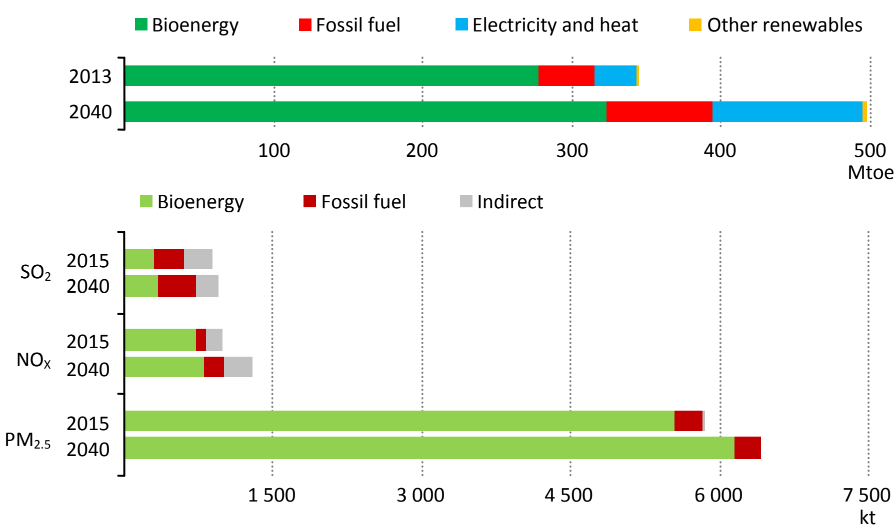

Sources: IEA; IIASA.

### *Outlook for the buildings sector*

Lack of access to clean and modern energy is a fundamental barrier to development in many parts of Africa. Around 80% of energy consumption in the buildings sector in sub-Saharan Africa is for cooking, compared with around 5% in developed countries. Pollution from the buildings sector accordingly is mainly about domestic energy use – around 90% of energy demand and 98% of $PM_{2.5}$ emissions from buildings arise from the residential sector in Africa. Solid biomass (mainly fuelwood and agricultural waste) is used almost exclusively for cooking in rural areas with a more diverse use of fuels in urban areas. Charcoal is commonly used for cooking in urban areas, which has severe consequences for deforestation and the environment. Electricity is used for cooking by around 80% of the urban population in South Africa, but by less than 5% in most other countries. For the continent as a whole, the buildings sector is responsible for almost 80% of $PM_{2.5}$ emissions. Indeed, the inefficient combustion of solid biomass in traditional stoves makes the buildings sector in Africa the major emitter of $PM_{2.5}$ worldwide, accounting for more than 15% of all energy-related $PM_{2.5}$ emitted today.

In the New Policies Scenario, around 1 billion people get access to electricity by 2040 but, even so, the combination of population growth in sub-Saharan Africa and progress in other parts of the world means that sub-Saharan Africa becomes the dominant region of those without electricity access in the world, representing 90% of all the people in the world that lack access to electricity, compared with around half today. This means that by 2040, some 500 million people in sub-Saharan Africa (mainly in rural areas) remain without electricity and continue to rely on the use of kerosene lamps, despite the many contemporary programmes for off-grid lighting which help to reduce their use. Although the picture in urban areas is different, the number of people reliant on fuelwood for cooking in rural areas (where consumption is much larger due to lower clean cooking access) hardly changes over the *Outlook* period. Rising incomes produce only a gradual shift in cooking fuels and the technologies used. In the New Policies Scenario, emissions of the three pollutants related to the buildings sector increase slightly (Figure 10.5). Indirect $NO_X$ emissions related to electricity use also increase as lower emissions intensity in power generation is offset by an almost four-fold increase of electricity demand. Most emissions related to household energy use remain to be caused by the combustion of bioenergy, though bioenergy growth flattens by around 2030 due to clean cooking promotion programmes. Yet the combination of a lack of policies to define clear quality standards for heating and cooking stoves on the continent, alongside an increasing population and widespread, continuing reliance on solid biomass for cooking, mean that pollution related to household energy use remains a major issue in Africa through the *Outlook* horizon.

**Figure 10.5 ▷ Energy demand in buildings and related pollutant emissions by fuel in Africa in the New Policies Scenario**




Sources: IEA; IIASA.

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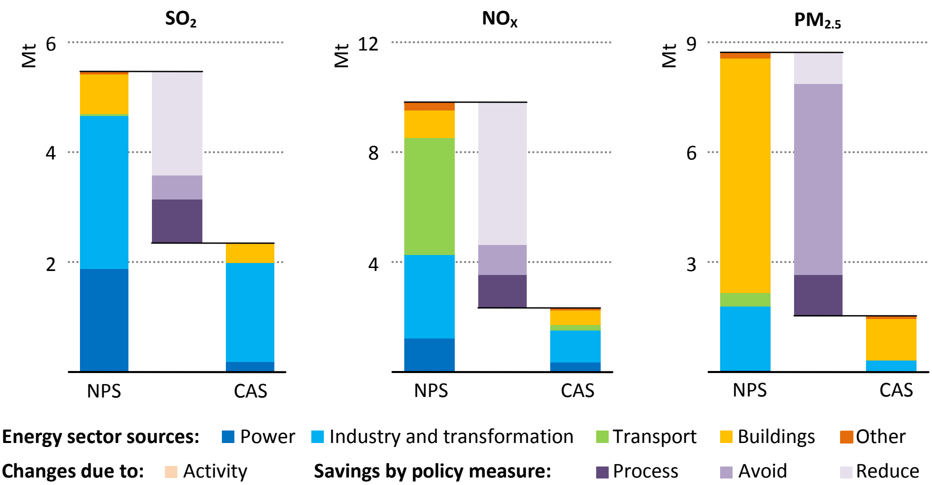
## *Improving the outlook for air quality to 2040: the Clean Air Scenario*

Much can be done to improve air quality for Africa's growing population. In the Clean Air Scenario, achievements in energy access as well as fuel and technology regulations lead to a large reduction in the number of people exposed to dangerous levels of air pollutants, and a reduction in overall concentrations of air pollution, giving rise to substantial health benefits to the population. The benefits can be measured, in particular, in the reduction of deaths from household air pollution in sub-Saharan Africa, where clean cooking access is now lowest in the world. In sub-Saharan Africa, 220 000 fewer premature deaths per year from household air pollution are realised compared with the New Policies scenario in 2040, a number which grows to 330 000 when compared with 2015, a reduction of around 70%.

The health improvements achieved in the Clean Air Scenario relative to the New Policies Scenario are a result of reductions of the three pollutants considered in this report (Figure 10.6). $PM_{2.5}$ and $NO_X$ both decline substantially, while they increase in the New Policies Scenario over time. $PM_{2.5}$ emissions in 2040 are 80% lower relative to the New Policies Scenario. This vast improvement in emissions is a direct result of achievements in extending access to modern forms of energy. The population without electricity access falls to zero by 2040, while 500 million people remain without electricity in 2040 in the New Policies Scenario. More than 60% of the additional capacity to broaden electricity access is from off-grid and mini-grid systems. Extension and expansion of the electricity grid serves the rest. Similarly, an additional 650 million people gain access to improved cookstoves, with universal access to clean cooking in Africa achieved by 2040. Over 100 million additional LPG stoves are deployed in urban areas and over 90 million in rural areas, with the consequent demand for LPG requiring additional infrastructure and fuel supply networks. The amount of biomass consumed for traditional uses in the residential sector falls from 270 million tonnes of oil equivalent (Mtoe) today to just over 100 Mtoe by 2040. The average annual investments in cooking technologies required to achieve full clean cooking access between now and 2040 almost doubles compared with the New Policies Scenario (where full access is not reached by 2040). Investment needed to achieve universal access to electricity also doubles compared with the New Policies Scenario, amounting to $17 billion annually.

While almost three-quarters of the savings in $PM_{2.5}$ emissions come from the households through energy access policies, an additional 20% of the $PM_{2.5}$ savings come from industry, where process emissions drop by more than 80% relative to the New Policies Scenario; 70% of these savings come from the more efficient production of cement. $NO_X$ emissions fall by more than three-quarters (or 7.5 Mt) in the Clean Air Scenario relative to the New Policies Scenario. Less than 10% of the savings come from South Africa (which is one of the few African countries with vehicle emissions standards currently in place), with around 55% coming from the rest of sub-Saharan Africa (where more ambitious standards are assumed in the Clean Air Scenario) and the remaining one-third from North Africa. Overall $NO_X$ emissions intensity reduces by 70% relative to the New Policies Scenario, with a 90% reduction in intensity in the transport sector. Savings of 3 Mt arise from road freight, and there are savings of around 300 kt from private cars and around 650 kt from buses relative to the New Policies Scenario. Over half of total $NO_X$ savings come from transport, with savings from the power generation sector contributing a further 15%. Pollution control measures for coal- and gas-fired power generation each contribute around 350 kt in savings. Energy efficiency in buildings (as a result of more efficient cookstoves) contributes a further 550 kt of savings. Half of the remaining $NO_X$ emissions arise from industry.

**Figure 10.6 ▷ Pollutant emissions savings by measure in Africa in the Clean Air Scenario relative to the New Policies Scenario, 2040**



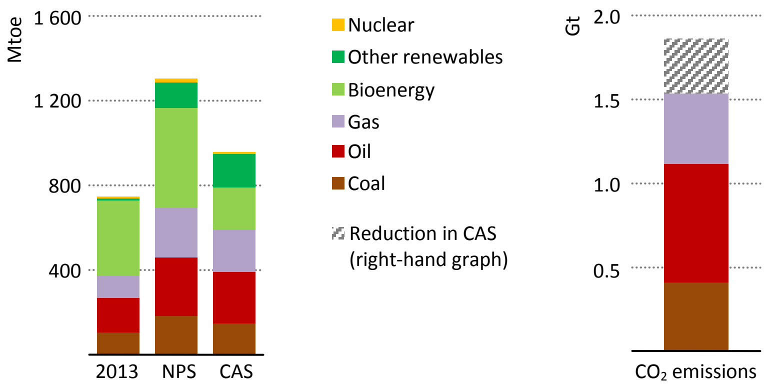

Note: NPS = New Policies Scenario; CAS = Clean Air Scenario.

Sources: IEA; IIASA.

$SO_2$ emissions fall by almost 60% in the Clean Air Scenario, a savings of 3.1 Mt relative to the New Policies Scenario. As with $NO_X$ emissions, the main instrument to achieve savings is emissions control regulations, which are responsible for almost 85% of the savings (around 2.7 Mt). The power sector is responsible for more than half of the total savings relative to the New Policies Scenario. This is a consequence of a higher share of renewable power generation and more emissions controls in coal- and oil-fired generation – the emissions intensity of coal generation falls by a factor of 10 relative to the New Policies Scenario, while for oil the reduction is seven-fold. Better pollution control measures in the industry and transformation sectors contribute 1 Mt of $SO_2$ savings compared with the New Policies Scenario. The majority of the $SO_2$ emissions savings come from sub-Saharan Africa, excluding South Africa, which already removes sulfur from power generation under current and planned policies in the New Policies Scenario.

On top of the health benefits, the Clean Air Scenario sees additional benefits in terms of other energy policy objectives (Figure 10.7). Total primary energy demand decreases by one-quarter as energy is used more efficiently: coal demand falls by 47 million tonnes of coal equivalent (18%) in 2040 relative to the New Policies Scenario; oil demand by 0.8 million barrels per day (13%); gas demand by 45 billion cubic metres (16%); and biomass use by 270 Mtoe (58%). The share of renewables in primary energy demand in 2040 (excluding biomass) increases from 10% in the New Policies Scenario to 17% in the Clean Air Scenario, an increase of one-quarter in absolute terms. The share of bioenergy drops from 36% to 20% of total energy demand in 2040. The changes in the energy mix also contribute to climate objectives: while emissions grow from 1.1 to 1.5 gigatonnes (Gt) of carbon dioxide ($CO_2$) by 2040 in the Clean Air Scenario, this is lower than in the New Policies Scenario, where $CO_2$ emissions increase to 1.8 Gt.

**Figure 10.7 ▹ Energy demand and $CO_2$ emissions in Africa by scenario, 2040**




Note: NPS = New Policies Scenario; CAS = Clean Air Scenario.

# ANNEXES

# Definitions

This annex provides general information on terminology used throughout the report including: units and general conversion factors; definitions on fuels, processes and sectors; regional and country groupings; and, abbreviations and acronyms.

## Units

| | | |
|---|---|---|
| **Area** | $km^2$ | square kilometre |
| **Coal** | Mtce | million tonnes of coal equivalent (equals 0.7 Mtoe) |
| **Emissions** | Mt | million tonnes |
| | ppm | parts per million (by volume) |
| | Gt $CO_2$-eq | gigatonnes of carbon-dioxide equivalent (using 100-year global warming potentials for different greenhouse gases) |
| | g $CO_2$/km | grammes of carbon dioxide per kilometre |
| | g $CO_2$/kWh | grammes of carbon dioxide per kilowatt-hour |
| **Energy** | boe | barrel of oil equivalent |
| | toe | tonne of oil equivalent |
| | ktoe | thousand tonnes of oil equivalent |
| | Mtoe | million tonnes of oil equivalent |
| | MBtu | million British thermal units |
| | kWh | kilowatt-hour |
| | MWh | megawatt-hour |
| | GWh | gigawatt-hour |
| | TWh | terawatt-hour |
| **Gas** | bcm | billion cubic metres |
| | tcm | trillion cubic metres |
| **Mass** | kg | kilogramme (1 000 kg = 1 tonne) |
| | kt | kilotonnes (1 tonne x $10^3$) |
| | Mt | million tonnes (1 tonne x $10^6$) |
| | Gt | gigatonnes (1 tonne x $10^9$) |
| **Monetary** | $ million | 1 US dollar x $10^6$ |
| | $ billion | 1 US dollar x $10^9$ |
| | $ trillion | 1 US dollar x $10^{12}$ |
| **Oil** | b/d | barrel per day |
| | kb/d | thousand barrels per day |
| | mb/d | million barrels per day |
| **Power** | GW | gigawatt (1 watt x $10^9$) |

## General conversion factors for energy

| *Convert to:* | TJ | Gcal | Mtoe | MBtu | GWh |
|---|---|---|---|---|---|
| *From:* | multiply by: | | | | |
| **TJ** | 1 | 238.8 | $2.388 \times 10^{-5}$ | 947.8 | 0.2778 |
| **Gcal** | $4.1868 \times 10^{-3}$ | 1 | $10^{-7}$ | 3.968 | $1.163 \times 10^{-3}$ |
| **Mtoe** | $4.1868 \times 10^{4}$ | $10^{7}$ | 1 | $3.968 \times 10^{7}$ | 11 630 |
| **MBtu** | $1.0551 \times 10^{-3}$ | 0.252 | $2.52 \times 10^{-8}$ | 1 | $2.931 \times 10^{-4}$ |
| **GWh** | 3.6 | 860 | $8.6 \times 10^{-5}$ | 3 412 | 1 |

Note: There is no generally accepted definition of boe; typically the conversion factors used vary from 7.15 to 7.35 boe per toe.

## Currency conversions

| ***Exchange rates*** *(2014 annual average)* | **1 US Dollar equals:** |
|---|---|
| British Pound | 0.61 |
| Chinese Yuan | 6.14 |
| Euro | 0.75 |
| Indian Rupee | 61.74 |
| Indonesian Rupiah | 11 863.75 |
| Japanese Yen | 105.69 |
| South African Rand | 10.84 |

## Definitions

**Advanced biomass cookstoves:** Advanced biomass cookstoves are biomass gasifier-operated cookstoves that run on solid biomass, such as wood chips and briquettes. These cooking devices have significantly lower emissions and higher efficiencies than the traditional biomass cookstoves (three-stone fires) currently used largely in developing countries.

**Agriculture:** Includes all energy used on farms, in forestry and for fishing.

**Ambient/outdoor air pollution:** The presence of solids, liquids or gases in ambient/outdoor air at concentrations that have a negative impact on the surrounding environment and people.

**Bioenergy:** Refers to the energy content in solid, liquid and gaseous products derived from biomass feedstocks and biogas. It includes solid biomass, biofuels and biogas. This includes biofuels for transport and products (e.g. wood chips, pellets, black liquor) to produce electricity and heat. Municipal solid waste and industrial waste are also included.

**Black carbon (BC):** Black carbon is formed by the incomplete combustion of fossil fuels, biofuels and biomass. It is the most strongly light-absorbing component of particulate matter and is a short-lived climate pollutant.

**Buildings** (sector)**:** The buildings sector includes energy used in residential (households), commercial (e.g. hotels, catering, shops) and institutional buildings (e.g. schools, hospitals, offices) and non-specified other. Building energy use includes space heating and cooling, water heating, lighting, appliances and cooking equipment.

**Bunkers:** Includes both international marine bunkers and international aviation bunkers.

**Clean cooking:** Cooking facilities that are considered safer, more efficient and more environmentally sustainable than the traditional facilities that make use of solid biomass (such as a three-stone fire). This refers primarily to improved solid biomass cookstoves, biogas systems, liquefied petroleum gas stoves, ethanol and solar stoves.

**Combined-cycle gas turbine** (CCGT)**:** CCGT plants consist of gas-turbines in which hot exhaust is re-used through a heat recovery steam generator (rather than discharged as in simple cycle turbines), allowing it to produce additional power.

**Deduster:** The most effective control technologies for particulate matter in combustion plants are electrostatic precipitators and fabric filters. Electrostatic precipitators electrically charge the particles and use an electric field to collect the dust on electrodes. Fabric filters, sometimes referred to as "baghouses", are porous filtration media, collecting dust from the passing flue gas.

**Eutrophication:** The process by which a body of water acquires a high level of nutrients promoting the growth of algae, which then results in the depletion of oxygen in the water, causing the death of fish and other organisms.

**Flue gas:** Gas exiting to the atmosphere via a flue, which is a pipe or channel for conveying exhaust gases from a fireplace, oven, furnace, boiler or steam generator. Quite often, flue gas refers to the combustion exhaust gas produced at power plants.

**Flue-gas desulfurisation:** A control technology device – often referred to as scrubber – to remove sulfur dioxide ($SO_2$) from the flue gas stream of combustion plants. The most common technology is the wet scrubber which uses a calcium-based sorbent (typically limestone) to react with the $SO_2$ and produce gypsum in a specifically designed vessel. Other technologies to control for $SO_2$ are spray dry scrubbers, sorbent injection or a circulating fluid bed scrubber.

**Household/indoor air pollution:** Chemical, biological and physical contamination of indoor/household air.

**Industry and transformation (sectors):** Includes fuel used within the manufacturing and construction industries. Key industry sectors include iron and steel, chemical and petrochemical, cement, pulp and paper and aluminium. Use by industries for the transformation of energy into another form or for the production of fuels, except for power and heat generation, is also reported under this category. In addition, this category includes non-energy use of fuels for chemical feedstocks and non-energy products. Consumption of fuels for the transport of goods is reported as part of the transport sector, while consumption by off-road vehicles is reported under industry.

**International aviation bunkers:** Includes the deliveries of aviation fuels to aircraft for international aviation. Fuels used by airlines for their road vehicles are excluded. The domestic/international split is determined on the basis of departure and landing locations and not by the nationality of the airline. For many countries this incorrectly excludes fuels used by domestically owned carriers for their international departures.

**International marine bunkers:** Covers those quantities delivered to ships of all flags that are engaged in international navigation. The international navigation may take place at sea, on inland lakes and waterways, and in coastal waters. Consumption by ships engaged in domestic navigation is excluded. The domestic/international split is determined on the basis of port of departure and port of arrival, and not by the flag or nationality of the ship. Consumption by fishing vessels and by military forces is also excluded and included in residential, services and agriculture.

**Investment:** All investment data and projections reflect "overnight investment", i.e. the capital spent is generally assigned to the year production (or trade) is started, rather than the year when it actually incurs. Investments for oil, gas, and coal include production, transformation and transportation; those for the power sector include refurbishments, uprates, new builds and replacements for all fuels and technologies for on-grid, mini-grid and off-grid generation, as well as investment in transmission and distribution. Investment data are presented in real terms in year-2014 US dollars.

**Modern energy access:** Access to modern energy services includes household access to a minimum level of electricity; household access to safer and more sustainable cooking and heating fuels and stoves; access that enables productive economic activity; and access for public services.

**New European Driving Cycle (NEDC):** Driving cycle used to assess average fuel consumption and emissions per kilometre for passenger cars, currently in use in the test procedures applied in Europe and in United Nations regulatory texts.

**Nitrogen oxides ($NO_X$):** Nitrogen oxides are a family of poisonous, highly reactive gases. $NO_X$ pollution is emitted by automobiles, trucks and various non-road vehicles, as well as power plants, industrial boilers, cement kilns and turbines.

**Nitrogen oxides control:** Low $NO_X$ burners and over-fire air are primary measures to abate $NO_X$ emissions from combustion plants. In essence, these technologies control the oxygen flow and moderate combustion temperatures to reduce the formation of $NO_X$. Post-combustion $NO_X$ control can be added to the primary measures to improve the effectiveness of $NO_X$ control. Selective catalytic reduction and selective non-catalytic reduction are the most commonly applied technologies. The technologies treat the flue gas with a chemical reagent (mostly ammonia or urea) to react with the $NO_X$ and form molecular nitrogen.

**Ozone ($O_3$):** A very reactive form of oxygen that has three atoms in its molecule. It is a major air pollutant in the lower atmosphere (ground level ozone, but a beneficial component of the upper atmosphere (the ozone layer).

**Particulate matter** (PM)**:** A mix of solid/liquid organic and inorganic substances that may be a primary or secondary pollutant. PM is made up of a number of components, including acids (such as nitrates and sulfates), organic chemicals, metals, and soil or dust particles.

**Premature deaths:** Deaths that are attributable to a given risk factor and are considered to have been preventable if the risk had been eliminated. All deaths are considered equally, regardless of age.

**Solid biomass:** Includes charcoal, fuelwood, dung, agricultural residues, wood waste and other solid wastes.

**Sulfur dioxide** ($SO_2$)**:** A colourless, poisonous gas with a strong odour. Occurring in nature in volcanic gases, large quantities of sulfur dioxide are formed in the combustion of sulfur-containing fuels.

**Sulfur oxides** ($SO_x$)**:** Refers to any of several compounds of sulfur and oxygen.

**Three-way catalytic converter:** An abatement technology that converts carbon monoxide (CO) and unburned hydrocarbons to $CO_2$ and water, using an oxidising reaction, and nitrogen oxides ($NO_X$) to nitrogen and oxygen using a reduction reaction.

**Total primary energy demand** (TPED)**:** Includes power generation, other energy sector excluding electricity and heat, and total final consumption (TFC) excluding electricity and heat. TPED does not include ambient heat from heat pumps or electricity trade. Sectors comprising TFC include industry, transport, buildings (residential, services and non-specified other) and other (agriculture and non-energy use).

**Traditional use of solid biomass:** The traditional use of solid biomass refers to the use of solid biomass with basic technologies, such as a three-stone fire, often with no or poorly operating chimneys.

**Transport:** Fuels used in the transport of goods or persons within the national territory irrespective of the economic sector within which the activity occurs. This includes fuels delivered to vehicles using public roads or for use in rail vehicles; fuel delivered to vessels for domestic navigation; fuels delivered to aircraft for domestic aviation; and energy consumed in the delivery of fuels through pipelines. Fuel delivered to international marine and aviation bunkers is presented only at the world level.

**World Harmonised Light-Test Procedure (WLTP):** Test procedure developed to assess average fuel consumption and emissions per kilometre for passenger cars, comprising a newly developed test cycle (referred to as WLTC). First endorsed by the World Forum for the Harmonisation of Vehicle Regulations (WP.29) in 2014, it is being further developed and is set to become the global reference for light-duty vehicle testing in the near future, progressively replacing region-specific test cycles, such as the New European Driving Cycle (NEDC) in Europe.

**Years-of-life-lost** (YLL)**:** Years of potential life lost as a result of premature death (assessed relative to a given life expectancy). YLL therefore takes into account the age at death, giving more weight to deaths at a younger age and less weight to deaths at an older age.

## Regional and country groupings

**Africa:** Algeria, Angola, Benin, Botswana, Cameroon, Congo, Côte d'Ivoire, Democratic Republic of Congo, Egypt, Eritrea, Ethiopia, Gabon, Ghana, Kenya, Libya, Mauritius, Morocco, Mozambique, Namibia, Niger, Nigeria, Senegal, South Africa, South Sudan, Sudan, United Republic of Tanzania, Togo, Tunisia, Zambia, Zimbabwe and other African countries and territories.[1]

**Caspian:** Armenia, Azerbaijan, Georgia, Kazakhstan, Kyrgyz Republic, Tajikistan, Turkmenistan and Uzbekistan.

**China:** Refers to the People's Republic of China, including Hong Kong.

**Developing Asia:** Bangladesh, Brunei Darussalam, Cambodia, China, Chinese Taipei, India, Indonesia, the Democratic People's Republic of Korea, Malaysia, Mongolia, Myanmar, Nepal, Pakistan, the Philippines, Singapore, Sri Lanka, Thailand, Viet Nam and other Asian countries and territories.[2]

**Developing countries:** Developing Asia, Middle East, Africa and Latin America regional groupings.

**Eastern Europe/Eurasia:** Albania, Armenia, Azerbaijan, Belarus, Bosnia and Herzegovina, Bulgaria, Croatia, Georgia, Kazakhstan, Kosovo, Kyrgyz Republic, Latvia, Lithuania, the former Yugoslav Republic of Macedonia, the Republic of Moldova, Montenegro, Romania, Russian Federation, Serbia, Tajikistan, Turkmenistan, Ukraine and Uzbekistan. For statistical reasons, this region also includes Cyprus[3,4], Gibraltar and Malta.

**European Union:** Austria, Belgium, Bulgaria, Croatia, Cyprus[2,3], Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Poland, Portugal, Romania, Slovak Republic, Slovenia, Spain, Sweden and United Kingdom.

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[1] Individual data are not available and are estimated in aggregate for: Burkina Faso, Burundi, Cape Verde, Central African Republic, Chad, Comoros, Djibouti, Equatorial Guinea, Gambia, Guinea, Guinea-Bissau, Lesotho, Liberia, Madagascar, Malawi, Mali, Mauritania, Reunion, Rwanda, Sao Tome and Principe, Seychelles, Sierra Leone, Somalia, Swaziland, Uganda and Western Sahara.

[2] Individual data are not available and are estimated in aggregate for: Afghanistan, Bhutan, Cook Islands, Fiji, French Polynesia, Kiribati, Lao PDR, Macau (China), Maldives, New Caledonia, Palau, Papua New Guinea, Samoa, Solomon Islands, Timor-Leste and Tonga, and Vanuatu.

[3] Note by Turkey: The information in this document with reference to "Cyprus" relates to the southern part of the Island. There is no single authority representing both Turkish and Greek Cypriot people on the Island. Turkey recognises the Turkish Republic of Northern Cyprus (TRNC). Until a lasting and equitable solution is found within the context of United Nations, Turkey shall preserve its position concerning the "Cyprus issue".

[4] Note by all the European Union Member States of the OECD and the European Union: The Republic of Cyprus is recognised by all members of the United Nations with the exception of Turkey. The information in this document relates to the area under the effective control of the Government of the Republic of Cyprus.

**Latin America:** Argentina, Bolivia, Brazil, Colombia, Costa Rica, Cuba, Curaçao, Dominican Republic, Ecuador, El Salvador, Guatemala, Haiti, Honduras, Jamaica, Nicaragua, Panama, Paraguay, Peru, Trinidad and Tobago, Uruguay, Venezuela and other non-OECD Americas countries and territories.[5]

**Middle East:** Bahrain, the Islamic Republic of Iran, Iraq, Jordan, Kuwait, Lebanon, Oman, Qatar, Saudi Arabia, Syrian Arab Republic, United Arab Emirates and Yemen.

**North Africa:** Algeria, Egypt, Libya, Morocco and Tunisia.

**North America:** Canada, Mexico and the United States

**OECD:** Australia, Austria, Belgium, Canada, Chile, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Japan, Korea, Luxembourg, Mexico, Netherlands, New Zealand, Norway, Poland, Portugal, Slovak Republic, Slovenia, Spain, Sweden, Switzerland, Turkey, United Kingdom and United States. For statistical reasons, this region also includes Israel.[6]

**Southeast Asia:** Brunei Darussalam, Cambodia, Indonesia, Lao PDR, Malaysia, Myanmar, Philippines, Singapore, Thailand and Viet Nam. These countries are all members of the Association of Southeast Asian Nations (ASEAN).

**Sub-Saharan Africa:** Africa regional grouping excluding the North Africa regional grouping.

## Abbreviations and Acronyms

| | |
|---|---|
| **APEC** | Asia-Pacific Economic Cooperation |
| **ASEAN** | Association of Southeast Asian Nations |
| **BC** | Black carbon |
| **CAAGR** | compound average annual growth rate |
| **CAFE** | corporate average fuel-economy standards (United States) |
| **CAS** | Clean Air Scenario |
| **CCGT** | combined-cycle gas turbine |
| **CCS** | carbon capture and storage |
| **$CH_4$** | methane |
| **CNG** | compressed natural gas |
| **CO** | carbon monoxide |
| **$CO_2$** | carbon dioxide |
| **$CO_2$-eq** | carbon-dioxide equivalent |
| **COP** | Conference of Parties (UNFCCC) |

[5] Individual data are not available and are estimated in aggregate for: Antigua and Barbuda, Aruba, Bahamas, Barbados, Belize, Bermuda, Bonaire, British Virgin Islands, Cayman Islands, Dominica, Falkland Islands (Malvinas), French Guyana, Grenada, Guadeloupe, Guyana, Martinique, Montserrat, Saba, Saint Eustatius, St. Kitts & Nevis, St. Lucia, St. Vincent and the Grenadines, Saint Maarten, Suriname, Turks & Caicos Islands.

[6] The statistical data for Israel are supplied by and under the responsibility of the relevant Israeli authorities. The use of such data by the OECD and/or the IEA is without prejudice to the status of the Golan Heights, East Jerusalem and Israeli settlements in the West Bank under the terms of international law.

| | |
|---|---|
| **CTG** | coal-to-gas |
| **CTL** | coal-to-liquids |
| **EPA** | Environmental Protection Agency (United States) |
| **EU ETS** | European Union Emissions Trading System |
| **EV** | electric vehicle |
| **FGD** | Flue-gas desulfurisation |
| **GAINS** | Greenhouse Gas and Air Pollution Interactions and Synergies |
| **GDP** | gross domestic product |
| **GHG** | greenhouse gases |
| **GTL** | gas-to-liquids |
| **HDV** | Heavy-duty vehicle |
| **HFO** | heavy-fuel oil |
| **IIASA** | International Institute for Applied Systems Analysis |
| **LCV** | light-commercial vehicle |
| **LDV** | Light-duty vehicle |
| **LNG** | liquefied natural gas |
| **LPG** | liquefied petroleum gas |
| **MEPS** | minimum energy performance standards |
| **NEDC** | New European Driving Cycle |
| **NGL** | natural gas liquids |
| **$NO_X$** | Nitrogen oxides |
| **NPS** | New Policies Scenario |
| **$O_3$** | Ozone |
| **OECD** | Organisation for Economic Co-operation and Development |
| **PLDV** | passenger light-duty vehicle |
| **PM** | particulate matter |
| **PPP** | purchasing power parity |
| **PV** | photovoltaics |
| **R&D** | research and development |
| **SME** | small and medium enterprises |
| **$SO_2$** | sulfur dioxide |
| **$SO_x$** | sulfur oxides |
| **TFC** | total final consumption |
| **TPED** | total primary energy demand |
| **UN** | United Nations |
| **UNDP** | United Nations Development Program |
| **UNEP** | United Nations Environment Program |
| **UNFCCC** | United Nations Framework Convention on Climate Change |
| **YLL** | Years-of-life-lost |
| **WEO** | World Energy Outlook |
| **WEM** | World Energy Model |
| **WHO** | World Health Organization |
| **WLTC** | World Harmonised Light-Test Cycle |
| **WLTP** | World Harmonised Light-Test Procedure |

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# Energy and Air Pollution

- Around 6.5 million premature deaths each year can be attributed to air pollution.
- Energy production and use are by far the largest man-made sources of air pollutants.
- Technologies to tackle air pollution are well known.

Clean air is vital for good health. Yet despite growing recognition of this imperative, the problem of air pollution is far from solved in many countries, and the global health impacts risk intensifying in the decades to come.

The scale of the public health crisis caused by air pollution and the importance of the energy sector to its resolution are the reasons why the IEA is focusing on this critical topic for the first time.

Based on new data for pollutant emissions in 2015 and projections to 2040, this special report, the latest in the *World Energy Outlook* series, provides a global outlook for energy and air pollution as well as detailed profiles of key countries and regions: the United States, Mexico, the European Union, the People's Republic of China, India, Southeast Asia and Africa.

In a Clean Air Scenario, the report proposes a pragmatic and attainable strategy to reconcile the world's energy requirements with its need for cleaner air. Alongside the multiple benefits to human health, this strategy shows that resolving the world's air pollution problem can go hand-in-hand with progress towards other environmental and development goals.

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