Organisation for Economic Co-operation and Development

ENV/WKP(2022)9

Unclassified **English - Or. English**

26 July 2022

ENVIRONMENT DIRECTORATE

The economic benefits of international co-operation to improve air quality in Northeast Asia

A focus on Japan, Korea and China

Environment Working Paper No. 197

By Elisa Lanzi (1), Enrico Botta (1), Daniel Ostalé Valriberas (1), Grace Alexander (1), Zbigniew Klimont (2), Gregor Kiesewetter (2), Chris Heyes (2), Rita Van Dingenen (3)

(1) OECD Environment Directorate
(2) International Institute for Applied Systems Analysis (IIASA)
(3) European Commission's Joint Research Centre

Authorised for publication by Alain de Serres, Director, Environment Directorate.

Keywords: air pollution, computable general equilibrium models, best available techniques

JEL Codes: C68, Q53, Q52

OECD Environment Working Papers are available at www.oecd.org/environment/workingpapers.htm

Elisa Lanzi, elisa.lanzi@oecd.org , +33 (0)1 45 24 14 78

JT03500680

OECD ENVIRONMENT WORKING PAPERS

OECD Working Papers should not be reported as representing the official views of the OECD or of its member countries. The opinions expressed and arguments employed are those of the author(s). Working Papers describe preliminary results or research in progress by the author(s) and are published to stimulate discussion on a broad range of issues on which the OECD works.

This series is designed to make available to a wider readership selected studies on environmental issues prepared for use within the OECD. Authorship is usually collective, but principal author(s) are named. The papers are generally available only in their original language – English or French – with a summary in the other language.

Comments on Working Papers are welcomed, and may be sent to:

OECD Environment Directorate

2 rue André-Pascal, 75775 Paris Cedex 16, France

or by email: *env.contact@oecd.org*

OECD Environment Working Papers are published on
www.oecd.org/environment/workingpapers.htm as well as
on the OECD iLibrary (www.oecdilibrary.org)

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 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.

Note by Republic of Türkiye: 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. Türkiye recognises the Turkish Republic of Northern Cyprus (TRNC). Until a lasting and equitable solution is found within the context of the United Nations, Türkiye shall preserve its position concerning the “Cyprus issue”.

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 Türkiye. The information in this document relates to the area under the effective control of the Government of the Republic of Cyprus.

Abstract

Air pollution is a global challenge to people's health and has severe economic consequences. The region of Northeast Asia is no exception. Across most regions in Japan, and in the entire territories of Korea and China, annual average concentrations of fine particulate matter are above the guideline levels indicated by the World Health Organisation, indicating a risk to health. Policy action to tackle air pollution across the three countries, could prevent air pollution related illnesses and deaths, without affecting economic growth.

This report presents projections for the impact of air pollution polices until 2050, with differing levels of regional coordination. Projections for current policies are compared with unilateral policy action, whereby each of the three countries introduce more stringent policies to tackle air pollution; alongside regionally coordinated policy action by all three countries; and policy action on a global level. The report presents the health, agricultural and economic impacts, and identifies considerable benefits from further coordination on air pollution policies, such as with regional and global policy action.

Keywords : air pollution, computable general equilibrium models, best available techniques

JEL codes : C68, Q53, Q52

Résumé

La pollution atmosphérique est un défi mondial pour la santé des personnes et a des graves conséquences économiques. La région de l'Asie du Nord-Est ne fait pas exception. Dans la plupart des régions du Japon et sur l'ensemble des territoires de la Corée et de la Chine, les concentrations moyennes annuelles de particules fines sont supérieures aux niveaux de référence de l'Organisation mondiale de la santé, ce qui indique un risque pour la santé. Une action politique pour lutter contre la pollution de l'air dans les trois pays pourrait prévenir les maladies et les décès liés à la pollution de l'air, sans affecter la croissance économique.

Ce rapport présente des projections de l'impact des politiques de lutte contre la pollution atmosphérique jusqu'en 2050, avec différents niveaux de coordination régionale. Les projections des politiques actuelles sont comparées à l'action politique unilatérale, dans le cadre de laquelle chacun des trois pays introduit des politiques plus strictes pour lutter contre la pollution de l'air. Autres scenarios considèrent une action politique coordonnée au niveau régional par les trois pays et l'action politique au niveau mondial. Le rapport présente les impacts sur la santé, l'agriculture et l'économie et identifie des avantages considérables en cas d'une coordination des politiques en matière de pollution de l'air, par exemple avec des actions politiques régionales et mondiales.

Mots clés : pollution de l'air, air pollution, modèles d'équilibre général calculable, meilleures techniques disponibles

Classification JEL: C68, Q53, Q52

Acknowledgments

This report presents the projected economic consequences of air pollution policies in Northeast Asian countries, and specifically in Japan, Korea and China, to 2050. The report builds on the OECD's CIRCLE project on the costs of inaction and on the 2016 report "The economic consequences of outdoor air pollution".

This report was prepared by Enrico Botta, Daniel Ostalé Valriberas, Elisa Lanzi, and Grace Alexander of the OECD Environment Directorate, Zbigniew Klimont, Gregor Kiesewetter and Chris Heyes of the International Institute for Applied Systems Analysis (IIASA), and Rita Van Dingenen of the European Commission's Joint Research Centre, under the guidance of Shardul Agrawala, Head of the Economy Environment Integration Division at OECD Environment Directorate.

The report benefitted from feedback of the Delegates of the Working Party on Integrating Environmental and Economic Policies (WPIEEP) during and after its meetings in October 2020 and March 2021, from the expert review of Shaohui Zang (Beihang University), Jia Xing (Tsinghua University), and So-jung You (Korea Ministry of Environment) and from the valuable comments and suggestions of OECD colleagues, including Rob Dellink, Alexander Mackie and Ruben Bibas (OECD Environment Directorate) and Camila Saffirio (OECD Directorate for Public Governance). The report was discussed by the WPIEEP and subsequently declassified by the Environment Policy Committee (EPOC) in September 2021. Illias Mousse Iye provided editorial support.

This report was prepared with the financial assistance of the Korean Ministry of Environment.

Table of contents

Tables

Figures

Boxes

Acronyms and Abbreviations

ASEAN	Association of Southeast Asian Nations
AQG	Air Quality Guidelines (from the World Health Organisation)
BAT	Best Available Techniques
BC	Black Carbon
BEV	Battery Electric Vehicle
CGE	Computable General Equilibrium
CP	Current Policy
CPA	China Policy Action Scenario
CO	Carbon Monoxide
COVID-19	Coronavirus Disease 2019
EC-JRC	European Commission’s Joint Research Centre
EU	European Union
FCEV	Fuel Cell Electric Vehicle
GAINS	Greenhouse Gas and Air Pollution Interactions and Synergies
GBD	Global Burden of Disease
GDP	Gross Domestic Product
GPA	Global Policy Action Scenario
HDV	Heavy Duty Vehicles
HTAP	Task Force on Hemispheric Transport of Air Pollution
IIASA	International Institute for Applied Systems Analysis
IEA	International Energy Agency
JPA	Japan Policy Action Scenario
KPA	Korea Policy Action Scenario
LDV	Light Duty Vehicles
LRTAP	Long-range Transboundary Air Pollution
NEAPA	Northeast Asia Policy Action Scenario
NH_3	Ammonia
NIER	Korea’s National Institute of Environmental Research

NMVOC	Non-Methane Volatile Organic Compound
NO_x	Nitrogen Oxides
OC	Organic Carbon
OECD	Organisation for Economic Co-operation and Development
O_3	Ground-level Ozone
PA	Policy Action
$PM_{2.5}$	Fine Particulate Matter
PPP	Purchasing Power Parity
SO_2	Sulphur Dioxide
TM5-FASST	Fast Scenario Screening Tool
UNECE	United Nations Economic Commission for Europe
USD	United States Dollar
VOC	Volatile Organic Compound
VSL	Value of a Statistical Life
WHO	World Health Organisation
WTP	Willingness to Pay

Executive summary

Air quality is a key concern in most countries around the world, including Japan, Korea and China. Across most regions in Japan, and the entire territories of Korea and China, annual average concentrations of fine particulate matter are above the guideline levels of 10 µg per cubic metre indicated by the World Health Organisation. Increasing evidence on the detrimental impact of air pollution on human health, the environment and economic growth implies a call for urgent action to improve air quality in the region.

This report aims to quantify the benefits of policy action on air pollution in Japan, Korea and China in the coming decades, with focus on the additional benefits from co-ordinated policy action between the three countries. The report compares a policy scenario in which current policies continue in the coming decades with scenarios in which each of the three countries implements ambitious policies that result in the wide adoption of the best available techniques to curb air pollution emissions. These single-country policy action scenarios are also compared with a co-ordinated policy action scenario in which the three countries act at the same time, and with a global policy action scenario.

The analysis relies on a step-wise methodology to provide projections of the benefits of policy action up to 2050. For the different scenarios, projections of economic activities are linked to emission projections, then to health and environmental impacts of air pollution, and finally to the economic consequences of air pollution. The economic consequences include macroeconomic effects as well as welfare effects associated with mortality and illness. The macroeconomic effects of the policy action reflect benefits from reduced air pollution impacts on health and agriculture as well as costs from investment in the best available techniques, considering both direct and indirect changes in economic activity. Indeed, with ambitious policy action on air pollution, firms and households are likely to invest in techniques or technologies that can reduce one or several pollutants and that provide a cleaner production or consumption option.

This report finds that, even with current policies, emissions of air pollutants in the three countries are projected to decrease by 10% to 50% by 2050, depending on the country and the pollutant; with the exception of ammonia which is projected to increase in the three countries. Meanwhile, ambitious policy action that stimulates the deployment of best available techniques is projected to lead to larger emission reductions, including an 80% decrease in fine particle emissions across the three countries in 2050 compared to 2020. The national context influences which sectors contribute most towards domestic emissions reductions. For instance, the largest reduction in fine particle emissions in the three countries results from improving municipal solid waste management, while in China, reductions of emissions from the residential sector are also projected to account for a large share of fine particulate emission reductions in 2050. In Korea and Japan, policies requiring further installation of high efficiency desulphurization units on industrial and power plant boilers offer the largest contribution to the projected mitigation of sulphur dioxide emissions.

The emission reductions are projected to lead to air quality improvements, as indicated by lower concentrations of fine particulate matter and ground-level ozone. If countries act alone, concentration levels of fine particle concentrations in 2050 are projected to half in China, and decrease by around a quarter in Japan and Korea compared to current policies. Co-ordinated policy action, which results in the implementation of best available techniques in the three countries, leads to further air quality improvements and in lower exposure to air pollution. In Japan, by 2050 co-ordinated policy action results in over 90% of the population being exposed to fine particle concentrations below the World Health Organisation (WHO) guideline of 10 µg per cubic metre. In Korea, most of the regions are projected to have concentration levels in line with the WHO air quality guideline interim target-3 (i.e. 15 µg per cubic metre). While in China average concentrations remain higher, progress is clear when considering the reduction in exposure to unsafe concentration levels according to the WHO guidelines (over 35 µg per cubic metre). Indeed, in China policy action would result in 97% of the population being below the unsafe threshold level[1] of 35 µg per cubic metre by 2050.

Thanks to the air quality improvements, mortality and morbidity caused by air pollution are also projected to decrease. In China, domestic policy action alone leads to a reduction in mortality of 25% compared with current policies in 2050, with limited additional benefits from co-ordinated action in the region. Air pollution-related mortality in Japan and Korea decreases by around 20% and 10%, respectively by 2050 when these countries act alone, while these benefits would increase to 29% in Japan and almost double in Korea with co-ordinated policy action. In China it is mostly domestic policy action that leads to a reduction in mortality, with a small reduction in premature deaths with coordinated action.

Air quality improvements are also projected to have beneficial effects on agricultural productivity in Japan, Korea and China. Indeed, air pollution, and specifically high concentrations of ground-level ozone, negatively impacts crops. With co-ordinated policy action, the production of crops is projected to increase on average by 1-2% by 2050 in the three countries, with additional improvements in the case of global policy action.

These beneficial effects on health and agriculture are projected to be achieved with no significant effect on economic growth by 2050. The costs associated with the investments in best available techniques are projected to be offset by the macroeconomic benefits of reduced air pollution. Acting alone is more costly, especially in Korea; in contrast, co-ordinated policy action is beneficial for all three countries. Global policy action is projected to boost macroeconomic benefits in Japan and Korea by 2050, reflecting improved competitiveness. China is projected to be mostly affected by the domestic costs of the investments in best available techniques, with little effects from the policy choices of other countries, including Japan and Korea.

While the net macroeconomic effects are negligible, ambitious policy action to tackle air pollution would provide substantial welfare benefits from reduced mortality and pain and suffering from illness to Japan, Korea and China, especially in case of co-ordinated policy action. If countries act alone, the additional yearly per capita benefits resulting from reduced mortality and morbidity are projected to amount to USD 200 in Japan, USD 180 in Korea and almost USD 500 in China by 2050, compared with current policies. A co-ordinated policy response across the three countries would increase the per capita benefits to USD 380 in Japan and USD 360 in Korea. Coordinated policy action has a smaller impact on per capita welfare benefits in China since domestic policy action is the main driver of air quality improvement in this country. If policies to control air pollution were adopted globally, the welfare benefits would increase in the three countries. While the welfare benefits of air pollution policies are clear, there might also be welfare losses, for instance for firms in the transition towards cleaner production.

The report highlights that further co-operation to reduce air pollution in the Northeast Asia region can result in health, environmental and economic benefits. Nevertheless, international co-operation in the region faces challenges that are difficult to surmount. A number of actions, including the promotion of compliance activities and better data and measurement techniques, can support the implementation of a co-ordinated approach to reduce air pollution in the region. Furthermore, increased international efforts to mitigate climate change might also contribute to improve air quality in the region and to encourage more policy action towards a green transition.

[1] The WHO Air Quality Guidelines stipulate that average $PM_{2.5}$ concentration should not exceed 10 $\mu g/m^3$. The WHO interim target-1, which is the first of a series of incrementally stringent air quality objectives up to the Guideline level, is 35 $\mu g/m^3$.

Introduction

Despite recent improvement, air quality remains a key concern for human health and for the environment in the Northeast Asian region.[2] Currently, more than three quarters of the population of Japan and virtually the entire populations of the People's Republic of China (hereafter referred to as China) and Korea are exposed to dangerous levels of fine particle concentration (i.e. concentrations above 10 µg/m^3).[3]

Increasing evidence from both the empirical and modelling economic literature shows that improving air quality can support economic growth in addition to contributing to better health and environmental outcomes. A number of studies highlight the negative impact of air pollution on low-skilled workers' productivity, such as fruit packers (Chang et al., 2016[1]); garments workers (Adhvaryu, Kala and Nyshadham, 2019[2]); and call centre workers (Chang et al., 2016[3]). Furthermore, there is increasing evidence of negative impacts also on cognitive capabilities, thus suggesting negative consequences also for the productivity of higher skilled workers (Ebenstein, Lavy and Roth, 2016[4]; Zhang, Chen and Zhang, 2018[5]). Overall, the economic benefits of addressing air pollution (i.e. higher labour productivity, lower health expenditures and higher agricultural productivity) can be substantial (Matus et al., 2008[6]; Nam et al., 2010[7]; OECD, 2016[8]; Amann et al., 2017[9]; Dechezleprêtre, Rivers and Stadler, 2019[10])

This report aims at quantifying the economic benefits of new ambitious policies to improve air quality in the Northeast Asian region, with focus on Japan, Korea, and China. The policy scenarios reflect policy action that would lead to the deployment of best available techniques to reduce emissions of air pollutants.[4] The report also aims at showing the additional benefits that could result from international co-operation by comparing domestic policy action scenarios with co-ordinated policy action scenarios. More specifically, the scenarios analysed are: (i) a baseline scenario that considers only the impact of air pollution policies currently in place; (ii) three single-country policy action scenarios where new ambitious policies to improve air quality are introduced in Japan, Korea and China separately; (iii) a scenario reflecting co-ordinated policy action in which the three countries put in place new ambitious policies; and (iv) a global policy action scenario. This last scenario sheds light on the role that countries outside the focal region play in controlling regional air quality, and the competitiveness issues that may arise when only a few countries adopt stringent policies.

Building on the methodology introduced in the report "*The Economic Consequences of Outdoor Air Pollution"* (OECD, 2016[8]), the modelling approach links economic activity to projected emissions, pollutant concentrations, biophysical impacts of outdoor air pollution and their feedback effects on the economy. The main modelling tool used in the analysis is the OECD's computable general equilibrium (CGE) model ENV-Linkages (Chateau, Dellink and Lanzi, 2014[11]), supported by results from the GAINS model (Amann et al., 2011[12]) of the International Institute for Applied Systems Analysis (IIASA) and the TM5-FASST model (Van Dingenen et al., 2018[13]) of the European Commission's Joint Research Centre

---

[2] The Northeast Asia region is here defined as the region including Japan, Korea, and People's Republic of China.

[3] This threshold corresponds to the Air quality guidelines of the World Health Organisation (WHO) for $PM_{2.5}$ (WHO, 2005[21])

[4] Best available techniques refers to techniques and technologies that reduce emissions of one or multiple air pollutants, which can be added to existing installations and operations, required on a newly built capacity, or can represent a new technology that provides the same function as previous technology but with lower emissions.

(EC-JRC). The report uses concentrations of fine particulate matter ($PM_{2.5}$) and ground-level ozone (O_3) as the two main indicators of air quality.

Relying on these modelling tools, this report quantifies the net macroeconomic consequences of the air pollution policy scenarios, which are defined as the net effect of the associated costs and benefits, including their indirect effects throughout the economy. In each scenario, firms and households invest in the best available techniques to reduce emissions of air pollutants. These investments result in costs to the economy. These policy costs are compared to the economic benefits from the reduced air pollution impacts. Air quality improvements result in economic market benefits from decreased health expenditures, and higher labour and agricultural productivity. Specific sectors and counties may also benefit from the changes in competitive position induced by the policy. The advantage of using a large-scale CGE model is that these indirect effects in the economy are brought together to identify the total net market effect. Additionally, the willingness to pay to reduce the risk of death and the disutility of illness are also included in the analysis to estimate the welfare benefits from reduced mortality and pain and suffering from illness that result from improved air quality.

The remainder of the report is structured as follows. Section 2 provides an overview of the current status of air quality in the region and of the key contributors to air pollution in the three countries, as well as a review of national policies and international co-operative actions in place in Japan, Korea and China. Section 3 summarises the methodology and describes the policy scenarios. Section 4 presents the emission projections in the different scenarios, and their consequences on air quality, human health and crop yields. Section 5 outlines the projected economic consequences of air pollution, including macroeconomic and welfare effects. Finally, Section 6 provides a discussion of results, highlighting additional actions that can support a co-ordinated approach to reduce air pollution in Northeast Asia.

1 Air quality in Japan, Korea and China

1.1. Key data on air quality

Air pollution is a major health concern in several countries in Northeast Asia, including Japan, Korea and China. Notwithstanding the important policy reforms recently introduced in these three countries (Botta and Yamasaki, 2020[14]; Yang, 2020[15]; Trnka, 2020[16]), average concentration levels of $PM_{2.5}$ and ground-level ozone, as estimated by the Global Burden of Disease database (or GBD) (IHME GBD, 2020[17]) for 2019, remain high in several areas (Figure 1.1).[5] While this section relies on GBD data to provide an overview of air quality in the three countries, there exist different data sources, including monitoring data. Box 1 provides a comparison of different data sources on air pollution.

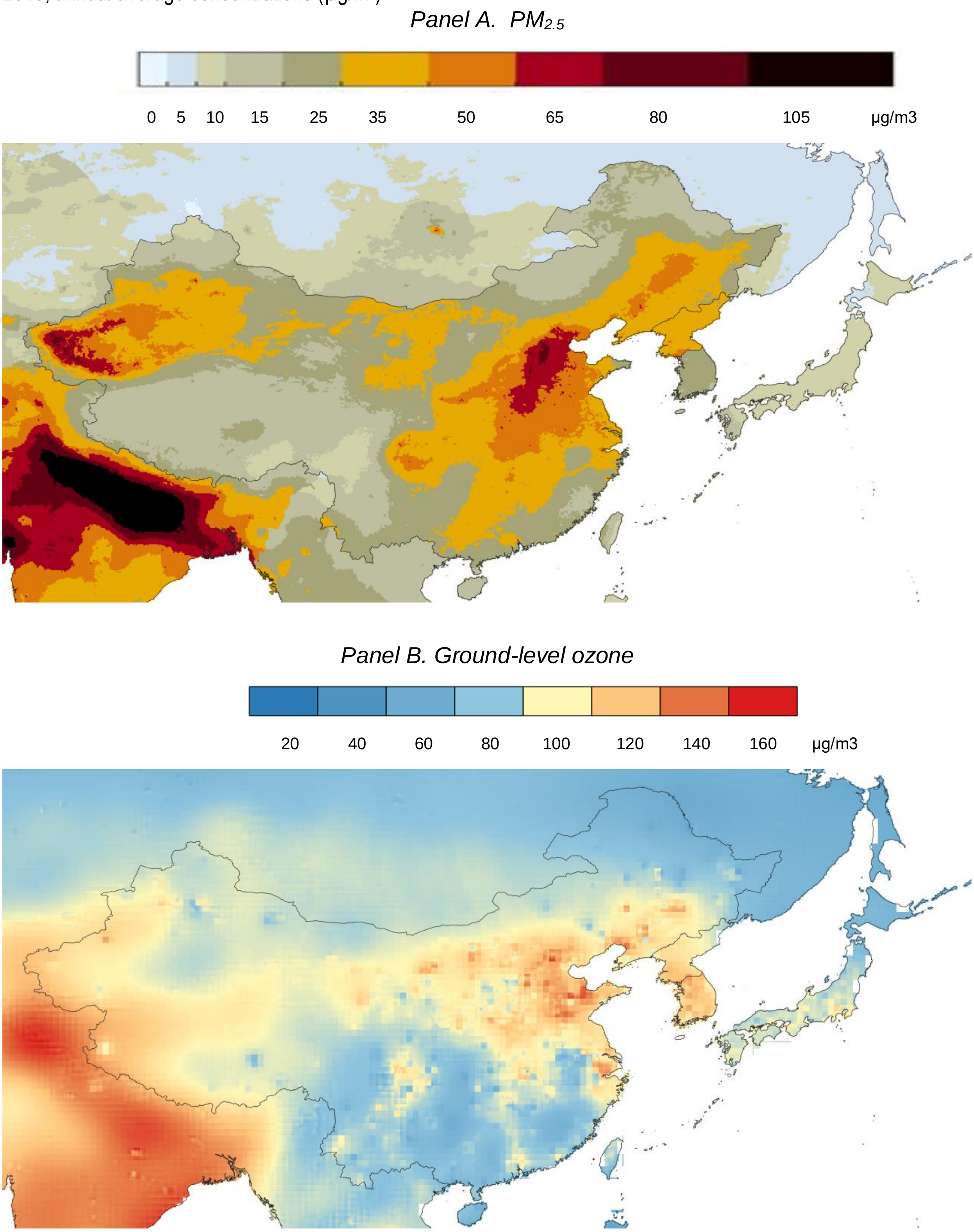
There are large variations in air quality across regions in the three countries. In Japan, mean population weighted $PM_{2.5}$ concentrations vary considerably across regions with ranges from above 15.5 $\mu g/m^3$ in Kyushu (Okinawa) to 10.4 $\mu g/m^3$ in Hokkaido. In Korea, in some areas of Gangwon Region, people suffer levels of air pollution that are higher than 29 $\mu g/m^3$, while in other regions, such as Jeju, mean population weighted concentration levels remain below 23 $\mu g/m^3$. In China, large variation in population density and presence of economic activities results in a wide range of concentration levels, with some regions, such as Hebei, recording air pollution levels above 70 $\mu g/m^3$ (OECD, 2021[18]).

Ground-level ozone concentration levels are more uniform compared to $PM_{2.5}$, reflecting the longer lifetime of ground-level ozone in the atmosphere, which allows ozone to spread further. Nevertheless, the Eastern and Western parts of China as well as Korea show average concentration levels of ground-level ozone above 100 $\mu g/m^3$. For Western China, this is partly due to geographical characteristics and to the presence of mountain areas.

[5] The concentrations of fine particulate matter and ground-level ozone illustrated in Figure 1.1 are produced to support risk exposure estimates for the Global Burden of Disease (IHME GBD, 2020[17]). This method combines available ground-based measurements with estimates derived from the remote sensing data. Further information about the methodology is elaborated in the supporting documentation (Supplementary appendix 1 pg.78) of the GBD study (IHME GBD, 2020[17]).

Figure 1.1. Concentrations of $PM_{2.5}$ and ground-level ozone

2019, annual average concentrations (µg/m³)



Note: Concentrations include both anthropogenic and natural sources.
Source: OECD Environment Statistics database (2021[18]), using Global Burden of Disease concentration estimates (IHME GBD, 2020[17]).

Box 1.1. Air pollution concentrations and population mean weighted exposure

Air pollution concentration and population mean weighted exposure are two related yet different concepts. Air pollution concentration is a measure of air quality in a given area, which is mainly measured using three approaches.

A first approach relies on air pollution concentration measurement data as provided by ground-based monitoring stations. Monitoring data is the most precise and reliable when considering air pollution in proximity of the monitoring stations. However, assumptions need to be made on how concentration varies as distance from the monitoring station increases. Furthermore, the different settings of monitoring stations across countries often complicate their use in international comparative analysis.

A second approach relies on the use of remote sensing instruments. Satellite data can be used to measure pollution concentration. As opposed to ground monitoring data, remote sensing allows using a standardised technique to measure air pollution on a global scale. However, it suffers from two key limitations: the measurements represent an average over a long time period (typically a year) and a more limited set of pollutants can be analysed compared to ground-based station data.

Finally, these two techniques can be combined to improve data reliability. This hybrid approach allows to overcome the key shortcomings of ground-based data (i.e. limited geographic coverage and lack of international comparability) and improves the accuracy of remote sensing estimates by combining different data source. The Global Burden of Disease data (GBD), which are used in this report in line with previous OECD research (OECD, 2016[8]; OECD, 2021[19]), combines satellite-based data, ground-level monitoring data and chemical transport model to estimate pollution exposure with high spatial resolution.

Once pollution concentration for a given area is estimated, this information is combined with data on the number of people living within that area to obtain population weighted exposure. Population weighted exposure is a particularly useful metric for policy-making, since it can be directly linked to benefits of air quality improvements. However, estimates for this indicator tend to provide higher concentration levels than the simple average of concentration data since they give more weight to densely populated areas that are often more polluted.

Source: (Mackie, Hascic and Cardenas Rodriguez, 2016[20]).

When considering progress on air quality, the Air Quality Guidelines (AQG) of the World Health Organisation (WHO, 2005[21]) provide a useful reference for recommended levels of average annual concentration of pollutants. The AQG recommend that concentrations of $PM_{2.5}$ should remain below 10 µg/m^3, with a first interim target of 35 µg/m^3, above which fine particle pollution is considered to be severe (see Box 1.2). The WHO guidelines also suggest two additional interim targets for $PM_{2.5}$ concentrations: interim target-2, which indicates a threshold of 25 µg/m^3 $PM_{2.5}$ annual concentrations and interim target-3, which is the closest to the AQG and indicates a threshold of 15 µg/m^3 $PM_{2.5}$ annual concentrations. The AQG for ground-level ozone corresponds to 100 µg/m^3 8-hour daily mean, with an interim target of 160 µg/m^3.

Box 1.2. WHO Air Quality Guidelines on outdoor air quality

The WHO Air Quality Guidelines (or AQG) provide guidance on exposure levels to air pollutants that are dangerous to human health. The AQG for $PM_{2.5}$ (i.e.10 µg/m^3) and PM_{10} (i.e. 20 µg/m^3) have been set at the lowest levels at which total, cardiopulmonary and lung cancer mortality have been shown to increase with more than 95% confidence in response to long-term exposure. Similarly, exposure at the guideline level for O_3 provides adequate protection of public health though some health effects may occur. The guidelines, which were issued for the first time in 1987, were last updated in 2005 and are currently under revision. In addition to the guidelines, the WHO has also issued the “interim targets”, which can be defined as objectives to incrementally increase air quality up the guideline value in regions that are affected by more severe pollution. The WHO associates the $PM_{2.5}$ interim target-1 of 35 µg/m^3 with a 15% higher mortality rate than the air quality guideline of 10 µg/m^3, while also noting that $PM_{2.5}$ concentrations under 10 µg per cubic metre can still be harmful (WHO, 2005[21]).

Table 1.1. WHO Air Quality Guidelines and interim targets for concentrations of particulate matter and ground-level ozone

	PM_{10} (µg/m^3) (annual concentration)	$PM_{2.5}$ (µg/m^3) (annual concentration)	**O_3 (µg/m^3)** (8-hour daily mean)
Interim target-1 (IT-1)	70	35	160
Interim target-2 (IT-2)	50	25	
Interim target-3 (IT-3)	30	15	
Air quality guideline (AQG)	20	10	100

Note: WHO Air Quality Guidelines list only one interim target for ground-level ozone concentrations.
Source: (WHO, 2005[21]).

Several areas in the three countries have air pollution levels above the WHO’s AQG. In China, the mean population weighted $PM_{2.5}$ concentrations remains above interim target-1 $PM_{2.5}$ of 35 µg/m^3, which coincides with the national standard. The latest available data (2017) for China shows that only 30% of major cities met the WHO AQG interim target-1 for $PM_{2.5}$ concentration levels (Yang, 2020[15]). Korean population has been exposed on average to concentration levels close to interim target-2 of the WHO guidelines, while in Japan the mean population exposure levels were just above the AQG’s levels in 2019.

In the three countries, the population has been exposed to ground-level ozone concentrations below 120 µg/m^3 annual daily maximum 8-hour average. The WHO guidelines for ground-level ozone are defined for single daily maximum levels, making it difficult to compare them to yearly averages. Importantly, the secondary nature of this pollutant makes understanding its generation mechanisms (see also below) particularly complex. For instance, the increase in ozone levels in South Korea has been linked to changes in chemical regimes (Bae et al., 2020[22]), stratospheric intrusion (Shin et al., 2020[23]) and changes in meteorological conditions (Kim et al., 2021[24]). Furthermore, some regional transport models have been found to overestimate ozone concentrations in Central Asia (e.g. (Chatani et al., 2020[25]; Shimadera et al., 2015[26]; Li et al., 2019[27]), and a similar bias is found in a review of model results for the northern hemisphere (Young et al., 2018[28]).

While this report presents average air pollution levels, the main drivers for worsening ozone air pollution is that several regions and cities experience pollution peaks. These are often linked to seasonal weather conditions or to seasonal activities, for instance linked to agricultural production. In Japan, the domestic air quality standard for photochemical oxidants, including ground-level ozone, was not met in any Prefecture in 2017 and eighty-seven days with concentration levels almost double those prescribed by the WHO AQG were recorded in the same year (Botta and Yamasaki, 2020[14]). Similarly, daily maximum 8-hour average O_3 concentrations during ozone seasons, i.e. periods of high concentration levels of ground-level ozone, have increased in the capital region of Korea (Seoul Metropolitan Area) (Bae et al., 2020[22]). Kim et al. (2021[24]) find that daily maximum 8-h moving average ozone concentrations, increased from 38 ppb in 2001 to 52 ppb in 2017 in Korea during warm seasons (April to September). In China, ground-level ozone concentrations have been increasing in cities (Ou et al., 2020[29]). Yang et al. (2020[30]) analyse O_3 concentration levels in 338 Chinese cities and find that virtually none met the WHO Guidelines in 2018.

1.2. Sources of air pollution

Economic activities contribute to the formation of primary as well as secondary pollutants (see Box 1.3). This report focuses specifically on pollutants that contribute towards the concentrations of fine particles and ground-level ozone in the atmosphere. Different economic activities are sources to different pollutants.

Box 1.3. Primary and secondary pollutants

Pollutants can be classified into primary and secondary pollutants. Primary emissions, such as carbon monoxide (CO) and sulphur dioxide (SO_2), are products of fuel and waste combustion, mostly emitted from industrial processes. Secondary pollutants, such as ground-level ozone, are formed when primary (precursor) pollutants react with other elements in the atmosphere (Daly and Zannetti, 2007[31]). Some pollutants, such as NO_X, methane and non-methane volatile organic compounds (NMVOCs) are precursor gases of both ground-level ozone and particulate matter ($PM_{2.5}$).

Measurements of ambient **$PM_{2.5}$** concentrations represent a mixture of the primary and secondary particles present in the atmosphere. Primary $PM_{2.5}$ emissions include black carbon (BC), organic carbon (OC), non-carbonaceous fine particles and are emitted directly into the atmosphere from activities such as the combustion of fossil fuels in stationary and mobile sources, biomass combustion, industrial processes, as well as agricultural and forest fires. Secondary $PM_{2.5}$ is generated through chemical reactions in the atmosphere involving pollutants such as sulphur dioxide (SO_2), nitrogen oxides (NO_X), NMVOCs and ammonia (NH_3). These reactions can take place some distance away from the original emission source (Hodan and Barnard, 2004[32]).

Ground-level ozone is a secondary pollutant, as it is not directly emitted into the atmosphere. Pollutants such as NMVOCs, NO_X, CO and methane (CH_4) are among its key precursors (Unger et al., 2006[33]). Specifically, ground-level ozone is a part of photochemical oxidants, which are secondary air pollutants formed by the action of sunlight on precursor gases.

Meteorological and climatic conditions, such as atmospheric temperature, can play a role in the photochemical reaction rates of precursors to ground-level ozone and $PM_{2.5}$ (Lam et al., 2011[34]). Other climatic factors, such as frequency of precipitations and presence of sunlight, can also influence the formation of the secondary pollutants. For instance, the higher levels of sunlight in summer months and elevated temperatures facilitate the formation of ground-level ozone.

The residential and the energy and industry sectors are the main contributors to the emissions of several pollutants in Japan, Korea and China (Figure 1.2), although their importance varies by country (see Figure C.1 in Annex C). These sectors account for more than half of primary emissions of fine particulate matter ($PM_{2.5}$), where residential emissions are dominated by organic carbon (OC) and black carbon (BC). They also correspond to a large share of emissions of pollutants, such as nitrogen oxides (NO_X) and sulphur dioxide (SO_2), that contribute to the formation of secondary $PM_{2.5}$ (see Box 1.3). Among industrial sectors, iron and steel production is by far the largest emitter of primary non-carbonaceous $PM_{2.5}$ in each of the three countries. The large Chinese coal mining sector, which account for 37% of total domestic CH_4 emissions, leads the Chinese energy and industry sectors to be a key source of this pollutant. Energy and industry accounts for 3% and 6% of emissions of this pollutant in Japan and Korea, and 42% in China.

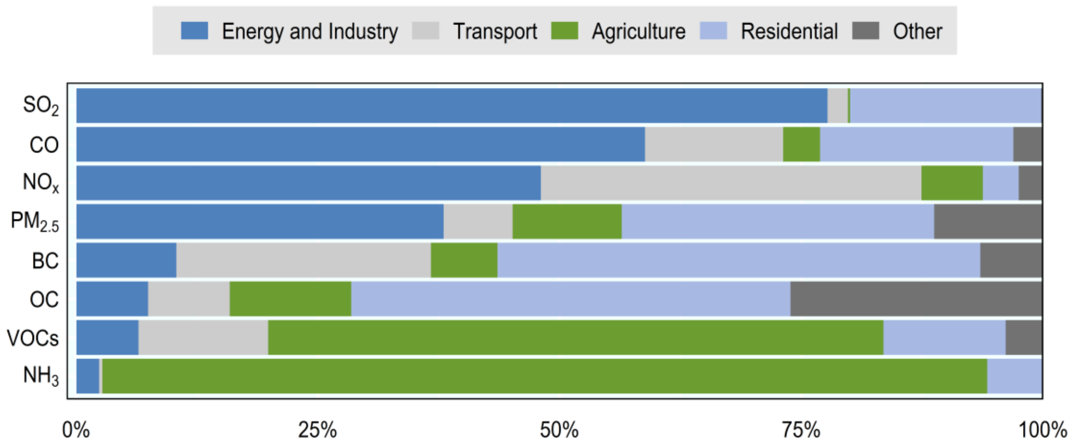
The transport sector also plays a key role in the emissions of several pollutants. This sector contributes to overall a third of total NO_X emissions, with land transport accounting on average for more 90% of total transport emissions of NO_X. In addition, transport plays a key role in BC emissions in Japan and Korea, where land transport accounts for around half of overall BC emissions.

The energy and industry and transport sectors are also the main contributor to ground-level ozone pollution, given their large role in emissions of ground-level ozone precursors. Indeed, ground-level ozone is not emitted directly into the air but generated by chemical reactions between pollutants (see Box 1.3). The biggest sources of NO_X emissions are motor vehicle exhaust emissions and fossil fuel based power generation, especially coal and gas. In China, the non-metallic minerals industry also is a key emitter of NO_X. Industrial activities (e.g. use of industrial solvent and paint coating), and motor vehicle exhaust emissions are among the key sources of NMVOCs. Chinese coal mines also play a large role in domestic methane emissions.

The agriculture sector is a key contributor to NH_3 emissions. Livestock accounts for around 80% of NH_3 emission in Japan and Korea and for around half of these emissions in China. In China, application of mineral nitrogen fertilizers is similarly important source and accounts for another 41% of total NH_3 emissions. The agricultural sectors also emits NMVOCs and large quantities of methane, mostly from livestock and rice farming.

Figure 1.2. Sectoral share in total emissions of air pollutants in Northeast Asia

Sectoral share, 2020.



Note: 2020 values are estimates. “Other” includes emissions from the waste sector (except agricultural waste, which is included in “Agriculture”).
Source: IIASA’s GAINS model.

Importantly, the widespread use of coal and biomass for domestic cooking and heating in China leads to a large role of the Chinese residential sector in emissions of a number of pollutants. In particular, in China residential emissions represent a much larger share of emissions of BC and OC (around 50% for China; 10% for BC and 20% for OC for Japan and Korea). Similarly, the share of CO and SO2 emissions from residential combustion is around 20% in China while much smaller in Japan and Korea (less than 10% for CO and SO2). Reductions of residential emissions from cooking and heating could also result in improved indoor air quality (see Box 1.4).

Box 1.4. Indoor Air Pollution

Alongside outdoor air pollution, indoor air pollution can have negative health impacts. Household pollution was the cause of an estimated 2.3 million deaths globally in 2019, with 16% of these deaths occurring in China, totalling 363 thousand deaths relating to household air pollution in China (GBD, 2019[35]).

Many of the pollutants affecting indoor air quality are the same as those causing outdoor air pollution. However, concentration levels and exposure may be higher in indoor environments (IEA, 2016[36]). Causes of household pollution can be attributed to the use of biomass for cooking and fuels, such as kerosene, for lighting. Incomplete combustion of solid biomass fuels, such as wood, charcoal and agricultural waste, accounted for 90% of indoor air pollution in 2015 (IEA, 2016[36]). Lack of ventilation and technologies can lead to indoor smoke containing particles 100 times higher than the recommended levels (IEA, 2016[36]).

Indoor air pollution is more problematic in poor and rural communities, where access to electricity and clean energy sources is limited. It is less of a problem in OECD countries, including Korea and Japan than in non-OECD countries, such as China. Previous estimates of the percentage of the population using solid fuel in both Japan and Korea have amounted to less than 5% (WHO, 2000[37]; WHO, 2004[38]). Furthermore from 2009 to 2019 the percentage of air pollution which was household air pollution has decreased in all three countries (see Table 1.2). However, in China despite the decrease, the percentage of household air pollution still remains relatively high (GBD, 2019[35]). Therefore, with additional policies to address air pollution, the most significant reductions in indoor air pollution levels would be in China, where there is a larger use of biofuels for heating and cooking purposes.

Table 1.2. Percentage of air pollution attributable to household air pollution

Country	2009	2019
China	34.2%	19.7%
Japan	0.4%	0.2%
Korea	0.2%	0.1%

Note: Household air pollution accounts for indoor solid fuel use for cooking and heating.
Source: Global Burden of Disease (GBD, 2019[35]).

Under current policies the use of biofuels globally will decrease in the coming decades (OECD, 2012[39]). However, the International Energy Agency (IEA) have projected that with policies measures to reduce indoor air pollution, a larger share of the population in China would see the benefits of reduced indoor air pollution. These measures include promoting the use of biogas, increase of energy access to replace the use of bioenergy fuels and increased use of cleaner cookstoves. Furthermore, replacing the use of kerosene lamps for alternatives such as electricity or solar lamps, would be important to reducing indoor black carbon pollution and its health effects (IEA, 2016[36]).

Domestic air quality is also influenced by transboundary pollution. Several air pollutants can be transported over long distances, thus affecting air quality in distant regions. This transfer of pollution across borders is well documented for several regions across the world. In particular, within the UNECE Convention on Long-range Transboundary Air Pollution (LRTAP), regular modelling work is performed using recent emission data to estimate the transboundary air pollution for Eurasia and North America. For instance, the Co-operative Programme for Monitoring and Evaluation of the Long-range Transmission of Air Pollutants in Europe (also known as EMEP) regularly reports on the quantity and significance of transboundary fluxes to governments and subsidiary bodies under the LRTAP Convention (HTAP, 2010[40]; EMEP, 2020[41]). Due to its transboundary effects, air pollution is a policy area where international regulatory cooperation is particularly useful, with potential benefits from sharing scientific knowledge (Kauffmann and Saffirio, 2020[42]).

Evidence suggests that emissions originating outside of the countries can affect air quality in Japan, Korea and China. According to the task force on Hemispheric Transport of Air Pollution (HTAP), the average contribution of China to Korean air pollution between the years 2000-2005 was 21% during the summer months, and contributed to 10% of air pollution in Korea and mainland Japan together. In the same time-period air pollution emissions from Korea contributed to 5.2% of air pollution in the North China Plains (HTAP, 2010[40]). A joint study between Korea's National Institute of Environmental Research (NIER) and NASA concluded that local emissions were often sufficient to exceed air quality standards in Korea but transboundary emissions was an important factor contributing up to 48 % of the $PM_{2.5}$ pollution (NASA - NIER, 2017[43]). Bae et al. (2020[44]) estimate that Chinese emissions contribute to up to 44% of $PM_{2.5}$ concentrations in the Seoul Metropolitan area. Similarly, various studies link emissions on mainland China to variation in annual mean concentrations of $PM_{2.5}$ and ground-level ozone in Japan, especially in the Western Japan and the Kanto area (Wild, 2007[45]; Ikeda et al., 2015[46]; Itahashi et al., 2017[47]). Cuesta et al. (2018[48]) also find evidence of ground-level ozone pollution plumes transported from the North China Plain to Northern China, Japan and Korea. Moreover, Liu et al. (2020[49]) note that transboundary $PM_{2.5}$ pollution from outside China accounted on average for 9.6% $PM_{2.5}$ related deaths in China in 2015. They also find that, for the same year, even without domestic anthropogenic emissions, in some Chinese regions $PM_{2.5}$ concentrations would have been higher than the WHO AQG (10 $\mu g/m^3$) due to transboundary pollution.

Transboundary pollution levels also depend on seasonal activities, such as coal burning used for heating and agricultural emissions (Kim, 2019[50]; Du et al., 2020[51]). Seasonal variations in transboundary air pollution levels were observed in Korea and Japan (Yim et al., 2019[52]).

1.3. Policy responses to air pollution

1.3.1. National policy responses

The current policy mix to control air pollution in Japan, Korea and China is a combination of “market” (or “pricing”) and “non-market based” policies. Furthermore, policies in place cover a wide range of pollutants and sectors, aiming to reduce air pollution from different sources. While the sources of air pollution are similar across the three countries, each of them has implemented national policies that respond to their specific needs and characteristics.

Japan

The current policy mix to address air pollution emissions from stationary sources in Japan relies mainly on regulations. Primary emissions of PM, sulphur oxides (SOx) and NOx are regulated through nation-wide emissions limit values that are geographically differentiated. A levy on SO_X emissions is in place. However, this is often considered to be a pollution liability instrument rather than a tax since the levy rate is fixed yearly, based on the costs to cover the health expenditures of patients affected by pollution peaks in the early ‘80s (OECD, 2010[53]). Other emissions are not taxed.

A number of voluntary approaches, whose common use is a unique feature of the Japanese policy mix to control air emissions, complements emission standards. Local governments adopted these instruments in the 1960-70s to quickly answer citizens’ demand for better environmental protection and proliferated over time. More recently, the 2006 revision of the Air Pollution Control Act targeted a 30% decrease in volatile organic compound (VOC) emissions by 2010 compared with 2000 levels through the use of legal tools and voluntary initiatives.

Emissions from mobile sources are controlled through policy mix, including regulations (emission limits), information instruments, subsidies and fuel taxes. Recently, subsidies have been introduced to stimulate the purchase of (so-called) “next-generation” vehicles, including hybrid, plug-in hybrid, electric, fuel cell and clean diesel vehicles. The inclusion of diesel vehicles, which are particularly harmful for air quality, would suggest reviewing the subsidy program. As in all Northeast Asian countries, taxes on diesel are lower than on gasoline. New fuel-efficiency standards for light duty vehicles (or LDVs) for 2030 and heavy duty vehicles (or HDVs) for 2025 have been set in 2019 (IEA, 2020[54]).

Korea

In Korea, emissions of industrial facilities are controlled through regulations and taxes. Recent reforms focused on the introduction of an integrated permitting system based on a best available techniques (BATs) approach. The permitting system, which entered into force in January 2017, is expected to cover 19 industries by 2021 while existing facilities will be given four years to improve their operations (OECD, 2019[55]). Taxes are levied on fine particles and other precursor gases.[6] However, only emissions above established thresholds are taxed for several pollutants. Recently a charge on NO_X emissions from industrial facilities has been introduced by the government (Bloomberg, 2019[56]; The Korea times, 2020[57]).

[6] Taxes are levied on total suspended particle (TSP) emissions. TSP is an indicator including emissions of particulate matter as well as PM precursor gases, including SO_2.

Recently, a number of measures have been introduced to further reduce emissions from stationary sources. For instance, coal-fired power generation is to be decreased under the 2017 Comprehensive Plan on Fine Dust[7], leading to a projected reduction of emissions in the sector by 25% by 2025 (Ministry of Environment, 2018[58]), and old and more polluting plants can be shut down during peak pollution periods (March to May) (Ministry of Environment, 2018[58]). The Plan also includes a number of measures to reduce VOCs emissions from the "energy and industry" sector, which account for more than two thirds of total VOCs emissions. To this end, the government plans to progressively tighten the standards for fugitive VOCs, including for gasoline storage facilities. Voluntary approaches are also part of the policy mix and, as of December 2019, 111 large businesses had signed a voluntary fine dust reduction agreement, implementing measures to reduce air pollution and installing catalysts to eliminate nitrous oxide (Ministry of Environment, 2020[59]). The release of emission information of large firms under the Fine Dust Seasonal Management System is likely to provide further incentives to firms to adopt voluntary measures to reduce emissions (Ministry of Environment, 2020[59]).

Tightening of standards for mobile source emissions, subsidies and recently introduced "emergency" measures are used to control emissions from road transport. The 2017 Plan introduced subsidies for the purchase of eco-friendly vehicle and allowed local governments to activate emergency measures, such as alternate-day driving limitations and adjusted operating hours of businesses, in case of pollution peaks. The plan also foresees the possibility of significantly expanding the national charging infrastructures to support the uptake of electric drive vehicles including the planned installation of 10 thousand rapid charging station at 500 large supermarkets and at 12 thousand gas stations by 2022 (Ministry of Environment, 2018[58]). Subsidies are also provided to apartment houses, business owners and large car parks for installing charging stations (Roh et al., 2020[60]). Additional recent reforms include the adoption of the Worldwide Harmonized Light-duty Vehicles Test Procedure (2017) and the alignment of diesel emissions standards to Euro VI limit values (2014). Subsidies for the scrapping of old and more polluting diesel vehicles have also been increased gradually over the years, and a stricter exhaust inspection will be introduced at beginning of 2021 (Ministry of Environment, 2018[58]). Furthermore, in 2019 the Government has announced a target of 430 thousand battery electric vehicles (BEV) and 67 thousand fuel cell electric vehicles (FCEV) on the road by 2022 (IEA, 2020[54]).

China

In China emissions from stationary sources are controlled through a mix of regulations, taxes and incentives. Emission limit values at a national level are in place for a number of pollutants (e.g., $PM_{2.5}$, NO_X, SO_X) while more stringent regulations are established for key regions. The emission limit values differentiate also between existing and new (operating from 2014) installations. Furthermore, a new integrated perming system[8] is being gradually phased in. The emissions of a number of pollutants is taxed (e.g. NO_X, SO_X) and local authority can tax additional pollutants. Additionally, China's Clear Air Action policies implemented in 2013, have been effective in decreasing sectoral emissions. Policy measures have included emission controls on industries and power plants. The implementation of these clean air policies have contributed to reductions in anthropogenic emissions between 2013 and 2017, with a decrease of 59% for SO_2, 21% for NOx, 23% for CO, 36% for PM_{10}, 33% for $PM_{2.5}$, 28% for BC and 32% for OC. However, NH_3 emissions did not decrease and NMVOCs increased between 2010 and 2017 (Zheng et al., 2018[61]).

[7] The 2017 Comprehensive Plan on Fine Dust aims to reduce concentrations levels of $PM_{2.5}$ and PM_{10} alongside other air pollutants.

[8] Within an integrated permitting system, a single permit is issued for the multiple negative externalities of an economic activity (e.g. air, water, noise and solid waste pollution).

Policies to control emissions from road vehicles have been recently updated. Passenger emission standards, which have been tightened progressively over the years, are currently in line with the Euro V standards and are expected to be further tightened in mid-2023 (National VI-b) to be largely equivalent to Euro VI. Incentives have been used to promote both the scrapping of old vehicles and the purchase of low emissions vehicles (e.g. credit line, grant, subsidies or other tax reliefs). In 2019, subsidies for electric car purchases were supposed to be reduced by about half as part of a gradual phase out of direct incentives but the subsidy scheme has been extended to 2022 due to low car sales (IEA, 2020[54]).

A number of large cities also introduced restrictions on car plate availability in order to reduce the stock of circulating vehicles. Auction systems, lotteries or a combination of the two are usually implemented. For instance, Beijing introduced a license plate lottery system in 2011 that allows potential car buyers to participate in a lottery every two months to win a purchase permit. In Shanghai, monthly license auctions are in place since 1995. By the end of 2017, seven cities had reportedly put limits on car purchases (Zhang, Bai and Zhong, 2018[62]). Local governments further encourage the adoption of low-emission vehicles by introducing partial or complete waivers from local licence plate availability restrictions. For instance, license plates for new energy vehicles in Beijing are distributed on a first-come, first-serve basis (China Daily, 2020[63]).

Policy action to promote a more widespread use of clean cookstoves in an effort to jointly mitigate climate change and air pollution, would result in beneficial effects on indoor air quality in China. Residential solid fuel combustion is a major source of pollution given that households' use of less advanced technologies than industrial settings (e.g. poor combustion conditions and lack of abatement facilities) lead to much higher emissions per unit of energy consumed. Despite rapid improvements in the past decades, approximately 60 % of people in China do not have access to clean fuels and technologies for cooking (World Bank, 2020[64]). Tightening of emissions standards for cookstoves, introducing energy efficiency labelling and stove replacement programmes could play an important role in reducing the impact of domestic heating (IEA, 2018[65]). Importantly, programs need to be designed to consider the different challenges, needs and opportunities of rural and urban areas (UNEP, 2019[66]).

1.3.2. International co-operation efforts to address air pollution

A number of international agreements to curb air pollution in the North Asian region have been introduced at the multilateral and bilateral level. These vary in scope and country participants. The Tripartite Environment Ministers' Meeting (TEMM) and the Joint Research Project on Long-Range Transboundary Air Pollutants in Northeast Asia (LTP) are trilateral agreements between Japan, Korea and China. The Northeast Asian Sub regional Programme for Environmental Cooperation (NEASPEC) and the Acid Deposition Monitoring Network in East Asia (EANET) see a larger membership (see Table 1.3). More recent initiatives include the UNEP 2015 and 2018 Asia-Pacific Clean Air Partnership (APCAP) joint Fora, which aimed at increasing co-ordination and co-operation among 26 countries in the region.

Table 1.3. Key multilateral agreements in Northeast Asia

Existing International Agreements	Year	Participants	Scope
NEASPEC (Northeast Asian Sub regional Programme for Environmental Cooperation)	1993	China, Japan, Mongolia, DPR Korea, Russian Federation (hereafter Russia), Korea	Comprehensive intergovernmental co-operation framework addressing environmental challenges in Northeast Asia
LTP Project (Joint Research Project on Long-Range Transboundary Air Pollutants in Northeast Asia)	1995	China, Japan, Korea	Transboundary air pollutants
TEMM (Tripartite Environment Ministers' Meeting)	1999	China, Japan, Korea	Comprehensive intergovernmental co-operation on environmental issues including air quality
EANET (Acid Deposition Monitoring Network in East Asia)	2001	Cambodia, China, Indonesia, Japan, Lao PDR, Malaysia, Mongolia, Myanmar, Philippines, Russia, Korea, Thailand, Vietnam	Acid Deposition

Source: (OECD, 2020[67]).

Several bilateral agreements between national, local governments and research centres are also in place. At the national level, efforts to address air pollution in the region include the Joint Committee on Environmental Protection, which meets annually under the 2004 Japan-China Agreement on Environmental Protection, and the 1993 Japan and Korea Agreement on Cooperation on Environmental Protection. Furthermore, the 1996 the Sino-Japan Friendship Centre for Environmental Protection provides assistance to Chinese authorities. At the municipal level, the 2018 Memorandum of Understanding signed between the cities of Seoul and Beijing promotes knowledge exchange and capacity building while the Inter-City Cooperation platform promotes co-operation on air quality management between Japanese and Chinese cities. Additional co-operation activities include collaboration between scientific communities, such as the Air Quality Joint Research team established between the National Institute of Environmental Research (NIER) and the Chinese Research Academy of Environmental Sciences (CRAES).

Existing co-operation agreements have allowed for the creation of networks between regional experts in the region and stimulate dialogue between policymakers. This is a crucial step in building the consensus on key scientific issues that is required for evidence based international regulatory co-operation on transboundary air pollution. However, a broad consensus is yet to be achieved and key barriers include a lack of consensus on a common methodology for monitoring, measuring and modelling transboundary air pollution (OECD, 2020[67]), asymmetric Government capacities, and competing interests.

2 Modelling analysis: scenarios and framework

2.1. Policy scenario design and description

While policies are already in place to address air pollution (as outlined in Section 2.3), additional policy action could further stimulate the deployment of emission abatement techniques that would improve air quality in the coming decades (see Box 2.1). In this context, this report considers policy scenarios that reflect the implementation of additional air pollution policies and their consequent wide adoption of best available techniques (BATs) to control air pollution, with time horizon to 2050. Estimates of sector- and country-specific investments necessary to deploy the BATs that are needed to achieve the maximum feasible reduction in emissions are obtained from IIASA's GAINS model (Amann et al., 2011[12]), which was used to develop such mid-term mitigation scenarios (Xing et al., 2011[68]; Zhao et al., 2013[69]; Rao et al., 2016[70]; Amann et al., 2020[71]).

Box 2.1. Possible additional policy actions in the coming decades

Ambitious policy reforms, which focus on improving the policy mixes in place, would further reduce air pollution and therefore decrease its negative health and environmental impacts. In the coming decades, Northeast Asian countries could consider a larger application of market instruments and regulations in their efforts to reduce air pollution. Emissions of stationary sources are often either not taxed or subject to a tax rate that is considered too low. Countries could also consider progressively widening the list of taxed emissions, including also those emissions that contribute to secondary formation of $PM_{2.5}$ and ground-level ozone, and reviewing the currently applied tax rates.

Investments in energy efficiency, including in industrial sectors, can be help to reduce emissions of air pollutants, while also mitigating climate change. Such investments would reduce energy use, thus emissions related to energy production. The industrial sector offers the largest opportunities for energy savings in China according to the IEA (2018[72]), especially through the adoption of electric heat pumps for low-temperature process heating and higher efficiency in motor-driven systems.

A number of additional policies and best practises could reduce air pollution emissions in the agriculture sector. Taxes and emission caps could contribute to reduce emissions due to fertiliser use (Neufeldt and Schäfer, 2008[73]; Henseler et al., 2020[74]). Strengthening subsidies that support the recovery and reuse of agricultural waste and the promotion of agricultural waste recycling techniques would help to reduce emissions due to the burning of agricultural waste (Wang et al., 2014[75]; Wang et al., 2016[76]).

Residential emissions could also be reduced thanks to the adoption of cleaner appliances, which can be stimulated with tighter emissions standards for cookstoves, labelling and stove replacement programmes. Indeed, notwithstanding rapid improvements in the past decades, approximately 60% of Chinese people do not have access to clean fuels and technologies for cooking (World Bank, 2020[64]).

The set of scenarios analysed reflects different degrees of national and international policy action to reduce pollution. The scenarios considered in the report are:

a) The baseline scenario, which is referred to as ***"Current Polices scenario" (CP)*** assumes no changes to current policies in place. Specifically, this scenario considers the national and regional laws and regulations on emissions, energy efficiency and climate change in place in 2017. The legislation covers emissions from a number of activities, including combustion plants, industrial processes, transport, agriculture, use of solvents and the residential sector.[9] In this baseline scenario, growth is projected to be steady for OECD countries while non-OECD countries are projected to enjoy high level of growth (OECD, 2019[77]).[10] Current policies do not imply that emission levels are constant over time: as certain economic activities grow faster than others, and growth is faster in some countries than others, regional emissions will evolve over time. Furthermore, efficiency improvements (e.g., energy use and total factor productivity growth) imply a weak relative decoupling of emissions from output growth (i.e., emissions grow more slowly than production volumes).

b) The ***"Japan Policy Action scenario" (JPA)***, the ***"Korea Policy Action scenario" (KPA)*** and the ***"China Policy Action scenario" (CPA)*** project the impacts of the adoption of ambitious policies to improve air quality in Japan, Korea, or China, respectively. These three scenarios assume that Japan, Korea or China individually implement additional policies that lead to a wide adoption of BATs to control air pollutant and methane emissions. For air pollutants, beyond introduction of the most stringent (achievable) emission limits for large scale stationary processes and combustion, road and non-road vehicles, medium and small-scale residential boilers, additional incentives and regulations are assumed to assure steady improvement of energy and nutrient efficiency; the latter requiring more efficient application of organic and mineral nitrogen fertilizers resulting in reduction of ammonia and soil NO_x emissions. Evaporative NMVOC losses from storage and distribution of liquid fuels are reduced as well as emissions from solvent use, including wide application of low solvent or water based products. For methane, key additional policies address venting emissions from fossil fuel (coal, oil, gas) production and distribution, development of efficient waste management system for industrial and municipal water and solid waste, reduction of emissions from rice production, and incentives to increase farm-based biogas production capacity. Introduction of these policies assures that the maximum technical mitigation potential is achieved in all sectors.

c) The internationally co-ordinated ***"Northeast Asia Policy Action" (NEAPA)*** scenario assumes that China, Japan and Korea reform their air quality policy frameworks. The policy reforms introduced in Japan, Korea and China are modelled to be the same as, respectively, in the JPA, KPA, and CPA scenarios. The type of policies and mitigation measures ensuring achievement of the ambitious environmental goals is the same as listed above for individual countries but with the addition of a co-ordinated effort to introduce BATs across the region.

d) The ***"Global Policy Action scenario" (GPA)***, reflects an idealised hypothetical scenario in which all countries in the world adopt ambitious policies to reduce emissions of air pollutants and methane. As in previous scenarios, the policy actions for Japan, Korea and China are the same as in the NEAPA scenario and in the three single-country scenarios (JPA, KPA and CPA).

[9] A detailed description of the emissions control policies considered is provided Amann et al. (2018[129]). For a detailed description of the climate, energy use and energy efficiency policies, please refer to the New Policies Scenario of the World Energy Outlook 2018 (IEA, 2018[65]).

[10] OECD (2019[77]) details the key assumptions and exogenous trends underpin this scenario.

Table 2.1. Scenario description

Scenario name	Key elements	
	Policy reforms introduced in	**Main Assumption**
CP (Baseline)	No country	Current policies
JPA	Japan	Policy action that stimulates the deployment of the best available techniques to control air pollution in acting countries and current policies in non-acting countries
KPA	Korea	
CPA	China	
NEAPA	Japan, Korea and China	
GPA	All countries, at the global level	All countries deploy BATs to control emissions

Emission levels in each country are the same in all policy action (PA) scenarios (for example, the emission reductions in Korea are the same in the KPA, NEAPA and GPA scenarios). However, air pollution concentration levels will be different due to changes in policy action in neighbouring countries. Therefore, the overall biophysical impacts[11] and the resulting economic consequences will also vary.

The policy action scenarios reflect the implementation of source- and region-specific technologies aimed at reducing the emissions of several pollutants (e.g., particulate matter, nitrous oxide, sulphur dioxide) and some greenhouse gases (e.g. methane). This reflects the current policy mix but also its possible extension in the coming decades. Specifically, as a result of simulations of the IIASA's GAINS model, these scenarios reflect the maximum technically feasible reduction of emissions in each country. The level of implementation of specific measures over time considers technical limitations (e.g., lifetime of installed capacities). However, there are no constraints associated with investment or operating costs.

The technologies considered in the analysis are suitable for mobile, stationary and fugitive sources. These technologies address technical mitigation opportunities available in the GAINS model for the key anthropogenic sources of pollution: transport, energy and industry, agriculture, residential combustion, and waste. Specifically, the technologies include (i) end-of-pipe technologies such as filters, scrubbers and catalyst (ii) capture and recovery systems (e.g., addressing NMVOC emissions from solvent use, NMVOCs and methane evaporative losses from fossil fuel production and distribution) (iii) cleaner and more efficient solid fuel stoves and boilers, (iv) improved waste management, and (v) measures to reduce ammonia and methane emissions in the agricultural sector.

2.2. Modelling framework: a five steps approach

This section describes the modelling approach used to quantify the economic consequences of current air quality polices and of the adoption of more ambitious policy action in the Northeast Asian region. The economic consequences of policy action and lack of action to address air pollution are projected using multiple models (the OECD's ENV-Linkages model, IIASA's GAINS model, and the EC-JRC's TM5-FASST model), which are linked through a step-wise approach in which the output of each model is used as input for the next step in the modelling exercise (see Figure 2.1).

First, the ENV-Linkages model is used to create detailed projections of sectoral economic activities. ENV-Linkages (Chateau, Dellink and Lanzi, 2014[11]), which is a computable general equilibrium (CGE) model, is leveraged to model the activity of 22 economic sectors to 2050 for 19 geographical regions, including China, Japan and Korea as individual regions. The advantage of using a global model is that policy action in specific countries can also be considered in the global context, which influences the economic consequences of the domestic policies.

[11] Impacts on human health and on crop productivity.

Then, projections of sectoral air pollution emissions are provided by the GAINS model. The following air pollutants are included in the analysis: ammonia (NH_3), black carbon (BC), carbon monoxide (CO), methane (CH_4), nitrogen oxides (NO_X), organic carbon (OC), particulate matter ($PM_{2.5}$) sulphur dioxide (SO_2), and non-methane volatile organic components (NMVOCs). The GAINS model, which is used as part of the standard modelling framework for negotiations under the Convention on Long-range Transboundary Air Pollution (IIASA, 2020[78]), provides emissions of key pollutants and activity levels for 48 countries and regions (Amann, Klimont and Wagner, 2013[79]).[12] GAINS also provides the estimates of the sectoral investments and household expenditure in BATs required to reduce emissions in the policy action scenarios (see Section 3.1.2).

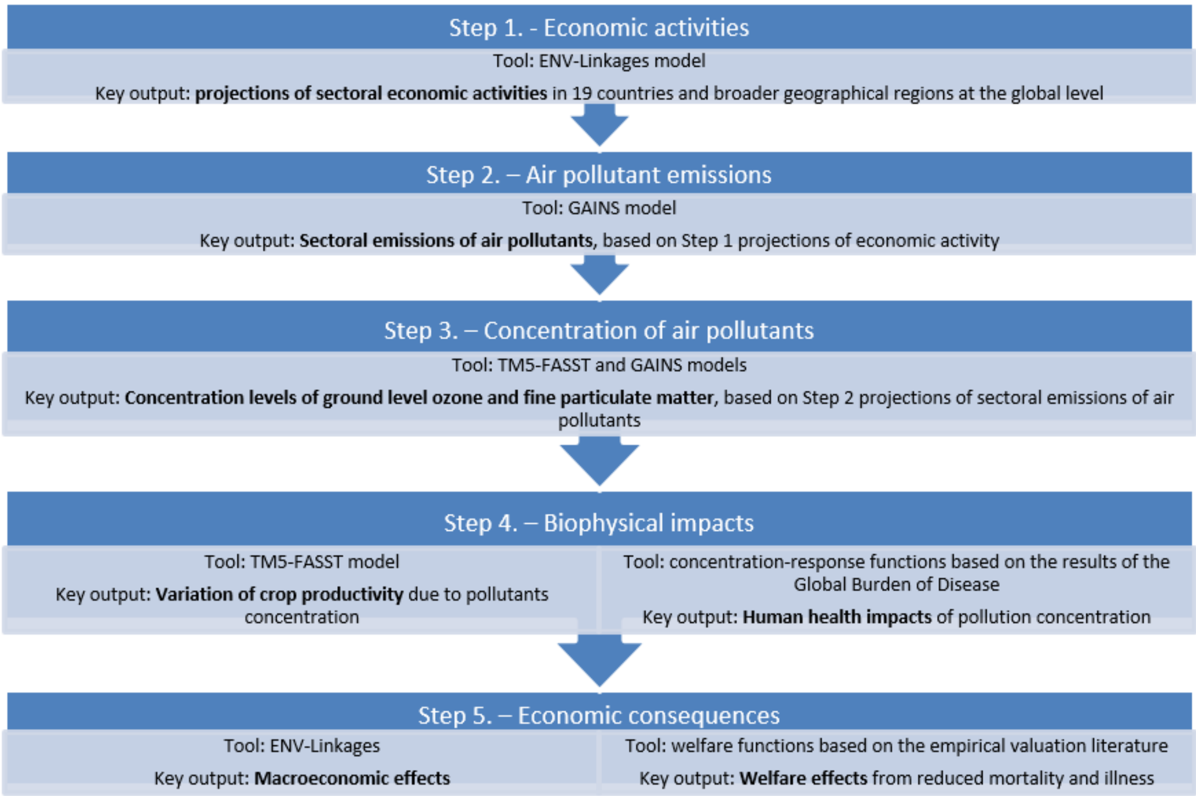
As a next step, the projections on total emissions for different pollutants are used to derive ground-level concentrations of $PM_{2.5}$ and ozone. The grid-level projections on the concentrations of $PM_{2.5}$ are calculated with the GAINS model, while ground-level ozone concentrations are calculated using the EC-JRC's TM5-FASST model (Van Dingenen et al., 2018[13]). Together with concentrations, indicators of population exposure to air pollution are also calculated. These take into consideration additional effects that can then influence the health impacts of air pollution, such as population growth and urbanisation.

The concentrations of fine particulate matter ($PM_{2.5}$) and ground-level ozone (O_3) are used to calculate the biophysical impacts of air pollution. These impacts can be grouped into two large categories: impacts on human health and on plant productivity. The health impacts are calculated using concentration-response functions that are parametrised to mimic the results of the Global Burden of Disease projections for $PM_{2.5}$ (Forouzanfar et al., 2015[80]) and ground-level ozone (Stanaway et al., 2018[81]); they include mortality, incidence of pollution-related illnesses, hospital admissions, and restricted activity days (see Annex B). The biophysical impacts on plants are calculated using the TM5-FASST model (Van Dingenen et al., 2009[82]), and describe changes in crop yields due to changes in levels of ground-level ozone concentrations.

Finally, the biophysical impacts are used to calculate the economic consequences of the different scenarios, including both macroeconomic and welfare effects. Macroeconomic effects result from the net effects of the benefits of reduced air pollution and the emission reduction costs and are calculated in the ENV-Linkages model. The welfare effects are monetised using results from direct valuation studies and include mortality, and pain and suffering from illness (see Section 3.1.1 and Annex B for details).

[12] The methodology used for create emission projections relies on the methodology used in the EU FP7 project on Low climate IMpact scenarios and the Implications of required Tight emission control Strategies (LIMITS) (Rao et al., 2016[70]), which was also used in previous OECD work (OECD, 2016[8]), and on the 30th Energy Modelling Forum (EMF30) modelling comparison exercise on the potential role of Short-Lived Climate Forcers (SLCF) mitigation in climate policy (Smith et al., 2020[130]), which also included the ENV-Linkages model (Chantret et al., 2020[132]; Harmsen et al., 2020[131]).

Figure 2.1. Methodological steps



Source: Adapted from (OECD, 2016[8])

These steps are repeated for each scenario. The benefits of policy action are then calculated as the difference in macroeconomic and welfare effects in a policy scenario, compared to the current policies (CP) scenario. This difference is then referred to as the macroeconomic and welfare benefits of policy action, respectively.

The modelling framework used in this report can only consider a subset of the environmental, health and economic impacts of air pollution, due to lack of available data on other impacts. Thus projected benefits of policy action outlined in this report, should be interpreted taking into account the additional benefits of air quality improvements that could not be included (see Box 2.2).

Box 2.2. Benefits of air quality improvement outside the scope of the modelling assessment

Besides the health impact accounted in the quantitative analysis of this report, there are additional impacts of $PM_{2.5}$ and ground-level ozone on human health, such as effects on fertility (Nieuwenhuijsen et al., 2014[83]), cognitive abilities in children (Basner et al., 2014[84]; Sunyer et al., 2015[85]; Allen et al., 2017[86]) and low weight at birth (Wang et al., 1997[87]), which were not included. These impacts are particularly important as they can effect school outcomes (Zhang, Chen and Zhang, 2018[5]), education levels and therefore earnings. There are also direct health impacts due to high concentrations of other pollutants, such as SO_2 and NO_2 (WHO, 2013[88]; Walton et al., 2015[89]). Concerning the agricultural sector, reducing fertiliser use can have additional positive impacts on water and soil quality, with consequent healthier ecosystems and lower health risks. Additional health benefits can occur specifically in urban areas for transport-related emission reductions. Some air pollution measures can contribute to reduce noise and traffic congestion, which can both negatively affect health. Finally, air pollution might be correlated with the spread of viral diseases such as COVID-19 (Setti et al., 2020[90]). Beyond the economic benefits from improved health and agricultural productivity, there are other economic and health benefits from improved air quality, which could not be quantified in this report. High concentrations of air pollution can affect buildings and cultural heritage (Screpanti and De Marco, 2009[91]), and lead to a reduction in tourism flows (Dong, Xu and Wong, 2019[92]). Other missing elements include impacts on biodiversity, forests and ecosystems (UNEP, 2010[93]). These impacts are likely to generate significant value losses, additional expenditures and an overall disutility, affecting human activity and economy. Improved air quality could also generate other beneficial effects on well-being. A recent OECD report (OECD, 2019[94]) highlights the potential benefits of environmental policies on well-being, considering for instance improvements in the quality of life from reduced traffic or improved air quality.

Furthermore, policy action on air pollution is likely to provide co-benefits for climate change, thanks to reductions in emissions of greenhouse gases and short-lived climate pollutants, such as black carbon. These synergies are due to the significant overlap in emission sources and the high warming impact of certain pollutants (e.g. black carbon and methane have a warming impact on climate that is, respectively, 460-1 500 times and 80 times stronger than CO_2) (CCAC, 2021[95]; CCAC, 2021[96]). Furthermore, climate mitigation policies can often lead to air quality improvement by reducing activities that rely on fossil fuel combustion. Finally, atmospheric warming can facilitate the formation of certain pollutants, such as ground-level ozone (Archer, Brodie and Rauscher, 2019[97]; US EPA, 2021[98]).

2.3. Quantifying the economic consequences of policy action to improve air quality

This section provides additional information on the final step (Step 5) of the quantitative analysis on quantifying the economic consequences of policy action to improve air quality. The macroeconomic and welfare effects contribute to determine the overall economic consequences of policies to address air pollution. Importantly, these two effects are strictly complementary. For instance, on the one hand, policy action decreases the healthcare costs and lost working days due to air pollution, thus providing macroeconomics benefits. On the other hand, lower morbidity provides also welfare benefits because of lower pain and suffering connected to air pollution induced diseases.

2.3.1. Macroeconomic effects

The net macroeconomic effects, which are projected using the OECD's ENV-Linkages model, are equal to the difference between the macroeconomic benefits that follow the reduced air pollution impacts and the macroeconomic costs due to the additional costs imposed by the investments in BATs in the main emitting sectors (manufacturing, energy generation, transport, residential and agriculture). Improved labour productivity, higher crop yields and lower health expenditures are the main direct macro-economic benefits considered in the model. These changes in air pollution impacts, as well as the investments in BATs are fed into ENV-Linkages model to calculate the total effect of the policy scenarios on macroeconomic activity, including indirect effects. For example, a reduction in hospital admissions provides a direct benefit in terms of lower healthcare expenditures, and an indirect benefit in terms of changes in households expenditures and value added of the health sector (see below for further detail). The costs of investing in BATs are included in ENV-Linkages as additional investment and equipment expenditure for firms and households. These investments affect sectoral and regional production patterns as well as competitiveness.

2.3.2. Welfare effects from changes in air pollution-related mortality and illness

The welfare benefits include lower mortality, and decreased pain and suffering from illness. The OECD Value of a Statistical Life (VSL) estimates are used to calculate the country-specific welfare costs associated to mortality for adults (OECD, 2020[99]). A benefit transfer methodology based on average national income is applied to estimate the VSL for countries not included in the OECD database (OECD, 2012[100]; OECD, 2014[101]). OECD VSL data is preferred to national VSL estimates to ensure comparability across countries since national methodologies often differ on a number of dimensions

The morbidity benefits include lower pain and suffering from a number of illnesses, such as bronchitis, respiratory and cardiovascular illness, and asthma symptom days for children. The unit values of the welfare costs of each of these health outcomes (morbidity endpoint), as used in previous work of the European Commission (Holland, 2014[102]) are leveraged to monetise the impact of lower suffering from such diseases. The same benefit transfer methodology used for mortality is applied to compute country-specific morbidity welfare costs.

3 Air quality improvements and health benefits of air pollution policies

3.1. Projected emissions of selected pollutants

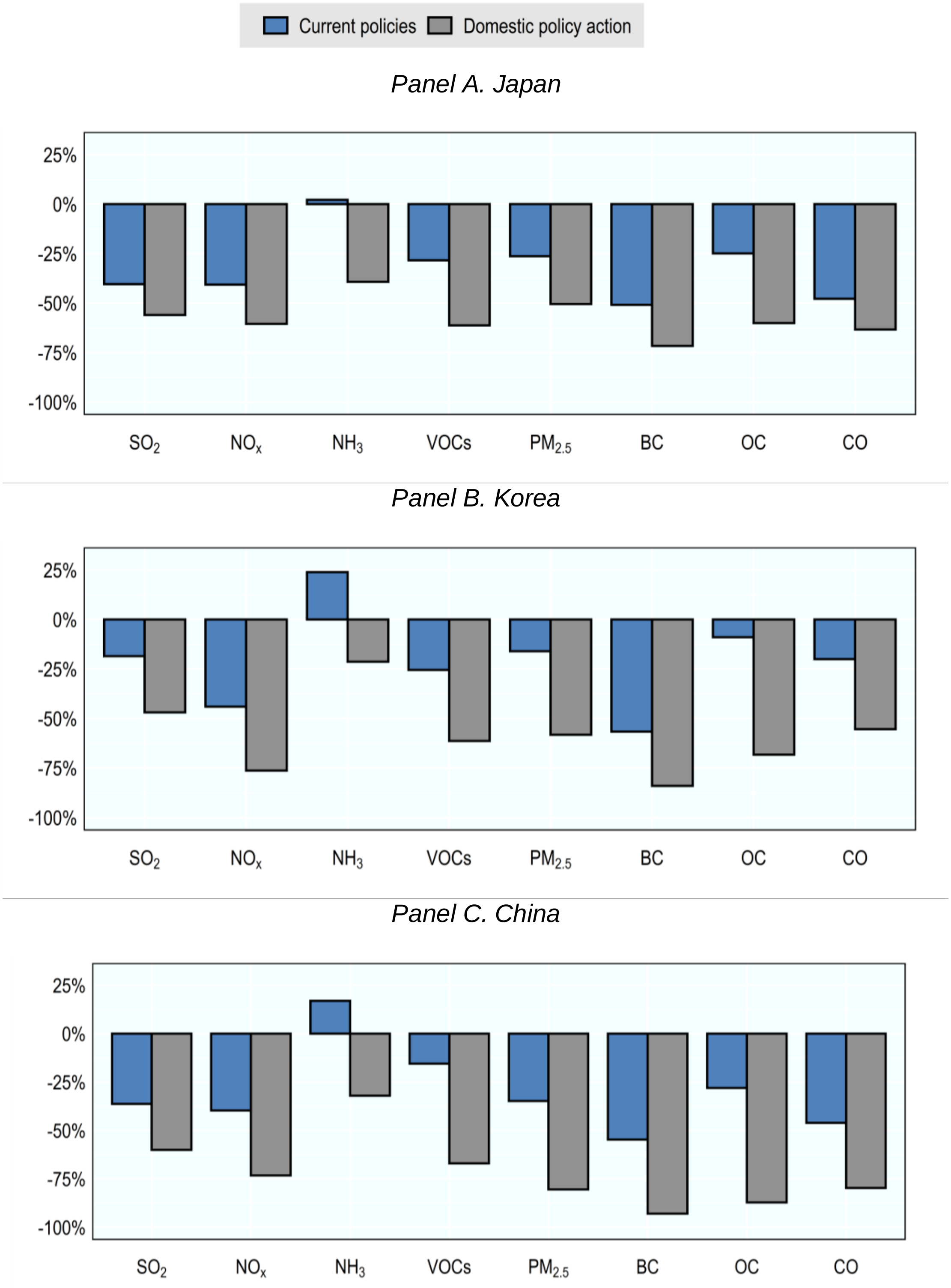
This section describes the projected trends in emissions of selected air pollutants in the current policies and policy action scenarios. As discussed in Section 3, for a specific country, the level of policy stringency does not differ across policy action scenarios, i.e. it is independent on the level of action in other countries. For instance, it is assumed that Korea will introduce the same reforms in the KPA, NEAPA and GPA scenarios. As such, this section discusses only the changes in emissions between the current policy scenario and the domestic policy action (PA) scenarios (JPA, KPA and CPA). While policy action in other countries cause changes in domestic emissions due to changes in sectoral and regional economic activity, the domestic policy action scenarios provide the best reference point for the assessment of the ambition level of the domestic policies, as global markets are least disturbed.

In the current policy scenario (CP), emissions of almost all pollutants are projected to slowly decrease over time. Enforcement of existing emission limits for stationary and mobile combustion sources is the main driver of the projected reductions of SO_2 and NO_X emissions in the three countries. The projected reductions of $PM_{2.5}$, BC, and SO_2 are achieved thanks to the transformation towards cleaner fuels for cooking and heating in households, especially in China where nearly 70% of $PM_{2.5}$ reduction is due to strategy, which replaces coal and biomass with gas and electricity. Only NH_3 emissions are projected to grow in all Northeast Asian countries, even if to a different extent (Figure 3.1). About two thirds of the projected increase is due to development in the livestock sector and one third from continued growth in application of chemical fertilizers, especially in China. Emissions of CH_4 from agriculture are projected to grow in all countries but only in China and Korea the total CH_4 increases by 2050 compared to 2020. In China, the waste sector is projected to contribute more than half of the increase in methane emissions followed by agriculture and gas production and distribution.

Ambitious policy action that results in the wide deployment of BATs would lead to a further decline of emissions beyond CP levels (Figure 3.1). The adoption of BATs would lead to a stronger reduction of primary $PM_{2.5}$ emissions, which are projected to be on average 80% lower than 2020 levels in 2050, with the largest reductions taking place in China. Furthermore, projected emissions of SO_2, NO_X, NMVOCs, and CO would be on average less than half the 2020 levels by 2050. Emissions of OC and BC are projected to be reduced the most compared to the CP scenario, with a reduction between 60% and 90% compared to 2020 levels by 2050.

Figure 3.1. Projected changes in emissions in the CP and single-country PA scenarios

Changes in total emissions by country/scenario in 2050 w.r.t. 2020 level

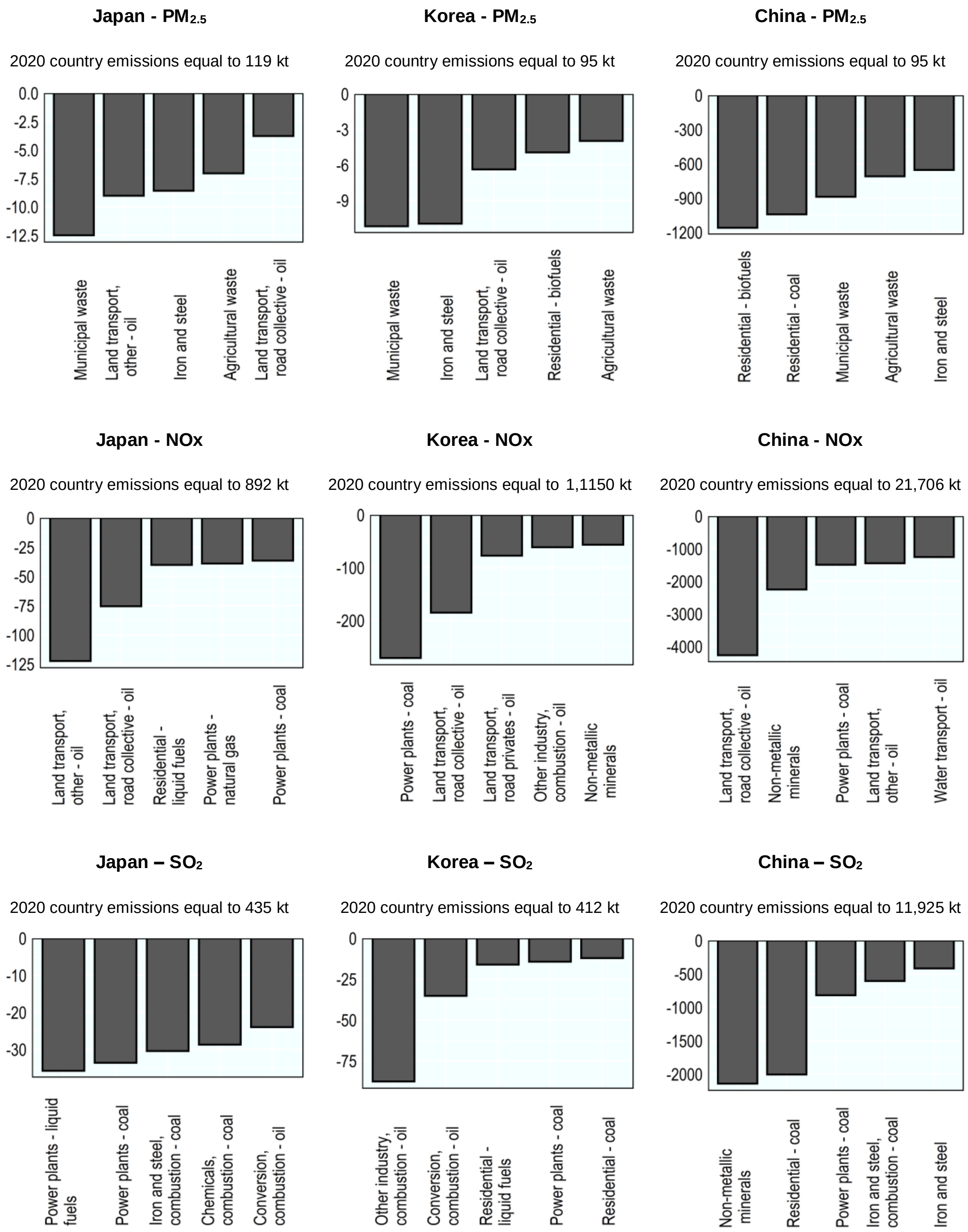


Source: IIASA's GAINS model.

The national context influences which sectors are projected to reach the highest domestic emission reductions (Figure 3.2). By 2050, the highest reduction in $PM_{2.5}$ emissions in the three Northeast Asian countries results from improving municipal solid waste management, which results in elimination of open burning of waste, thanks to the enforcement of bans of open burning of agricultural waste. In China, however, reductions of emissions from the “residential” sector are projected to account for more than 30% of the $PM_{2.5}$ emission reductions in the policy action scenarios in 2050. These reductions are achieved through implementation of policies supporting use of cleaner coal and briquettes in more efficient stoves and boilers as well as wider use of clean burning biomass stoves. A large share of emission reductions is projected to result in the transport sector, thanks to the introduction of lowest achievable emission standards for road and non-road vehicles, and the power sector requirement of the application of Euro VI equivalent technology on vehicles and selective catalytic reduction (SCR) installations in coal and gas power plants. These control technologies are offer the largest mitigation potential for NOx emission reduction across all countries. Additionally, a large share of NOx emissions is projected to be reduced in the non-metallic mineral sector in China. Finally, for SO_2 policies requiring further installation of high efficiency desulphurization units on industrial and power plant boilers, burning coal and oil, offers the largest contribution to the projected mitigation of emissions in Korea and Japan. In China, where coal power plants have been among the first targets of air quality policy and coal use declines, emissions are projected to decline in several industries, including non-metallic miner industry, and residential coal use for cooking and heating.

Figure 3.2. Projected changes in sectoral emissions for $PM_{2.5}$, NO_x and SO_2 in the single-country PA scenarios

Changes in total annual emissions by sector in 2050 w.r.t. 2020 level, top five sectors for absolute emissions reduction. Unit of measure: Kilotonnes

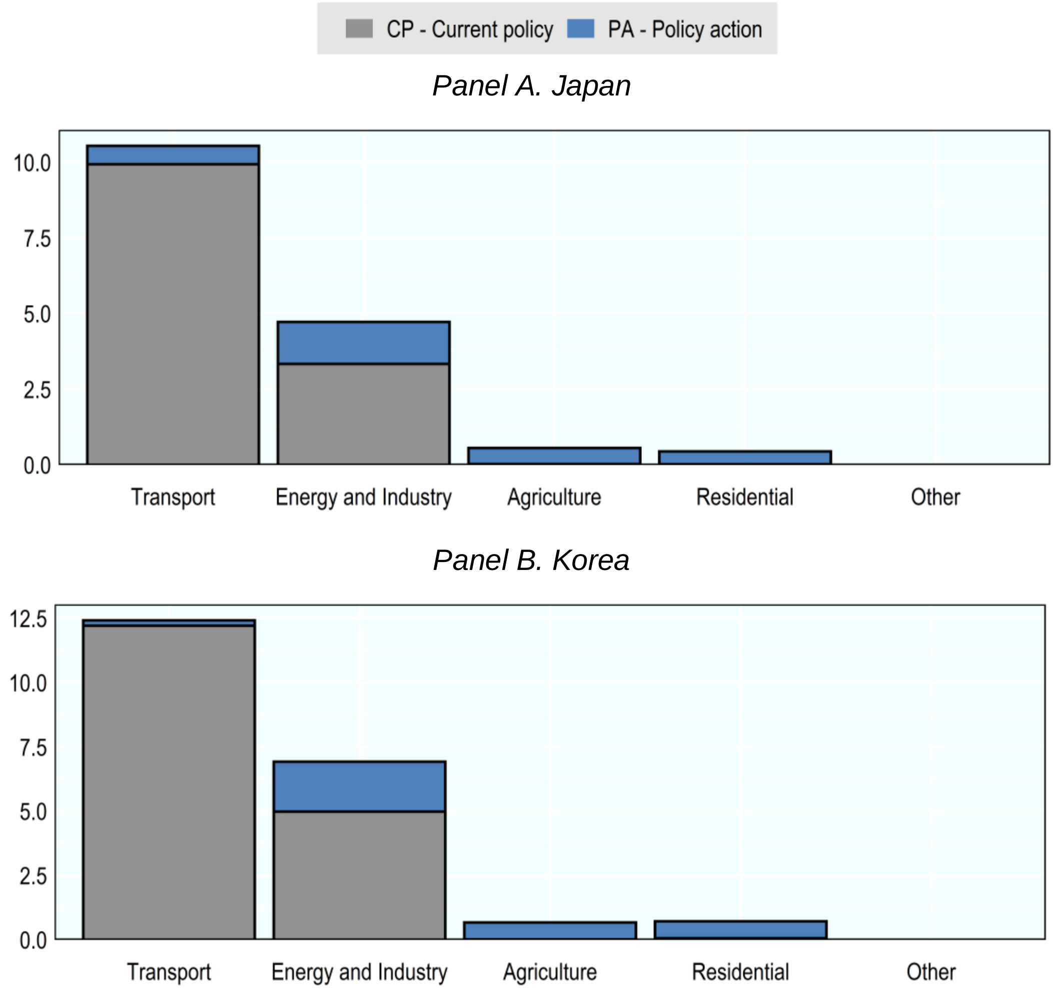


Source: IIASA's GAINS model.

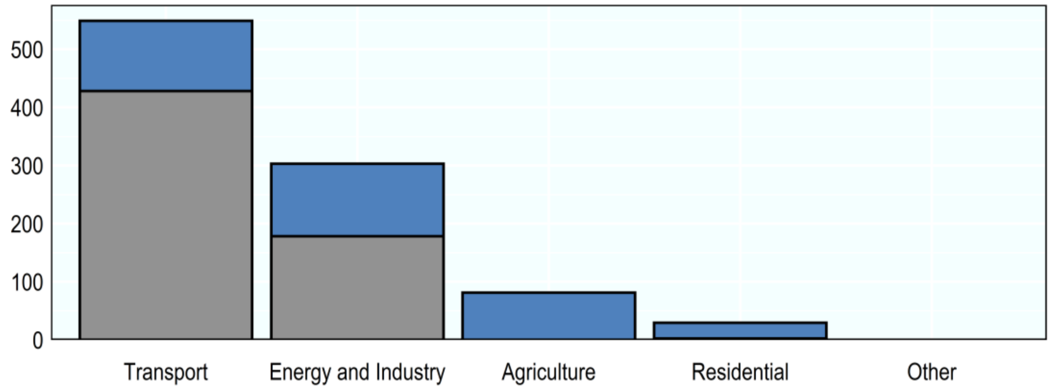
These emission reductions are obtained through investments in the best available techniques to reduce emissions, as provided by IIASA's GAINS and as described in Section 3. The investments vary across countries and sectors. The Current Policies scenario reflects policies in place that induce continued sectoral investments in emissions reduction techniques that lead to reductions in emissions even without further policy action. Policy Action scenarios achieve additional emission reductions through higher investments in BATs in all sectors. To achieve the maximum technically feasible reduction in emissions, in China sectoral investment would increase overall by around 60% in 2050 in the policy action scenario compared to the current policies scenario. In Japan and Korea, a 20% increase would be needed. Importantly, investments in the transport sector are the highest both under the current policies and the policy action scenarios in all three countries (Figure 3.3). The energy and industry sector account for the largest share of increase in investment in the policy action scenario in Japan and Korea while transport and the energy and industry sectors play an equal role in the increase in investments in China (Figure 3.3).

Figure 3.3. Investment in BATs in the CP and PA scenarios

2050 (Billion USD 2017 PPP).



Panel C. China



Source: IIASA's GAINS model.

3.2. Projected concentrations of $PM_{2.5}$ and ground-level ozone

Currently, concentration levels of $PM_{2.5}$ in Northeast Asian countries largely vary by country and within-country regions (cf. Figure 1.1). These differences are projected to persist in the coming decades until the middle of the century. Furthermore, concentrations of $PM_{2.5}$ are projected to remain at levels that are dangerous for human health in the coming decades in several areas in Northeast Asia (Figure 3.4, Panel A). By 2050, if no further policy is adopted, some regions in Northeast Asia are projected to experience high concentration levels of $PM_{2.5}$ (above the interim target-1 suggested by the WHO Air Quality Guidelines of 35 $\mu g/m^3$). These regions are located in East China, in provinces such as Henan, Shandong and Hebei. While high $PM_{2.5}$ concentrations in Northern China are mostly related to desert dust, other inner areas in China will also suffer from elevated levels of air pollution from anthropogenic origin. These central regions usually correspond to large urban areas that generate pollution, such as the city of Chengdu in East Sichuan. In Korea, the West coast of the country will continue to suffer worse levels of air pollution than the Eastern area. Seoul, the surrounding provinces (Northwest) and the Southwest coastal area are projected to experience concentration levels of $PM_{2.5}$ above the interim target-1 (15 $\mu g/m^3$). In Japan, the metropolitan area of Tokyo will suffer a moderate level of air pollution, between 8 and 12 $\mu g/m^3$ (see Figure 3.4 and Annex C for further detail).

Domestic policy action can lead to substantial reduction in $PM_{2.5}$ concentration in all countries. In China the adoption of BATs is projected to halve average $PM_{2.5}$ concentrations compared to the projected level for 2050 in the CP scenario (Figure 3.5).[13] However, average concentration of $PM_{2.5}$ in China are projected to be equal to 19.1 $\mu g/m^3$, still above the WHO AQG (10 $\mu g/m^3$). Benefits in Japan and Korea are projected to be smaller but still substantial and concentrations of $PM_{2.5}$ would be between 22% and 25% lower than in the current policies scenario. Interestingly, in Japan, all regions would enjoy air quality in line with the WHO AQG.

Co-ordinated policy action in the NEAPA scenario (Figure 3.4, Panel B) is projected to lead to additional improvements in air quality in the region, Japan and Korea are projected to gain the most from co-ordinated policy action in the region, with average concentration levels of $PM_{2.5}$ reaching 6.2 $\mu g/m^3$ in Japan (28% lower than 2050 CP projections) and 15.5 $\mu g/m^3$ in Korea (28% lower than 2050 CP projections). In Korea, most of the regions are projected to have concentration levels in line with the WHO AQG interim target-3

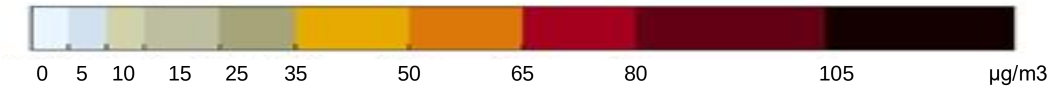
[13] The combined NAEPA scenario is chosen as a reference point for showing the effects on concentrations, rather than the single-country scenarios as was done for the emissions projections, as the combined scenario provides a good insight in the joint effects. Concentration levels are calculated for all scenarios, as shown in Figure 3.7.

(i.e. 15 µg/m³), with the exception of the West coast where $PM_{2.5}$ concentration are projected to be higher and in line with the WHO AQG interim target-2 (i.e. 25 µg/m³). In China, areas with severe air pollution levels (exceeding WHO interim target-1 of 35 µg/m³) would shrink to regions with high natural dust contributions (North/Northwest China) and small patches in the most polluted areas of Hebei province in the Northeast.

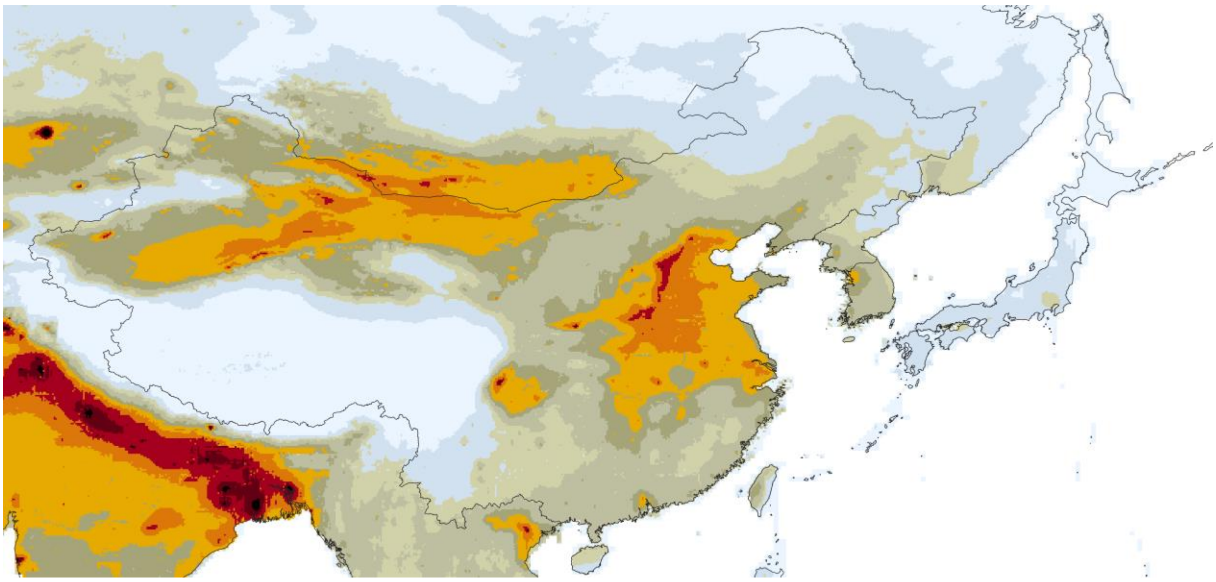
Global policy action would lead to relatively small additional improvements in $PM_{2.5}$ concentrations in the three countries compared with the NEAPA scenario. However, some regions of Korea and China will still experience higher concentrations of $PM_{2.5}$, especially in the West coast regions of Korea and Southeast coast of China (see Figure C.3 in Annex C).

Figure 3.4. Projected concentrations of $PM_{2.5}$ in the CP and NEAPA scenarios

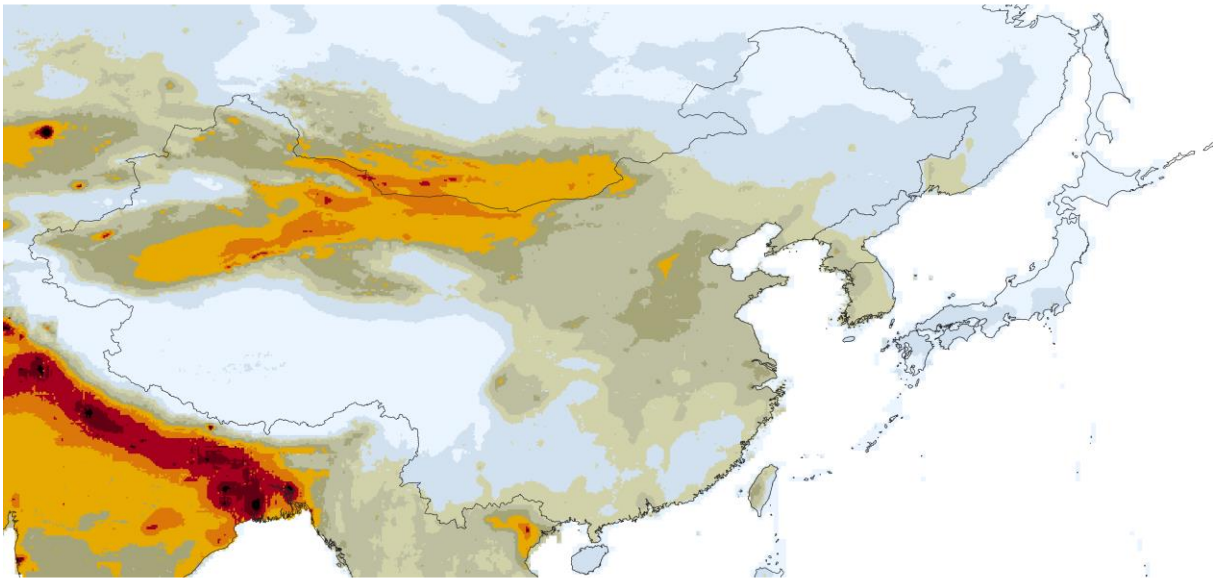
2050, Annual average $PM_{2.5}$ concentrations, µg/m³



Panel A. Current policy (CP) scenario



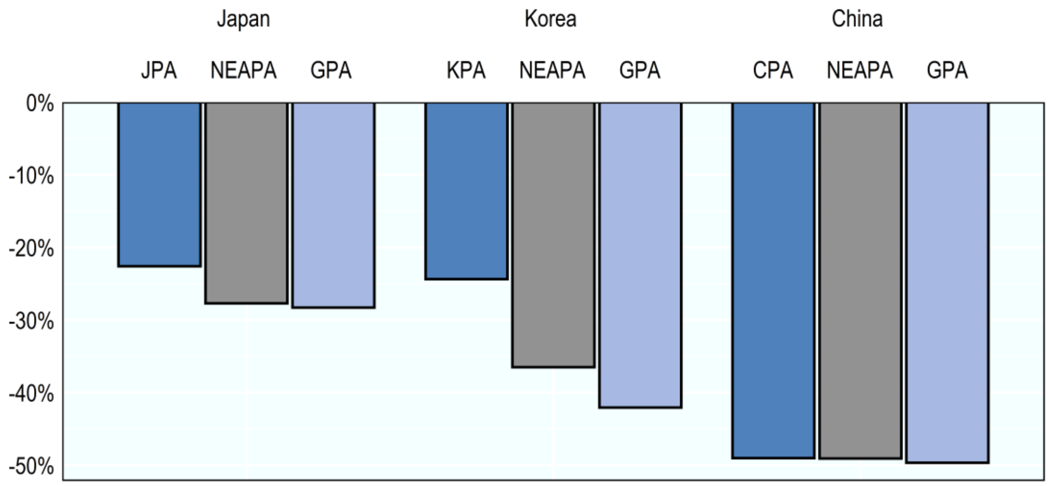
Panel B. Northeast Asia Policy Action (NEAPA) scenario



Note: See 1.1.1.Part I.Annex C for detailed maps of Japan and Korea.
Source: IIASA's GAINS model.

Figure 3.5. Projected average $PM_{2.5}$ concentrations in the CP, NEAPA and GPA scenarios

Difference in concentrations w.r.t to anthropogenic $PM_{2.5}$ concentrations in the CP scenario in 2050.

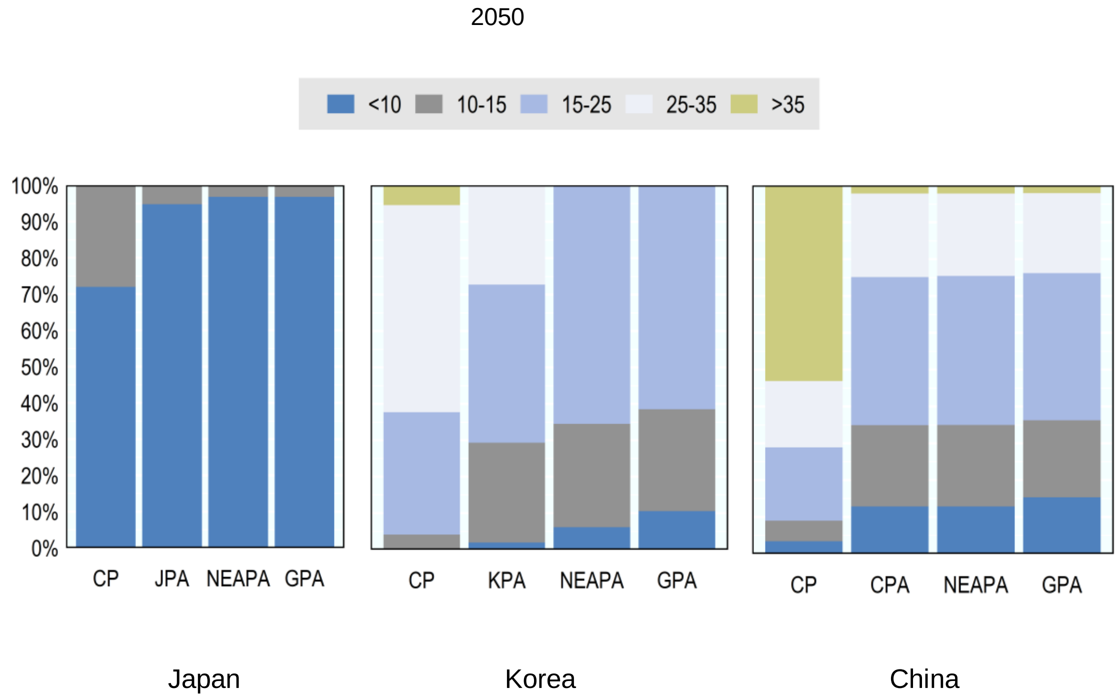


Source: IIASA GAINS model.

Improvements in concentrations result in lower levels of exposure to air pollution. However, since the largest share of the population lives in urban areas, exposure to high $PM_{2.5}$ concentrations remains high in several areas. In China, the improvements are projected to bring 98% of the population below 35 µg/m^3 and 75% below 25 µg/m^3 (Figure 3.6). However, even in the GPA scenario, only less than 15% of the population is projected to be in areas with air pollution concentrations below the WHO AQG of 10 µg/m^3. In Korea, the share of population living in areas with average concentrations below the WHO AQG interim-3 target (15µg/m^3), is projected to increase to almost 40% in the GPA scenario and 35% in the NEAPA scenario, from a very small share of less than 5% in the CP scenario. In Japan, 95% of the population is projected to be exposed to $PM_{2.5}$ concentrations below the WHO AQG of 10µg/m^3 in the co-ordinated policy action scenario (compared with 72% in CP projections for 2050). While the improvements in air quality are compared to the WHO Air Quality Guidelines, this does not imply that levels of $PM_{2.5}$ concentrations below 10µg/m^3 imply no health impacts. In fact, recent literature highlights that even low levels of $PM_{2.5}$ concentrations can cause negative health impacts and sets a zero-risk threshold for fine particles at 2.5 µg/m^3 concentrations (Burnett et al., 2014[103]; Cohen et al., 2018[104]).

Figure 3.6. Population exposure to $PM_{2.5}$ levels in the in the CP, NEAPA and GPA scenarios

Percentage of population exposed to $PM_{2.5}$ concentration levels of the WHO Air Quality Guidelines, µg/m³

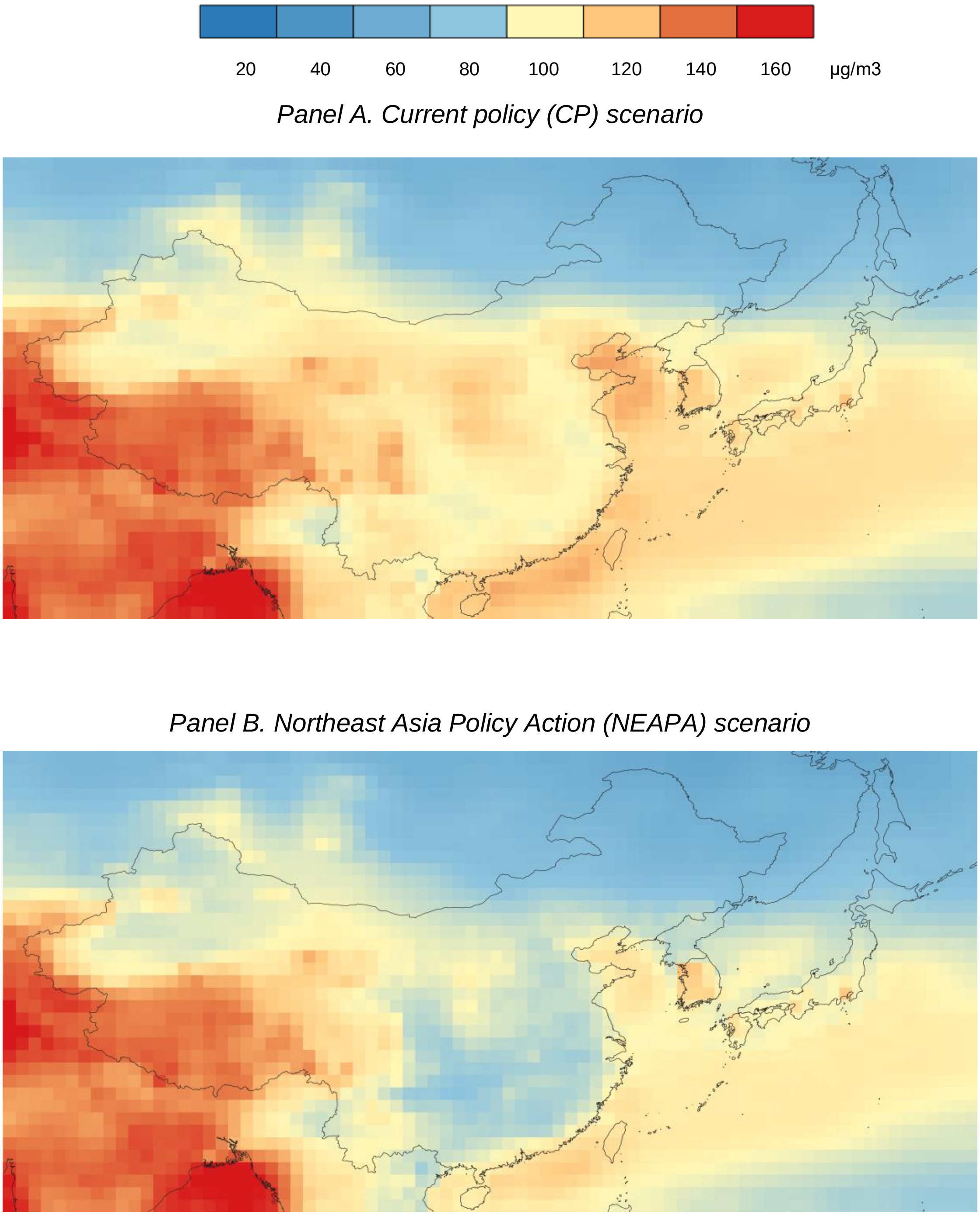


Note: $PM_{2.5}$ levels correspond to the WHO Air Quality Guidance target and interim targets.
Source: IIASA's GAINS model.

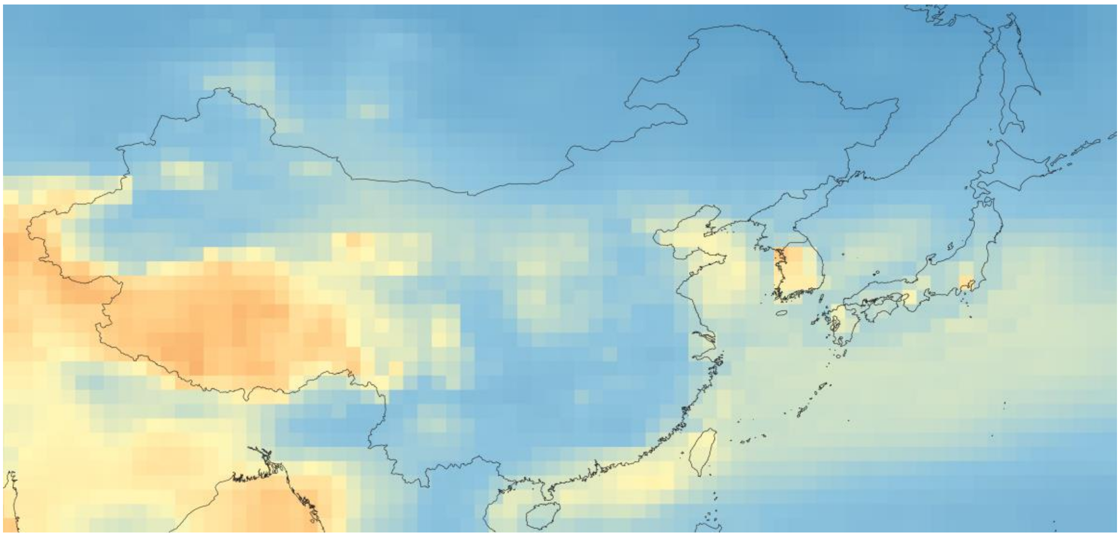
Concentration levels of ground-level ozone are projected to remain high in the coming decades in Northeast Asia (Figure 3.7) in the current policy scenario. Policy action would be particularly beneficial in China. In the scenario with global policy action, ozone pollution would substantially decrease in West China, where concentrations are projected to be highest in absence of additional policy action, reducing the average concentration levels of ground-level ozone in the country by 20% by 2050. Transboundary air pollution from regions such as South Asia, Europe and North America can contribute towards ground-level ozone pollution in Northeast Asia (Fu et al., 2012[105]). With global policy action, concentrations of ground-level ozone would reduce further due to the decrease in ground-level ozone emitted in other regions that through transboundary transport mechanisms can contribute to air pollution in Northeast Asia.

Figure 3.7. Projected concentrations of ground-level ozone in the CP and GPA scenarios

2050, ground-level ozone concentrations, µg/m[3]



Panel C. Global Policy Action (GPA) scenario



Source: EC-JRC's TM5-FASST model

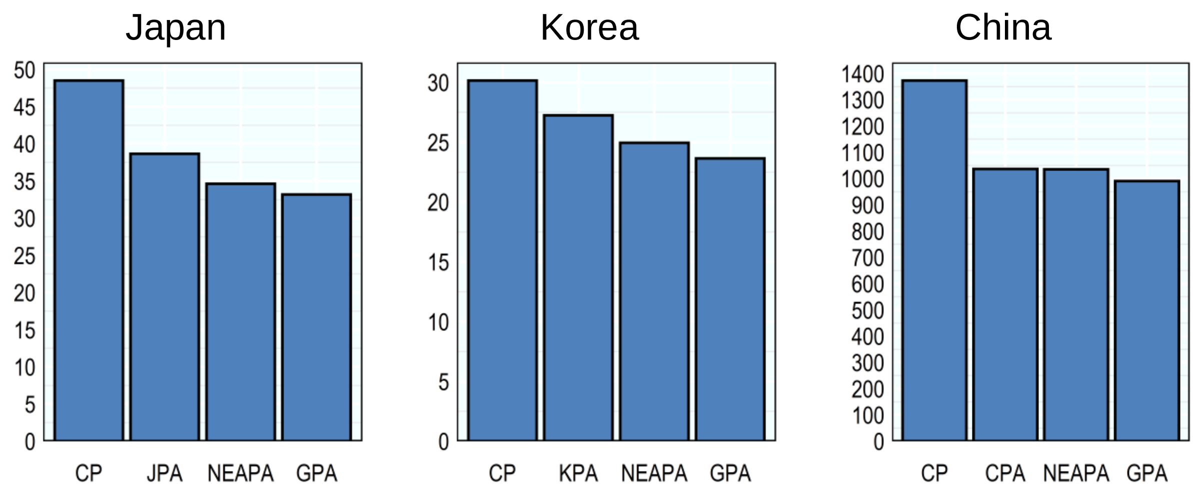
3.3. Projected health impacts of air pollution

In Northeast Asian countries, fine particulate matter ($PM_{2.5}$) and ground-level ozone are responsible for millions of deaths every year. With current policies, air pollution-related deaths in Northeast Asia are projected to increase in the area (1.2 million yearly deaths in 2025 and 1.4 million in 2050, in aggregate in Japan, Korea and China), as illustrated in Figure 3.8. While emissions of several air pollutants are projected to gradually fall over time, the average exposure to pollution and its associated health consequences are projected to increase. This effect is caused by projected urbanisation and changes in the composition of the population, not least the increase in the number of elderly ("ageing"), who tend to be more vulnerable to air pollution.

Domestic policy action would decrease air pollution-related deaths in Japan (-20%), Korea (-10%) and China (-25%) compared to the 2050 projected levels in the current policies scenario (see Figure 3.8). The number of saved lives would be substantially higher in the NEAPA scenario, with 7 750 lives saved in aggregate in the three countries. Most of the additional reductions in air pollution-related deaths are projected to take place in Japan and Korea, whereas in China it is mostly domestic policy action that leads to a reduction in mortality. For the three countries, domestic policy action results in a small additional reduction in air pollution-related mortality.

Figure 3.8. Projected deaths due to $PM_{2.5}$ and ground-level ozone in CP, single-country PA, NEAPA and GPA scenarios

Thousands of yearly deaths in Japan, Korea and China in 2050



Note: While this report presents a single value for the health impacts, there is an uncertainty range, which is discussed in (OECD, 2016[8]).
Source: Global Burden of Disease (GBD, 2018[106]; Institute for Health Metrics and Evaluation (IHME), 2018[107]) and ENV-Linkages' model projections.

Air quality improvements would not only reduce deaths, but also decrease morbidity effects (i.e. illnesses),[14] with morbidity impacts being on average around 25% lower across the three countries, in the NEAPA scenario compared to the current policy scenario (Table 3.1). Global policy action provides few additional benefits in Japan, Korea and China, following the small change in concentration on fine particles (as illustrated in Section 4.2),[15] which is the main driver of the health impacts. Only hospital admissions are projected to further decrease compared to the NEAPA scenario since it is the only morbidity impact which is affected by both $PM_{2.5}$ and ground-level ozone pollution. In the GPA scenario, concentrations of ground-level ozone are projected to decrease compared to the NEAPA scenario, as illustrated in Figure 3.7.

[14] As previously explained, this paper focuses on a subset of illnesses that can be quantified at the global level: chronic bronchitis in adults, and acute bronchitis and asthma symptoms in children, lost workdays, restricted activity days and hospital admissions. Other illnesses (e.g. impacts on fertility and birth weight) could not be quantified. See Methodology for calculation of mortality and morbidity endpoints and their valuation for the methodology of the calculations of morbidity impacts of air pollution.

[15] In Japan, Global Policy Action would not results in a decrease of the health impacts associated with $PM_{2.5}$, such as asthma or bronchitis, since the resulting $PM_{2.5}$ concentration levels are similar to those observed in the NEAPA Scenario (see Figure). The additional health benefits are the results of lower ozone pollution.

Table 3.1. Projected health impacts of air pollution in the CP and NEAPA scenarios

2050 – Thousands

	Japan			Korea			China		
	CP	NEAPA	GPA	CP	NEAPA	GPA	CP	NEAPA	GPA
Respiratory diseases (number of cases)									
Bronchitis in children aged 6 to 12	106	72	72	70	57	54	2 947	2 230	2 219
Chronic bronchitis in adults	31	21	21	20	17	16	860	650	647
Asthma symptom days (number of days)									
Asthma symptom in children aged 5 to 19	1,050	717	717	693	564	541	29 266	22 147	22 040
Healthcare impacts (number of admissions)									
Equivalent hospital admissions	53	42	37	28	24	22	1 573	1 174	1 014
Restricted activity days (number of days)									
Lost working days	11 048	7 545	7 545	7 293	5 941	5 690	308 057	233 120	232 001
Restricted activity days	44 042	30 077	30 077	29 074	23 682	22 682	1 228 019	929 297	924 838

Source: Global Burden of Disease (GBD, 2018[106]; Institute for Health Metrics and Evaluation (IHME), 2018[107]), Holland (2014[102]) and ENV-Linkages' model projections.

While not included in the modelling analysis, improvements in indoor air quality can also contribute to reduce mortality. Indeed, the use of biofuels in cookstoves can result in high levels of indoor air pollution (see Box 1.4 for further information). China is most affected by this due to the higher use of traditional cookstoves compared with Japan and Korea, with projections that in 2050, 75.7 million people in China might be using stoves which contribute towards higher levels of indoor air pollution. This would impact the number of people exposed to high concentrations of air pollutants indoors, leading to health impacts and deaths. Alongside the deaths due to outdoor air pollution, the impact of indoor air pollution would add 315 thousand air pollution related deaths in 2050 in China. With policy action, deaths related to indoor air pollution will decrease by 76% compared with the current policy scenario (IEA, 2018[65]), due to the reduced use of cookstoves that produce high levels of indoor air pollution.[16]

3.4. Projected changes in agricultural productivity

Pollutants such as ground-level ozone can reduce plants' physiological functions resulting in reduced productivity and yields. Consequently, improvements in air quality would result in higher crop yields, as shown in Figure 3.9. According to the EC-JRC's TM5-FASST model (Van Dingenen et al., 2009[82]), policy action in each country would result in improved crop yields, including wheat and rice, in comparison to current policies. The effect of air pollution on a certain crop's productivity can differ by region depending

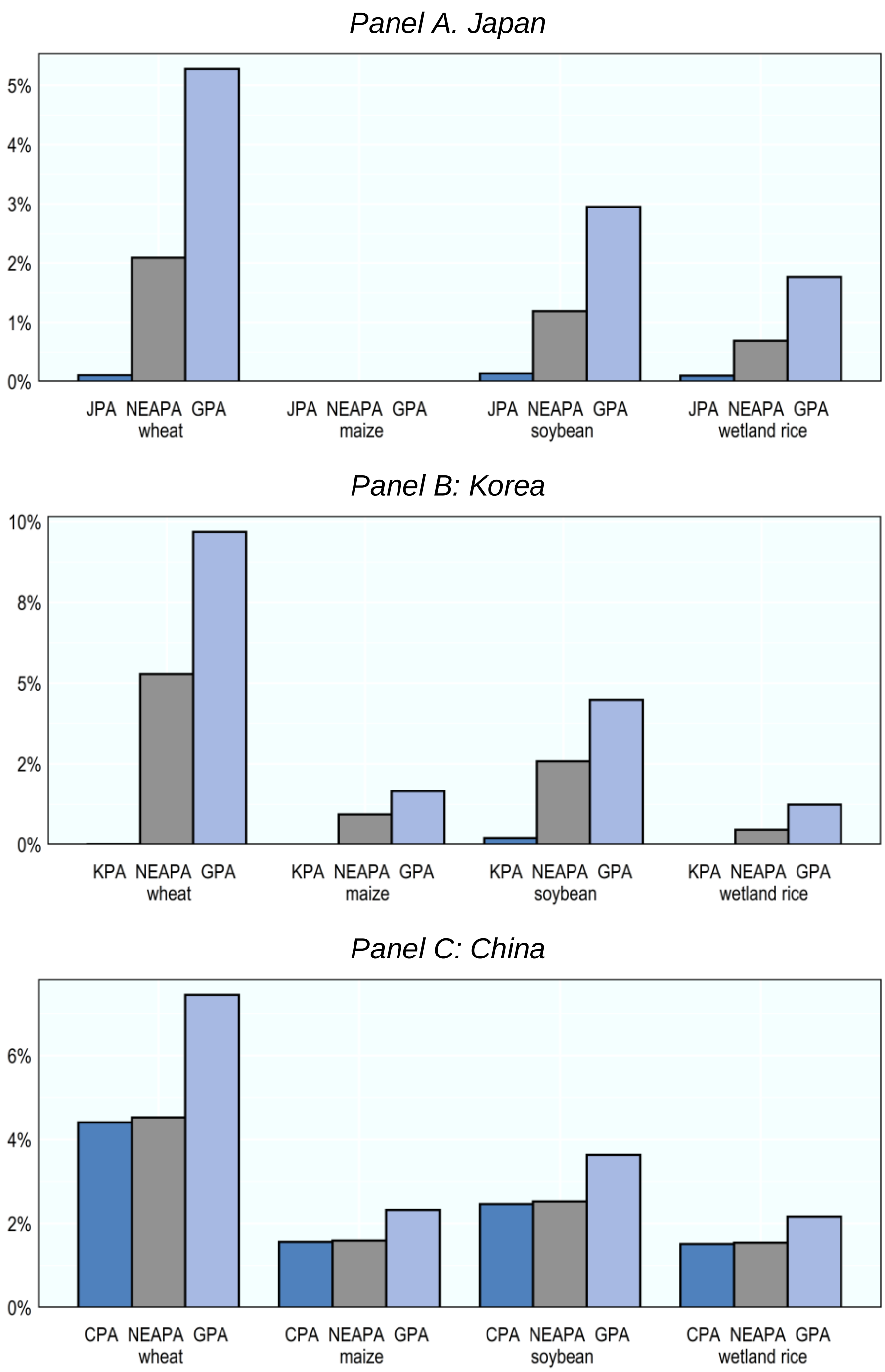
[16] These projected estimates for reduced indoor air pollution in China are based on the IEA's Sustainable Development Scenario, where cookstoves such as traditional biofuel cookstoves are replaced with alternatively fuelled cookstoves that produce less indoor air pollution (IEA, 2018[65]).

on the level of air pollution and the type of crop that is grown. For instance, rice, wheat and soybean are the main three crops grown in Japan (Chen, 2018[108]), while maize is largely imported (Wu and Guclu, 2013[109]; Ranum et al., 2014[110]). Therefore, the impact of air pollution reduction policies on crops such as maize would not be as large compared to the impact on the rice, soybean and wheat crops in Japan.

If policy action is taken by all three countries (i.e. NEAPA scenario), crop yields are projected to further increase in the region. For instance, compared with the Current Policy scenario, in the NEAPA scenario improved air quality results in higher crop yields for wheat, with an increase of 2% in Japan, 5% in Korea and 5% in China in 2050. However, the effect of ground-level ozone emitted from other regions outside Northeast Asia could still influence crop production within the three countries (HTAP, 2010[40]). If policy action to reduce air pollution was taken at the global level then crop yields would increase in Japan, Korea and China in comparison to the Current Policy and NEAPA scenarios (Figure 3.9). Ground-level ozone emitted from other regions such as Europe, North America and South Asia, can contribute to ground-level ozone in the region (Fu et al., 2012[105]), which can impact crop productivity in Northeast Asia (HTAP, 2010[40]). In the Global Policy scenario, emissions of air pollutants, including precursor gases of ground-level ozone, are projected to decline globally, thus resulting in decreased concentrations of ground-level ozone in Northeast Asia and reduced subsequent crop damage.

Figure 3.9. Projected increase in crop yields in the policy action scenarios compared to the CP scenario

Percentage change w.r.t. Current Policy scenario, 2050



Note: Scales differ by country.
Source: EC-JRC's TM5 FASST Model

4 Economic consequences of air pollution policies

4.1. Projected macroeconomic effects

The implementation of policies to reduce air pollution has consequences for economic output and growth through economic benefits but also due to the costs incurred from implementing said policies (see Section 3 on methodology). In the policy scenarios considered, both macroeconomic benefits and costs are relatively small in size, especially for Japan and Korea where there are already strict policies in place to address air pollution in the current policy scenario (CP) (Figure 4.1). For all countries and across all scenarios, the costs and benefits tend to offset each other, thus resulting in no significant effect on economic growth by 2050.

In Japan, the yearly macroeconomic costs and benefits offset each other in all scenarios by 2050. Internationally co-ordinated policy action (in the NEAPA scenario) results in higher benefits, from reduced transboundary air pollution, and lower costs, thanks to an improvement in competitiveness when Japan does not act alone. For Japan, these positive effects of international co-operation are larger with global policy action, which result in Japan having no macroeconomic costs. This result is due to the indirect effects of the implementation of the policies at the global level, not least those arising from changes in competitiveness of Japanese producers on the domestic and international market. These indirect effects are sufficiently positive to compensate for the domestic investments to reduce air pollution.

Results are similar in Korea, although, when acting alone Korea is projected to incur macroeconomic costs that are slightly higher than the benefits by 2050. Furthermore, the macroeconomic benefits are higher when other countries also act, highlighting that Korea benefits from reduced transboundary air pollution. Similarly to Japan, macro-economic costs are projected to be zero in the GPA scenario.

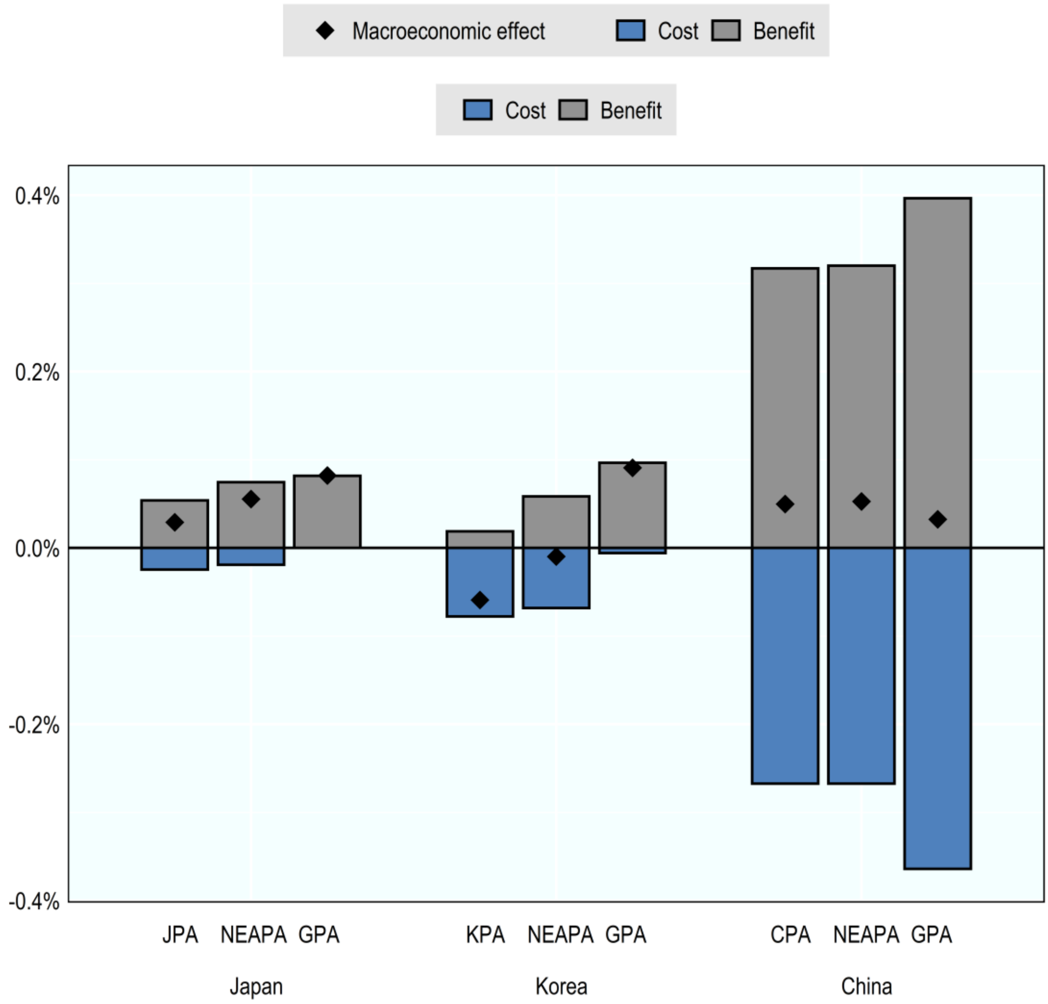
Results for China also show that macroeconomic costs are offset by benefits, with no substantial net effect of policy action on GDP. Both costs and benefits are higher than in the other two countries, reflecting the fact that China has more scope to invest in reducing emissions and to avoid market damages, compared to the current policies scenario. Co-ordinated policy action in the region does not significantly affect results for China: most macroeconomic benefits are the consequence of domestic emission reductions and policy action, with no significant additional benefits when Japan and Korea also undertake policy action. However, there are additional benefits when policy action is implemented globally. Specifically, China benefits from reduced emissions in a wider regional area, including neighbouring Asian countries, which results in lower ground-level ozone in China's Southwest region. Likewise, macroeconomic costs are largely unaffected when Japan and Korea also undertake policy action, due to the size of the Chinese economy and the relatively small share of Japan and Korea in China's trade flows. In contrast to Japan and Korea, in China the macroeconomic costs increase with global policy action as the policy costs in other countries result in lower demand and thus in lower exports for China.[17] However, these international actions also bring benefits, and thus the overall macroeconomic costs in China, in the GPA scenario, are still offset by the

[17] The lower production in China does not result into further reductions of air pollution compared with the scenario where only China takes policy action (CPA). In the CPA Chinese emissions already decrease significantly compared with the current policy scenario. Modelling policy action in the rest of the world (the GPA scenario) does not further reduce China's emissions significantly, but it affects Chinese exports and therefore, its economy.

macroeconomic benefits of reduced air pollution (e.g. Ou et al. (2020[29]) estimates that that goods produced in China for foreign markets accounted for about 13% of total domestic NMVOCs emissions, which is an ozone precursor, in 2013) (Figure 4.1).

Figure 4.1. Projected macroeconomic consequences of policy action to reduce air pollution

Percentage change in GDP w.r.t. CP, 2050.

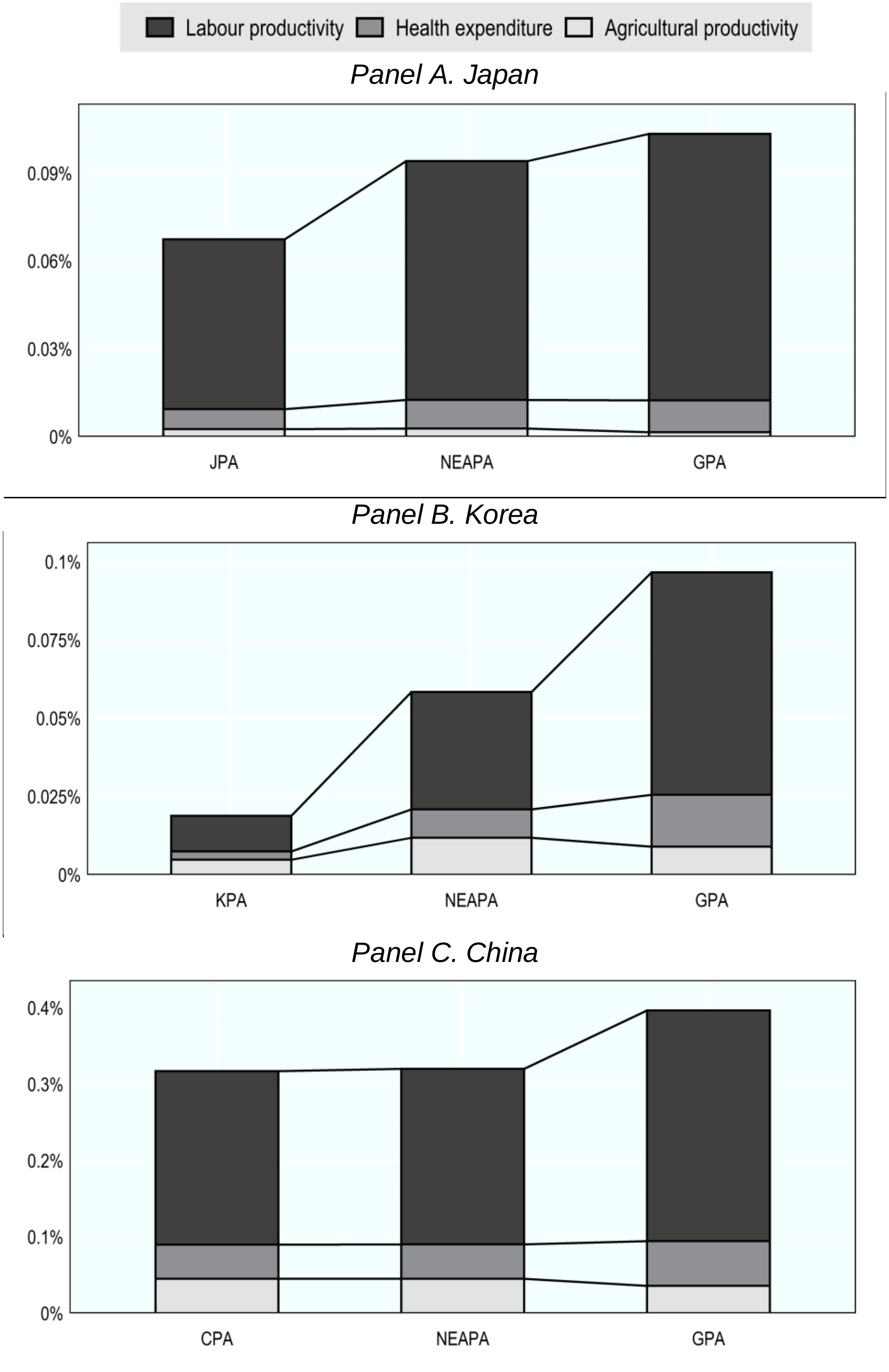


Source: OECD ENV-Linkages model.

Most of the macroeconomic benefits from the reduced air pollution impacts are due to the health improvements that follow the emission reductions and improved air quality. Specifically, labour productivity improvements represent the largest share of the macroeconomic benefits in the three regions, followed by changes in health expenditures and with changes in agricultural productivity representing a smaller percentage (Figure 4.2Figure 4.2). The relative contribution of the different impacts changes with co-ordinated policy action (NEAPA scenario), especially in China and Korea. In these countries, the macroeconomic benefits from improved agricultural productivity increase in the case of co-ordinated and global policy action. The increase in agricultural productivity follows from the decrease in ground-level ozone co-ordinated under the GPA scenario, emitted domestically as well as emissions from neighbouring countries, including India. The importance of long-distance transboundary air pollution for ground-level ozone in China is confirmed by Li et al. (2014[111]) and Kumar et al. (2014[112]).

Figure 4.2. Breakdown of macroeconomic benefits in the different scenarios

Percentage change in GDP w.r.t. CP, 2050



Note: The results in these figures reflect simulations implemented with air pollution benefits only; i.e. discarding the costs of policy action. The cumulative results presented correspond to the macroeconomic benefits (grey bars) in Figure 4.1.

Source: OECD ENV-Linkages model.

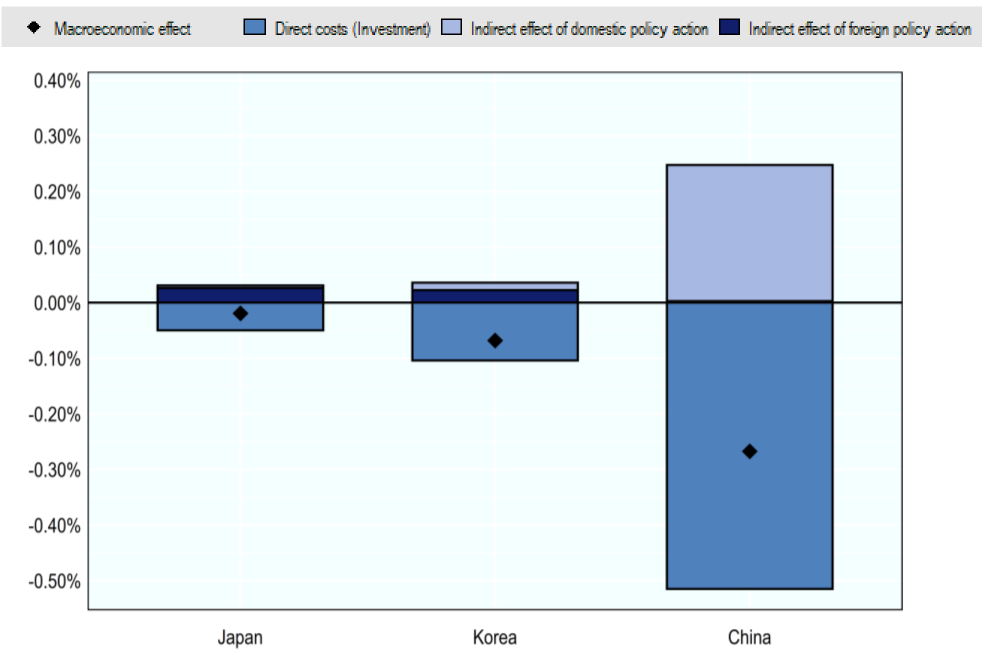
The mechanisms behind the macroeconomic costs are more difficult to understand and depend on the indirect effects of the investment costs in BATs on the economy, not least on trade and competitiveness. The macroeconomic costs (as illustrated by the blue bars in Figure 4.1), comprise of three effects: (i) the direct effect associated with the investments in BATs; (ii) the indirect effect of domestic policy action, and (iii) the effect of policy action in other countries, namely foreign policy action.

The decomposition of the macroeconomic costs in these three effects is illustrated in Figure 4.3 for the NEAPA scenario. When the three countries act alone, the direct costs of the investments in BATs are partially offset by an increase in GDP that follows these investments. While domestic firms face additional costs compared to foreign firms, the investments also represent an opportunity for economic growth thanks to the more efficient production technologies. When the three countries act together, there is a small increase in GDP in Japan and Korea, as competitiveness in these countries increases when they are not acting individually, while the Chinese economy is hardly affected.

While not illustrated in Figure 4.3, similar results are obtained when considering the effect of global policy action on the macroeconomic costs of the three countries. Japan and Korea gain from a small additional increase in competitiveness. However, the Chinese economy faces additional costs due to the reduction in global demand. For this reason, China is the only country that has additional macroeconomic costs in the GPA scenario (see Figure 4.1).

Figure 4.3. Decomposition of macroeconomic costs in the NEAPA scenario

Percentage change in GDP w.r.t. CP, 2050



Note: The results in this figure reflect simulations implemented with investment costs only, i.e. disregarding the benefits from reduced air pollution impacts. The macroeconomic costs (diamonds) correspond to the macroeconomic costs (blue bars) in the NEAPA scenario in Figure 4.1.

Source: OECD ENV-Linkages model.

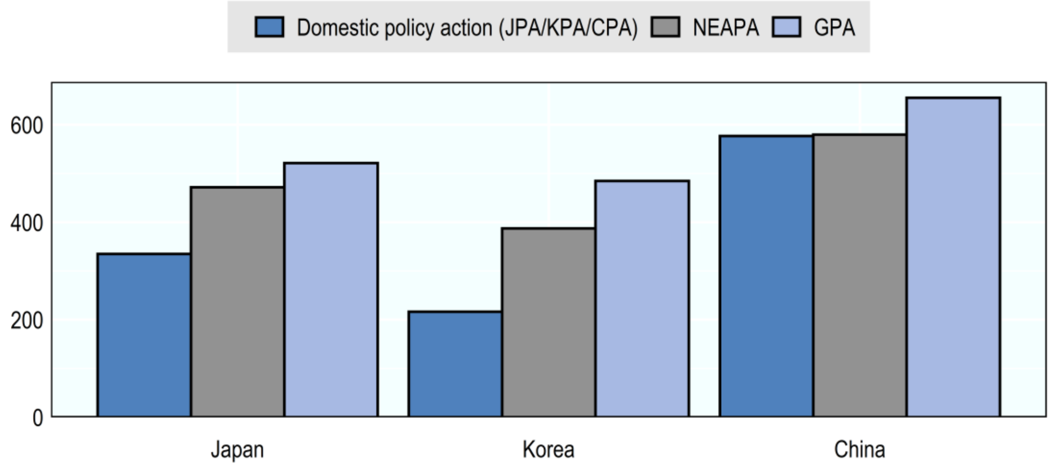
4.2. Projected welfare benefits from reduced mortality and pain and suffering from illness

The health impacts of air pollution also entail welfare effects due to lower mortality and lower disutility of illness. The welfare losses due to mortality are calculated using the OECD's value of statistical life (VSL) (Roy and Braathen, 2017[113]).[18] Similarly to the costs of mortality, monetary valuation of the disutility of illness is calculated by multiplying the willingness-to-pay to reduce the risk of falling ill by the number of cases of illness (see Table in Section 4.3).

For the Northeast Asian region, the aggregate welfare benefits due to lower mortality are projected to increase over time, as more air quality improvements are achieved. By 2050 the aggregate yearly welfare benefits exceed USD 850 billion by 2050 with internationally co-ordinated policy action (NEAPA scenario) and USD 950 billion with global policy action (GPA scenario). In the NEAPA scenario, the yearly per capita welfare benefits in Japan and Korea are projected to be around 470 and 390 USD in 2050, respectively (Figure 4.4), whereas in China they are projected to be around 580 USD. Similarly to the NEAPA scenario, Japan and Korea are projected to enjoy similar per capita gains in the GPA scenario while China stands to gain the largest per capita benefits.

Figure 4.4. Projected welfare benefits from reduced air pollution related mortality

USD per capita, 2017 PPP exchange rates, w.r.t to Current Policy, 2050



Note: While this report presents a single value for the economic costs associated with deaths, these values are uncertain. Uncertainty ranges are presented in (OECD, 2016[8])

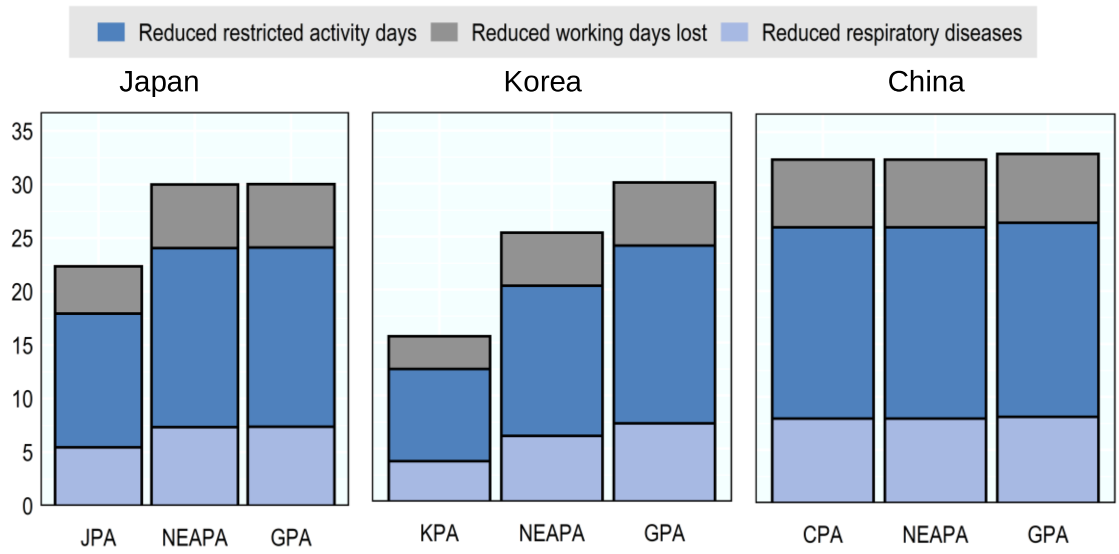
Source: Environment Database; Mortality and welfare cost from exposure to air pollution, Holland (2014[102]) and ENV-Linkages' model projections.

[18] The OECD Environment Database provides VSL values for OECD and G20 countries. Values for other countries have been adapted based on their income, following the methodology used in previous OECD studies (OECD, 2015[121]; OECD, 2014[101]).

Additionally, the yearly benefits from avoided morbidity impacts are projected to exceed USD 48 billion by 2050 in the NEAPA scenario, and USD 49 billion by 2050 in the GPA scenario. In all countries, the largest benefits derive from lower disruption in normal activity (reduction in the number of restricted activity days and of lost working days) and lower incidence of respiratory diseases. In both the single-country policy action and NEAPA scenario, China is the country that would benefit the most from reduced morbidity impacts in per capita terms. Korea enjoys the largest per capita benefit in the GPA scenario (Figure 4.5).

Figure 4.5. Projected welfare benefits from avoided air pollution related illness

USD per capita, 2017 PPP exchange, 2050, w.r.t to Current policy



Note: In the figure, "Reduced respiratory diseases" includes reduced cases of chronic bronchitis in adults, reduced hospital admission, and bronchitis and asthma symptoms in children.
Source: Environment Database; Mortality and welfare cost from exposure to air pollution, Holland (2014[102]) and ENV-Linkages' model projections.

Additional welfare benefits of policy action can also occur through other channels. These include for instance, additional health impacts of air pollution, such as those on fertility, birth weight, school performance. Welfare is also likely to be higher for people living in and visiting cities with better air quality, as air quality can for instance damage building and cultural heritage.

If air pollution policies certainly lead to welfare benefits due to the positive impacts on health and the environment, the costs of the policies might have a negative welfare effect. Policy action imposes additional costs on firms and households and, while there might be beneficial effects in the long term, these costs might have short term socio-economic consequences that negatively affect welfare. For example, one common concern of environmental policies is that they might have a negative effect on employment in targeted sectors (Chateau, Bibas and Lanzi, 2018[114]). However, overall environmental policies could also trigger innovation and better production processes, which would be beneficial in the long-term.

5 Discussion

The results in this report highlight the potential benefits of policy action to reduce air pollution, in Japan, Korea and China. The results also highlight the additional benefits from co-ordinated policy action. Countries should use the full potential of the multiple regional co-operation mechanisms in place and strengthen their synergies to build a more systematic framework to address transboundary air pollution (OECD, 2020[67]).

A number of actions can support the implementation of a co-ordinated approach to reduce air pollution in the region. For instance, better data and measurement techniques could increase efficiency and efficacy of monitoring and enforcement activities. Improved data and clear criteria to assess and rank the risk of facilities could save resources and make enforcement efforts more effective and efficient by better tailoring frequency of inspections to the level of risk (OECD, 2018[115]).

Compliance promotion activities with regards to countries' efforts to meet emission reduction obligations, could benefit from higher horizontal co-operation among agencies and the use of new technologies. Well-functioning horizontal mechanisms to share information on regulatory enforcement and inspections could also be put in place, for instance to share information to identify violations that may allow agencies in other regions to detect similar compliance issues faster. At the same time, new technologies, such as drones , remote inspections, or big data, may allow agencies to better target inspections and decrease inspecting times (OECD, 2021[116]).

Ensuring that third parties affected by pollution could report violations and challenge non-compliance with environmental laws in courts is also an important tool to promote and monitor compliance with existing policies. To this end, the barriers that non-governmental organisations and citizens face in suing violators in courts, including financial barriers, may need to be addressed. Countries may also benefit from a better balance between compliance promotion and enforcement activities. The provision of trainings and guidance during inspections, and information dissemination activities are useful to enhance compliance on air quality standards. Together with these activities that could help achieve a higher level of international regulatory co-operation, increased international effort to mitigate climate change might also contribute to improve air quality in the region. The current pledges on climate change mitigation are indeed encouraging as a step towards a green transition that would also lead to lower air pollution.

References

Adhvaryu, A., N. Kala and A. Nyshadham (2019), *Management and Shocks to Worker Productivity*, National Bureau of Economic Research, Cambridge, MA, https://doi.org/10.3386/w25865. [2]

Allen, J. et al. (2017), "Cognitive Effects of Air Pollution Exposures and Potential Mechanistic Underpinnings", *Current Environmental Health Reports*, Vol. 4/2, pp. 180-191, https://doi.org/10.1007/s40572-017-0134-3. [86]

Amann, M. et al. (2018), *Progress towards the achievement of the EU's air quality and emissions objectives*, International Institute for Applied Systems Analysis (IIASA). [129]

Amann, M. et al. (2011), "Cost-effective control of air quality and greenhouse gases in Europe: Modeling and policy applications", *Environmental Modelling & Software*, Vol. 26/12, pp. 1489-1501, https://doi.org/10.1016/j.envsoft.2011.07.012. [12]

Amann, M. et al. (2017), *Costs, benefits and economic impacts of the EU Clean Air Strategy and their implications on innovation and competitiveness. IIASA report*, (http://gains.iiasa.ac.at), https://ec.europa.eu/environment/air/pdf/clean_air_outlook_economic_impact_report.pdf (accessed on 30 July 2020). [9]

Amann, M. et al. (2020), "Reducing global air pollution: The scope for further policy interventions: Achieving clean air worldwide", *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, Vol. 378/2183, https://doi.org/10.1098/rsta.2019.0331. [71]

Amann, M., Z. Klimont and F. Wagner (2013), "Regional and Global Emissions of Air Pollutants: Recent Trends and Future Scenarios", *Annual Review of Environment and Resources*, Vol. 38/1, pp. 31-55, https://doi.org/10.1146/annurev-environ-052912-173303. [79]

Archer, C., J. Brodie and S. Rauscher (2019), "Global warming will aggravate ozone pollution in the U.S. mid-atlantic", *Journal of Applied Meteorology and Climatology*, Vol. 58/6, pp. 1267-1278, https://doi.org/10.1175/JAMC-D-18-0263.1. [97]

Bae, C. et al. (2020), "Long-range transport influence on key chemical components of PM2.5 in the seoul metropolitan area, south korea, during the years 2012-2016", *Atmosphere*, Vol. 11/1, p. 48, https://doi.org/10.3390/ATMOS11010048. [44]

Bae, C. et al. (2020), "Surface ozone response to satellite-constrained NOx emission adjustments and its implications", *Environmental Pollution*, Vol. 258, p. 113469, https://doi.org/10.1016/j.envpol.2019.113469. [22]

Basner, M. et al. (2014), "Auditory and non-auditory effects of noise on health", *The Lancet*, Vol. 383/9925, pp. 1325-1332, https://doi.org/10.1016/s0140-6736(13)61613-x. [84]

Bloomberg (2019), *South Korea Hits Industries With Nitrogen Oxide Emissions Charge*, https://news.bloomberglaw.com/environment-and-energy/south-korea-hits-industries-with-nitrogen-oxide-emissions-charge (accessed on 3 September 2020). [56]

Botta, E. and S. Yamasaki (2020), “Policies, regulatory framework and enforcement for air quality management: The case of Japan”*, OECD Environment Working Papers*, No. 156, OECD Publishing, Paris, https://dx.doi.org/10.1787/b2de0bc1-en. [14]

Burnett, R. et al. (2014), “An Integrated Risk Function for Estimating the Global Burden of Disease Attributable to Ambient Fine Particulate Matter Exposure”, *Environmental Health Perspectives*, Vol. 122/4, pp. 397-403, https://doi.org/10.1289/ehp.1307049. [103]

CCAC (2021), *Black carbon | Climate & Clean Air Coalition, accessed on May 2021*, https://www.ccacoalition.org/en/slcps/black-carbon (accessed on 17 May 2021). [96]

CCAC (2021), *Methane | Climate & Clean Air Coalition, accessed on May 2021*, https://www.ccacoalition.org/es/slcps/methane (accessed on 17 May 2021). [95]

Chang, T. et al. (2016), “Particulate pollution and the productivity of pear packers”, *American Economic Journal: Economic Policy*, Vol. 8/3, pp. 141-169, https://doi.org/10.1257/pol.20150085. [1]

Chang, T. et al. (2016), *The Effect of Pollution on Worker Productivity: Evidence from Call-Center Workers in China*, National Bureau of Economic Research, Cambridge, MA, https://doi.org/10.3386/w22328. [3]

Chantret, F. et al. (2020), “Can better technologies avoid all air pollution damages to the global economy?”, *Climatic Change*, Vol. 163/3, pp. 1463-1480. [132]

Chatani, S. et al. (2020), “Identifying key factors influencing model performance on ground-level ozone over urban areas in Japan through model inter-comparisons”, *Atmospheric Environment*, Vol. 223, p. 117255, https://doi.org/10.1016/j.atmosenv.2019.117255. [25]

Chateau, J., R. Bibas and E. Lanzi (2018), “Impacts of Green Growth Policies on Labour Markets and Wage Income Distribution: A General Equilibrium Application to Climate and Energy Policies”*, OECD Environment Working Papers*, No. 137, OECD Publishing, Paris, https://dx.doi.org/10.1787/ea3696f4-en. [114]

Chateau, J., R. Dellink and E. Lanzi (2014), “An Overview of the OECD ENV-Linkages Model: Version 3”*, OECD Environment Working Papers*, No. 65, OECD Publishing, Paris, https://dx.doi.org/10.1787/5jz2qck2b2vd-en. [11]

Chen, H. (2018), “Plant Production Science The spatial patterns in long-term temporal trends of three major crops’ yields in Japan The spatial patterns in long-term temporal trends of three major crops’ yields in Japan”, https://doi.org/10.1080/1343943X.2018.1459752. [108]

China Daily (2020), *Beijing license plate: 8-year wait for new energy car - Chinadaily.com.cn*, https://www.chinadaily.com.cn/a/201901/31/WS5c52a306a3106c65c34e7930.html (accessed on 18 September 2020). [63]

Cohen, A. et al. (2018), “Global estimates of mortality associated with long-term exposure to outdoor fine particulate matter”, *Proceedings of the National Academy of Sciences*, Vol. 115/38, pp. 9592-9597, https://doi.org/10.1073/pnas.1803222115. [104]

Costa, D. and M. Kahn (2004), “Changes in the Value of Life, 1940–1980”, *Journal of Risk and Uncertainty*, Vol. 29/2, pp. 159-180, https://doi.org/10.1023/b:risk.0000038942.18349.88. [125]

Cuesta, J. et al. (2018), "Transboundary ozone pollution across East Asia: daily evolution and photochemical production analysed by IASI + GOME2 multispectral satellite observations and models", *Atmospheric Chemistry and Physics*, Vol. 18/13, pp. 9499-9525, https://doi.org/10.5194/acp-18-9499-2018. [48]

Daly, A. and P. Zannetti (2007), *An Introduction to Air Pollution-Definitions, Classifications, and History*, http://www.arabschool.org.sy (accessed on 4 September 2020). [31]

Dechezleprêtre, A., N. Rivers and B. Stadler (2019), "The economic cost of air pollution: Evidence from Europe", *OECD Economics Department Working Papers*, No. 1584, OECD Publishing, Paris, https://dx.doi.org/10.1787/56119490-en. [10]

Dentener, F. (ed.) (2010), *UNECE: Hemispheric Transport of Air Pollution 2010: Part A: Ozone and Particulate Matter*, United Nations publication, Geneva, Switzerland, https://unece.org/DAM/env/lrtap/Publications/11-22134-Part-A.pdf (accessed on 4 February 2021). [40]

Dong, D., X. Xu and Y. Wong (2019), "Estimating the Impact of Air Pollution on Inbound Tourism in China: An Analysis Based on Regression Discontinuity Design", *Sustainability*, Vol. 11/6, p. 1682, https://doi.org/10.3390/su11061682. [92]

Du, X. et al. (2020), "Transboundary air pollution from coal-fired power generation", *Journal of Environmental Management*, Vol. 270, p. 110862, https://doi.org/10.1016/j.jenvman.2020.110862. [51]

Ebenstein, A., V. Lavy and S. Roth (2016), "The long-run economic consequences of high-stakes examinations: Evidence from transitory variation in pollution", *American Economic Journal: Applied Economics*, Vol. 8/4, pp. 36-65, https://doi.org/10.1257/app.20150213. [4]

EMEP (2020), *EMEP Overview*, https://www.emep.int/emep_overview.html (accessed on 4 December 2020). [41]

European Commission (2013), *The Clean Air Policy Package*, pp. No. SWD(2013)531, European Commission, Brussels, http://ec.europa.eu/governance/impact/ia_carried_out/docs/ia_2013/swd_2013_0531_en.pdf. [122]

Forouzanfar, M. et al. (2015), "Global, Regional, and National Comparative Risk Assessment of 79 Behavioural, Environmental and Occupational, and Metabolic Risks or Custers of Risks in 188 Countries, 1990-2013: A Systematic Analysis for the Global Burden of Disease Study 2013", *The Lancet*, Vol. 386/10010, pp. 2287-2323, https://doi.org/10.1016/S0140-6736(15)00128-2. [80]

Fu, J. et al. (2012), "Sensitivity and linearity analysis of ozone in East Asia: The effects of domestic emission and intercontinental transport", *Journal of the Air & Waste Management Association*, Vol. 62/9, pp. 1102-1114, https://doi.org/10.1080/10962247.2012.699014. [105]

GBD (2019), *GBD Results Tool | GHDx*, http://ghdx.healthdata.org/gbd-results-tool (accessed on 16 November 2020). [35]

GBD (2018), "Global Burden of Disease Study 2017: All cause Mortality and Life Expectancy 1950-2017, Global Burden of Disease Collaborative Network.", *Seattle, United States: Institute for Health Metrics and Evaluation (IHME)*. [106]

Guillemette, Y. and D. Turner (2018), “The Long View: Scenarios for the World Economy to 2060”, *OECD Economic Policy Papers*, No. 22, OECD Publishing, Paris, https://dx.doi.org/10.1787/b4f4e03e-en. [117]

Hammitt, J. and L. Robinson (2011), “The Income Elasticity of the Value per Statistical Life: Transferring Estimates between High and Low Income Populations”, *Journal of Benefit-Cost Analysis*, Vol. 2/1, pp. 1-29, https://doi.org/10.2202/2152-2812.1009. [127]

Harmsen, M. et al. (2020), “Taking some heat off the NDCs? The limited potential of additional short-lived climate forcers’ mitigation”, *Climatic change*, pp. 1443–1461. [131]

Henseler, M. et al. (2020), “Nitrogen Tax and Set-Aside as Greenhouse Gas Abatement Policies Under Global Change Scenarios: A Case Study for Germany”, *Environmental and Resource Economics*, Vol. 76, pp. 299-329, https://doi.org/10.1007/s10640-020-00425-0. [74]

Hodan, W. and W. Barnard (2004), “Evaluating the Contribution of PM2.5 Precursor Gases and Re-entrained Road Emissions to Mobile Source PM2.5 Particulate Matter Emissions Prepared by MACTEC Under Contract to the Federal Highway Administration”, *MACTEC Federal Programs, Research Triangle Park, NC.*. [32]

Holland, M. (2014), *Cost-benefit Analysis of Final Policy Scenarios for the EU Clean Air Package*, Corresponding to IIASA TSAP Report No. 11, International Institute for Applied Systems Analysis (IIASA), Laxenburg, http://ec.europa.eu/environment/air/pdf/TSAP%20CBA.pdf (accessed on 9 March 2021). [102]

IEA (2020), *Global EV Outlook 2020 Entering the decade of electric drive?*, OECD Publishing, Paris, https://doi.org/10.1787/d394399e-en (accessed on 4 July 2020). [54]

IEA (2020), *World Energy Outlook 2020*, OECD Publishing, Paris, https://dx.doi.org/10.1787/557a761b-en. [128]

IEA (2018), *Market Report Series: Energy Efficiency 2018*, International Energy Agency, Paris, http://www.iea.org/t&c/ (accessed on 4 July 2020). [72]

IEA (2018), *World Energy Outlook 2018*, International Energy Agency, Paris, https://dx.doi.org/10.1787/weo-2018-en. [65]

IEA (2016), *Energy and Air Pollution - World Energy Outlook 2016 Special Report*, IEA, http://pure.iiasa.ac.at/id/eprint/13467/1/WorldEnergyOutlookSpecialReport2016EnergyandAirPollution.pdf (accessed on 6 November 2020). [36]

IHME GBD (2020), “Global age-sex-specific fertility, mortality, healthy life expectancy (HALE), and population estimates in 204 countries and territories, 1950–2019: a comprehensive demographic analysis for the Global Burden of Disease Study 2019”, *The Lancet*, Vol. 396/10258, pp. 1160-1203, https://doi.org/10.1016/s0140-6736(20)30977-6. [17]

IIASA (2020), *The GAINS Model - IIASA*, https://iiasa.ac.at/web/home/research/researchPrograms/air/GAINS.html (accessed on 21 July 2020). [78]

Ikeda, K. et al. (2015), “Source region attribution of PM2.5 mass concentrations over Japan”, *GEOCHEMICAL JOURNAL*, Vol. 49/2, pp. 185-194, https://doi.org/10.2343/geochemj.2.0344. [46]

IMF (2019), *World Economic Outlook Database*, International Monetary Fund, https://www.imf.org/external/pubs/ft/weo/2019/02/weodata/index.aspx. [126]

Institute for Health Metrics and Evaluation (IHME) (2018), "Global Life Expectancy, All-Cause Mortality, and Cause-Specific Mortality Forecasts 2016-2040.", *Seattle, United States: Institute for Health Metrics and Evaluation (IHME).*, https://vizhub.healthdata.org/gbd-foresight/ (accessed on 2 December 19). [107]

Itahashi, S. et al. (2017), "Nitrate transboundary heavy pollution over East Asia in winter", *Atmospheric Chemistry and Physics*, Vol. 17/6, pp. 3823-3843, https://doi.org/10.5194/acp-17-3823-2017. [47]

Kauffmann, C. and C. Saffirio (2020), "Study of International Regulatory Co-operation (IRC) arrangements for air quality: The cases of the Convention on Long-Range Transboundary Air Pollution, the Canada-United States Air Quality Agreement, and co-operation in North East Asia"*, OECD Regulatory Policy Working Papers*, No. 12, OECD Publishing, Paris, https://dx.doi.org/10.1787/dc34d5e3-en. [42]

Kim, H. et al. (2021), "Synoptic weather and surface ozone concentration in South Korea", *Atmospheric Environment*, Vol. 244, p. 117985, https://doi.org/10.1016/j.atmosenv.2020.117985. [24]

Kim, M. (2019), "The effects of transboundary air pollution from China on ambient air quality in South Korea", *Heliyon*, Vol. 5/12, p. e02953, https://doi.org/10.1016/j.heliyon.2019.e02953. [50]

Kumar, R. et al. (2014), "Effects of dust aerosols on tropospheric chemistry during a typical pre-monsoon season dust storm in northern India", *Atmospheric Chemistry and Physics*, Vol. 14/13, pp. 6813-6834, https://doi.org/10.5194/acp-14-6813-2014. [112]

Lam, Y. et al. (2011), "Impacts of future climate change and effects of biogenic emissions on surface ozone and particulate matter concentrations in the United States", *Atmospheric Chemistry and Physics*, Vol. 11/10, pp. 4789-4806, https://doi.org/10.5194/acp-11-4789-2011. [34]

Lanphear, B. (ed.) (2015), "Association between Traffic-Related Air Pollution in Schools and Cognitive Development in Primary School Children: A Prospective Cohort Study", *PLOS Medicine*, Vol. 12/3, p. e1001792, https://doi.org/10.1371/journal.pmed.1001792. [85]

Lanzi, E. et al. (2021), "The economic benefits of air quality improvements in Arctic Council countries", *OECD Publishing, forthcoming, Paris*. [133]

Li, J. et al. (2019), "Model evaluation and intercomparison of surface-level ozone and relevant species in East Asia in the context of MICS-Asia Phase III - Part 1: Overview", *Atmospheric Chemistry and Physics*, Vol. 19/20, pp. 12993-13015, https://doi.org/10.5194/acp-19-12993-2019. [27]

Liu, S. et al. (2020), "Revealing the impacts of transboundary pollution on PM2.5-related deaths in China", *Environment International*, Vol. 134, p. 105323, https://doi.org/10.1016/j.envint.2019.105323. [49]

Li, X. et al. (2014), "Effects of trans-Eurasian transport of air pollutants on surface ozone concentrations over Western China", *Journal of Geophysical Research: Atmospheres*, Vol. 119/21, pp. 12,338-12,354, https://doi.org/10.1002/2014jd021936. [111]

Mackie, A., I. Hascic and M. Cardenas Rodriguez (2016), *Population Exposure to Fine Particles Methodology and Results for OECD and G20 Countries*, OECD Green Growth Papers, No. 2016/02,, http://www.oecd.org/greengrowth (accessed on 2 June 2021). [20]

Matus, K. et al. (2008), "Toward integrated assessment of environmental change: Air pollution health effects in the USA", *Climatic Change*, Vol. 88/1, pp. 59-92, https://doi.org/10.1007/s10584-006-9185-4. [6]

Ministry of Environment (2020), *Press Release: (Joint-Report) Results from Introduction of the Fine Dust Seasonal Management System in December 2019*, https://eng.me.go.kr/eng/web/board/read.do?pagerOffset=0&maxPageItems=10&maxIndexPages=10&searchKey=titleOrContent&searchValue=air+pollution&menuId=461&orgCd=&boardId=1349010&boardMasterId=522&boardCategoryId=&decorator=&firstItemIndex= (accessed on 10 September 2020). [59]

Ministry of Environment (2018), "Comprehensive Plan on Fine Dust Management. No. 46", *Korea Environmental Policy Bulletin*, Vol. XV/2. [58]

Nam, K. et al. (2010), "Measuring welfare loss caused by air pollution in Europe: A CGE analysis", *Energy Policy*, Vol. 38, http://web.mit.edu/selin/www/pubs/nam_energypolicy.pdf (accessed on 30 July 2020). [7]

NASA - NIER (2017), *Introduction to the KORUS-AQ Rapid Science Synthesis Report*, https://espo.nasa.gov/sites/default/files/documents/KORUS-AQ-ENG.pdf (accessed on 18 June 2020). [43]

Neufeldt, H. and M. Schäfer (2008), "Mitigation strategies for greenhouse gas emissions from agriculture using a regional economic-ecosystem model", *Agriculture, Ecosystems and Environment*, Vol. 123/4, pp. 305-316, https://doi.org/10.1016/j.agee.2007.07.008. [73]

Nieuwenhuijsen, M. et al. (2014), "Air pollution and human fertility rates", *Environment International*, Vol. 70, pp. 9-14, https://doi.org/10.1016/j.envint.2014.05.005. [83]

OECD (2021), *Air pollution exposure* (indicator), https://dx.doi.org/10.1787/8d9dcc33-en (accessed on 25 June 2021). [18]

OECD (2021), *OECD Regulatory Policy Outlook 2021*, OECD Publishing, Paris. [116]

OECD (2021), "The economic benefits of air quality improvements in Arctic Council countries", *OECD Publishing, Paris*. [19]

OECD (2020), *Air quality and health: Mortality and welfare cost from exposure to air pollution (database)*, Statistics, OECD Environment, https://doi.org/10.1787/c14fb169-en (accessed on 3 November 2020). [99]

OECD (2020), *Study of International Regulatory Co-operation (IRC) arrangements for air quality: The cases of the Convention on Long-Range Transboundary Air Pollution, the Canada-United States Air Quality Agreement, and co-operation in North East Asia*, OECD Publishing, Paris, https://www.oecd-ilibrary.org/governance/study-of-international-regulatory-co-operation-irc-arrangements-for-air-quality_dc34d5e3-en (accessed on 3 December 2020). [67]

OECD (2019), *Accelerating Climate Action: Refocusing Policies through a Well-being Lens*, OECD Publishing, Paris, https://dx.doi.org/10.1787/2f4c8c9a-en. [94]

OECD (2019), *ENVIRONMENT DIRECTORATE JOINT MEETING OF THE CHEMICALS COMMITTEE AND THE WORKING PARTY ON CHEMICALS, PESTICIDES AND BIOTECHNOLOGY Best Available Techniques (BAT) for Preventing and Controlling Industrial Pollution Activity 3: Measuring the Effectiveness of BAT Policies*. [55]

OECD (2019), *Global Material Resources Outlook to 2060: Economic Drivers and Environmental Consequences*, OECD Publishing, Paris, https://dx.doi.org/10.1787/9789264307452-en. [77]

OECD (2018), *OECD Regulatory Enforcement and Inspections Toolkit*, https://www.oecd-ilibrary.org/docserver/9789264303959-en.pdf?expires=1537808911&id=id&accname=ocid84004878&checksum=4DF425625EB0F0107C8F2688DF6775EE (accessed on 24 September 2018). [115]

OECD (2016), *The Economic Consequences of Outdoor Air Pollution*, OECD Publishing, Paris, https://dx.doi.org/10.1787/9789264257474-en. [8]

OECD (2015), *The Economic Consequences of Climate Change*, OECD Publishing, Paris, https://dx.doi.org/10.1787/9789264235410-en. [121]

OECD (2014), *The Cost of Air Pollution: Health Impacts of Road Transport*, OECD Publishing, Paris, https://dx.doi.org/10.1787/9789264210448-en. [101]

OECD (2012), *Mortality Risk Valuation in Environment, Health and Transport Policies*, OECD Publishing, Paris, https://dx.doi.org/10.1787/9789264130807-en. [100]

OECD (2012), *OECD Environmental Outlook to 2050*, OECD Publishing, Paris, https://www.oecd-ilibrary.org/docserver/9789264122246-en.pdf?expires=1604508320&id=id&accname=ocid84004878&checksum=150946E863ADFA5844C64BA49786A5F1 (accessed on 6 November 2020). [39]

OECD (2010), *OECD Environmental Performance Reviews: Japan 2010*, OECD Environmental Performance Reviews, OECD Publishing, Paris, https://dx.doi.org/10.1787/9789264087873-en. [53]

OECD (2006), *Cost-Benefit Analysis and the Environment: Recent Developments*, OECD Publishing, Paris, https://dx.doi.org/10.1787/9789264010055-en. [124]

Ou, J. et al. (2020), "Role of export industries on ozone pollution and its precursors in China", *Nature Communications*, Vol. 11/1, pp. 1-12, https://doi.org/10.1038/s41467-020-19035-x. [29]

Ranum, P. et al. (2014), "Issue: Technical Considerations for Maize Flour and Corn Meal Fortification in Public Health Global maize production, utilization, and consumption", *Annals of the new York academy of sciences*, Vol. 1312/1, pp. 105-112, https://doi.org/10.1111/nyas.12396. [110]

Rao, S. et al. (2016), "A multi-model assessment of the co-benefits of climate mitigation for global air quality", *Environmental Research Letters*, Vol. 11/12, p. 124013, https://doi.org/10.1088/1748-9326/11/12/124013. [70]

Roh, M. et al. (2020), "Modeling Air Pollutant Emissions in the Provincial Level Road Transportation Sector in Korea: A Case Study of the Zero-Emission Vehicle Subsidy", *Energies*, Vol. 13/15, p. 3999, https://doi.org/10.3390/en13153999. [60]

Roy, R. and N. Braathen (2017), "The Rising Cost of Ambient Air Pollution Thus Far in the 21st Century: Results from the BRIICS and the OECD Countries", *OECD Environment Working Papers*, No. 124, OECD Publishing, Paris, https://doi.org/10.1787/19970900 (accessed on 26 April 2019). [123]

Roy, R. and N. Braathen (2017), "The Rising Cost of Ambient Air Pollution thus far in the 21st Century: Results from the BRIICS and the OECD Countries", *OECD Environment Working Papers*, No. 124, OECD Publishing, Paris, https://dx.doi.org/10.1787/d1b2b844-en. [113]

Screpanti, A. and A. De Marco (2009), "Corrosion on cultural heritage buildings in Italy: A role for ozone?", *Environmental Pollution*, Vol. 157/5, pp. 1513-1520, https://doi.org/10.1016/j.envpol.2008.09.046. [91]

Setti, L. et al. (2020), "Letter to the Editor SARS-Cov-2 RNA Found on Particulate Matter of Bergamo in Northern Italy: First Preliminary Evidence", *medRxiv*, p. 2020.04.15.20065995, https://doi.org/10.1101/2020.04.15.20065995. [90]

Shimadera, H. et al. (2015), "Performance comparison of CMAQ and CAMx for one-year PM2.5 simulation in Japan", *International Journal of Environment and Pollution*, Vol. 57/3-4, pp. 146-161, https://doi.org/10.1504/IJEP.2015.074498. [26]

Shin, D. et al. (2020), "Variations in Ozone Concentration over the Mid-Latitude Region Revealed by Ozonesonde Observations in Pohang, South Korea", *Atmosphere*, Vol. 11/7, p. 746, https://doi.org/10.3390/atmos11070746. [23]

Smith, S. et al. (2020), *The Energy Modeling Forum (EMF)-30 study on short-lived climate forcers: introduction and overview*, Springer Science and Business Media B.V., https://doi.org/10.1007/s10584-020-02938-5. [130]

Stanaway, J. et al. (2018), "Global, regional, and national comparative risk assessment of 84 behavioural, environmental and occupational, and metabolic risks or clusters of risks for 195 countries and territories, 1990–2017: a systematic analysis for the Global Burden of Disease Study 2017", *The Lancet*, Vol. 392/10159, pp. 1923-1994, https://doi.org/10.1016/s0140-6736(18)32225-6. [81]

The Korea times (2020), *$1.90 per 1kg: South Korea adopts emission charge for nitrogen oxides to curb fine dust*, https://www.koreatimes.co.kr/www/nation/2018/12/371_260863.html (accessed on 3 September 2020). [57]

Trnka, D. (2020), "Policies, regulatory framework and enforcement for air quality management: The case of Korea", *OECD Environment Working Papers*, No. 158, OECD Publishing, Paris, https://dx.doi.org/10.1787/8f92651b-en. [16]

UNEP (2019), *Air Pollution in Asia and the Pacific: Science-based Solutions*, https://www.ccacoalition.org/en/resources/air-pollution-asia-and-pacific-science-based-solutions-summary-full-report. [66]

UNEP (2010), *Protecting Arctic Biodiversity: limitation and strengths of environmental agreements*, https://wedocs.unep.org/handle/20.500.11822/7871 (accessed on 8 December 2020). [93]

Unger, N. et al. (2006), "Cross influences of ozone and sulfate precursor emissions changes on air quality and climate", *Proceedings of the National Academy of Sciences of the United States of America*, Vol. 103/12, pp. 4377-4380, https://doi.org/10.1073/pnas.0508769103. [33]

US EPA (2021), “Ozone Pollution, accessed on May 2021”, https://www.epa.gov/ozone-pollution (accessed on 27 August 2018). [98]

Van Dingenen, R. et al. (2018), “TM5-FASST: A Global Atmospheric Source–receptor Model for Rapid Impact Analysis of Emission Changes on Air Quality and Short-lived Climate Pollutants”, *Atmospheric Chemistry and Physics*, Vol. 18, pp. 16173-16211, https://doi.org/10.5194/acp-18-16173-2018. [13]

Van Dingenen, R. et al. (2009), “The global impact of ozone on agricultural crop yields under current and future air quality legislation”, *Atmospheric Environment*, Vol. 43/3, pp. 604-618, https://doi.org/10.1016/j.atmosenv.2008.10.033. [82]

Vrontisi, Z. et al. (2016), “Economic impacts of EU clean air policies assessed in a CGE framework”, *Environmental Science & Policy*, Vol. 55, pp. 54-64, https://doi.org/10.1016/j.envsci.2015.07.004. [119]

Walton, H. et al. (2015), *Understanding the Health Impacts of Air Pollution in London For: Transport for London and the Greater London Authority*, Title: TFL 90419 Task 5: Understanding the Health Impacts of Air Pollution in London, https://www.london.gov.uk/sites/default/files/HIAinLondon_KingsReport_14072015_final_0.pdf (accessed on 30 November 2020). [89]

Wang, B. et al. (2016), “Advances in Recycling and Utilization of Agricultural Wastes in China: Based on Environmental Risk, Crucial Pathways, Influencing Factors, Policy Mechanism”, *Procedia Environmental Sciences*, Vol. 31, pp. 12-17, https://doi.org/10.1016/j.proenv.2016.02.002. [76]

Wang, X. et al. (2014), “Impact of agricultural waste burning in the Shandong Peninsula on carbonaceous aerosols in the Bohai Rim, China”, *Science of the Total Environment*, Vol. 481/1, pp. 311-316, https://doi.org/10.1016/j.scitotenv.2014.02.064. [75]

Wang, X. et al. (1997), “Association between air pollution and low birth weight: a community-based study.”, *Environmental Health Perspectives*, Vol. 105/5, pp. 514-520, https://doi.org/10.1289/ehp.97105514. [87]

WHO (2013), *Health risks of air pollution in Europe – HRAPIE project. Recommendations for concentration-response functions for cost-benefit analysis of particulate matter, ozone and nitrogen dioxide*, World Health Organization, Regional Office for Europe, Bonn, Germany, https://www.euro.who.int/en/health-topics/environment-and-health/air-quality/publications/2013/health-risks-of-air-pollution-in-europe-hrapie-project.-recommendations-for-concentrationresponse-functions-for-costbenefit-analysis-of-particulate-matter,-ozone-and-nitrogen-dioxide (accessed on 30 November 2020). [88]

WHO (2005), *WHO Air quality guidelines for particulate matter, ozone, nitrogen dioxide and sulfur dioxide,*, http://apps.who.int/iris/bitstream/handle/10665/69477/WHO_SDE_PHE_OEH_06.02_eng.pdf;jsessionid=DFDA9BAE204770F4BA4490E3A309C33A?sequence=1. [21]

WHO (2004), *National burden of disease due to indoor air pollution*, World Health Organization, http://www.who.int/indoorair/health_impacts/burden_national/en/ (accessed on 9 November 2020). [38]

WHO (2000), *National Burden of Disease Estimates*, WHO Press, http://www.who.int/indoorair/publications/fuelforlife/ (accessed on 9 November 2020). [37]

Wild, O. (2007), *Atmospheric Chemistry and Physics Discussions*, http://www.atmos-chem-phys-discuss.net/7/1995/2007/ (accessed on 16 July 2020). [45]

World Bank (2020), *World development indicators - accessed on July 2020*. [64]

World Bank (2015), *World Development Indicators*, Washington, DC., https://data.worldbank.org/indicator. [118]

World Bank (2014), *Doing Business 2015: Going Beyond Efficiency*, The World Bank, https://doi.org/10.1596/978-1-4648-0351-2. [120]

Wu, F. and H. Guclu (2013), "Global Maize Trade and Food Security: Implications from a Social Network Model", *Risk Analysis*, Vol. 33/12, pp. 2168-2178, https://doi.org/10.1111/risa.12064. [109]

Xing, J. et al. (2011), "Projections of air pollutant emissions and its impacts on regional air quality in China in 2020", *Atmospheric Chemistry and Physics*, Vol. 11/7, pp. 3119-3136, https://doi.org/10.5194/acp-11-3119-2011. [68]

Yang, C. (2020), "Policies, regulatory framework and enforcement for air quality management: The case of China", *OECD Environment Working Papers*, No. 157, OECD Publishing, Paris, https://dx.doi.org/10.1787/7d1d1a82-en. [15]

Yang, G., Y. Liu and X. Li (2020), "Spatiotemporal distribution of ground-level ozone in China at a city level", *Scientific Reports*, Vol. 10/1, pp. 1-12, https://doi.org/10.1038/s41598-020-64111-3. [30]

Yim, S. et al. (2019), "Air quality and acid deposition impacts of local emissions and transboundary air pollution in Japan and South Korea", *Atmospheric Chemistry and Physics*, Vol. 19/20, pp. 13309-13323, https://doi.org/10.5194/acp-19-13309-2019. [52]

Young, P. et al. (2018), *Tropospheric ozone assessment report: Assessment of global-scale model performance for global and regional ozone distributions, variability, and trends*, University of California Press, https://doi.org/10.1525/elementa.265. [28]

Zhang, X., X. Bai and H. Zhong (2018), "Electric vehicle adoption in license plate-controlled big cities: Evidence from Beijing", *Journal of Cleaner Production*, Vol. 202, pp. 191-196, https://doi.org/10.1016/j.jclepro.2018.07.265. [62]

Zhang, X., X. Chen and X. Zhang (2018), "The impact of exposure to air pollution on cognitive performance", *Proceedings of the National Academy of Sciences of the United States of America*, Vol. 115/37, pp. 9193-9197, https://doi.org/10.1073/pnas.1809474115. [5]

Zhao, B. et al. (2013), "NOx emissions in China: historical trends and future perspectives", *Atmospheric Chemistry and Physics*, Vol. 13/19, pp. 9869-9897, https://doi.org/10.5194/acp-13-9869-2013. [69]

Zheng, B. et al. (2018), "Trends in China's anthropogenic emissions since 2010 as the consequence of clean air actions", *Atmospheric Chemistry and Physics*, Vol. 18/19, pp. 14095-14111, https://doi.org/10.5194/acp-18-14095-2018. [61]

Annex A. ENV-Linkages model and air pollution feedback modelling

Overview of the ENV-Linkages model

The OECD ENV-Linkages model is a dynamic multi-sectoral, multi-regional CGE model that links economic activities to energy and environmental issues. A more comprehensive model description is given in Chateau et al. (2014[11]). While ENV-Linkages can provide emission projections for greenhouse gases and air pollutants, for this report, emissions of air pollutants are provided by the GAINS model, based on ENV-Linkages' economic projections.

Production in ENV-Linkages is assumed to operate under cost minimisation with perfect markets and constant return to scale technology. The production technology is specified as nested constant elasticity of substitution (CES) production functions in a branching hierarchy. This structure is replicated for each output, while the parameterisation of the CES functions may differ across sectors. The nesting of the production function for the agricultural sectors is further re-arranged to reflect substitution between intensification (e.g. more fertiliser use) and extensification (more land use) of crop production, or between intensive and extensive livestock production. The structure of electricity production assumes that a representative electricity producer maximises its profit by using the different available technologies to generate electricity using a CES specification with a large degree of substitution. The structure of non-fossil electricity technologies is similar to that of other sectors, except for a top nest combining a sector-specific resource with a sub-nest of all other inputs. This specification acts as a capacity constraint on the supply of the electricity technologies.

Energy is a composite of fossil fuels and electricity. In turn, fossil fuel is a composite of coal and a bundle of the "other fossil fuels". At the lowest nest, the composite "other fossil fuels" commodity consists of crude oil, refined oil products and natural gas. The values of the substitution elasticities are chosen as to imply a higher degree of substitution among the other fuels than with electricity and coal.

The model adopts a putty/semi-putty technology specification, where substitution possibilities among factors are assumed higher with new vintage capital than with old vintage capital. In the short run, this ensures inertia in the economic system, with limited possibilities to substitute away from more expensive inputs. However, in the longer run, this implies relatively smooth adjustment of quantities to price changes. Capital accumulation is modelled as in the traditional Solow/Swan neo-classical growth model.

Household consumption demand is the result of static maximisation behaviour, which is formally implemented as an "extended linear expenditure system". A representative consumer in each region – who takes prices as given – optimally allocates disposal income among the full set of consumption commodities and savings. Savings are considered as a standard good in the utility function and do not rely on forward-looking behaviour by the consumer. The government in each region collects various taxes to finance government expenditures. Assuming fixed public savings (or deficits), the government budget is balanced through the adjustment of the income tax on consumer income. In each period, investment net-of-economic depreciation is equal to the sum of government savings, consumer savings and net capital flows from abroad.

International trade is based on a set of regional bilateral flows. The model adopts the Armington specification, assuming that domestic and imported products are not perfectly substitutable. Moreover, total imports are also imperfectly substitutable between regions of origin. Allocation of trade between partners then responds to relative prices at the equilibrium.

Market goods equilibria imply that, on the one side, the total production of any good or service is equal to the demand addressed to domestic producers plus exports; and, on the other side, the total demand is allocated between the demands (both final and intermediary) addressed to domestic producers and the import demand.

ENV-Linkages is fully homogeneous in prices and only relative prices matter. All prices are expressed relative to the numéraire of the price system that is arbitrarily chosen as the index of OECD manufacturing exports prices. Each region runs a current account balance, which is fixed in terms of the numéraire. One important implication from this assumption in the context of this report is that real exchange rates immediately adjust to restore current account balance when countries start exporting/importing emission permits.

As ENV-Linkages is a recursive-dynamic model and does not incorporate forward-looking behaviours, price-induced changes in innovation patterns are not represented in the model. However, the model does entail technological progress through an annual adjustment of the various productivity parameters in the model, including autonomous energy efficiency and labour productivity improvements. Furthermore, as production with new capital has a relatively large degree of flexibility in choice of inputs, existing technologies can diffuse to other firms. Thus, within the CGE framework, firms choose the least-cost combination of inputs, given the existing state of technology. The capital vintage structure also ensures that such flexibilities are larger in the long run than in the short run.

The sectoral and regional aggregation of the model, as used in the analysis for this report, are given in Table A.1 and Table A.2, respectively.

Table A.1. Sectoral aggregation of ENV-Linkages

Agriculture	Manufacturing
Paddy rice	Paper and paper products
Wheat and meslin	Chemicals
Other grains	Non-metallic minerals
Vegetables and fruits	Metals n.e.s.
Sugar cane and sugar beet	Fabricated metal products
Oil seeds	Other manufacturing
Plant fibres	Motor vehicles
Other crops	Electronic equipment
Livestock	Textiles
Forestry	
Fisheries	
Natural resources and energy	**Services**
Coal	Land transport
Crude oil	Air transport
Gas extraction and distribution	Water transport
Other mining	Construction
Petroleum and coal products	Trade other services and dwellings
Electricity (5 technologies*)	Other services (government)

Note: Fossil fuel based electricity: combustible renewable and waste based electricity; nuclear electricity; hydro and geothermal; solar and wind.
Source: ENV-Linkages.

Table A.2. Regional aggregation of ENV-Linkages

Macro regions	**ENV-Linkages countries and regions**
OECD America	Canada Chile Mexico United States
OECD Europe	EU large 4 (France, Germany, Italy, United Kingdom) Other OECD EU (other OECD EU countries) Other OECD (Iceland, Norway, Switzerland, Türkiye, Israel)
OECD Pacific	Oceania (Australia, New Zealand) Japan Korea
Rest of Europe and Asia	China Non-OECD EU (non-OECD EU countries) Russia Caspian region Other Europe (non-OECD, non-EU European countries)
Latin America	Other Latin-American countries
Middle East & North Africa	Middle-East North Africa
South and South-East Asia	India Indonesia ASEAN9 (other ASEAN countries) Other Asia (other developing Asian countries)
Sub-Saharan Africa	Other Africa (other African countries)

Source: ENV-Linkages.

The baseline economic trends are described in the recent *Global Material Resources Outlook to 2060* (OECD, 2019[77]). For the dynamic calibration of ENV-Linkages to 2050, macroeconomic projections are based on two long-run macroeconomic growth models. First, the growth scenarios result from simulations of the OECD Economics Department (Guillemette and Turner, 2018[117]). These projections cover 42 OECD and G20 countries up to 2060. Second, the ENV-Growth model, hosted at the OECD Environment Directorate, is used to complete these projections for countries not covered by the OECD's Economic Department. Together, macroeconomic projections are provided for almost 180 countries.

The baseline construction also reproduces specific sectoral trends for the energy and agricultural sectors. Energy system projections are calibrated to the *2018 World Energy Outlook* (IEA, 2018[65]) and they are fundamental to ensure that energy-related emissions reflect the latest energy trends.Modelling the economic feedbacks of air pollution in ENV-Linkages

Modelling the economic feedbacks of air pollution in ENV-Linkages

The economic feedbacks of air pollution are modelled directly in ENV-Linkages following a production function approach, as outlined in *The Economic Consequence of Outdoor Air Pollution* (OECD, 2016[8]). This means that market impacts directly affect specific elements in the economic system, such as labour productivity or land productivity. The impacts are thus modelled as changes in the most relevant parameters of the production function underlying the model structure.

Changes in ***health expenditures*** are implemented in the model as a change in demand for health services (in the model part of the aggregate non-commercial services sector). These health expenditures reflect costs related to treatments of the illnesses as well as hospital admissions. The additional health expenditures affect both households and government expenditures on healthcare. The distinction between households and government expenditures is based on World Bank data on the proportion of healthcare expenditures paid by households and by the government (World Bank, 2015[118]). Health expenditures caused by outdoor air pollution are calculated multiplying the number of cases for each illness (e.g. chronic bronchitis) with a corresponding unit cost value (e.g. the health expenditures linked to a case of chronic bronchitis), using a methodology similar to the cost of illness approach in which only the tangible healthcare costs are considered. The reference unit values for the healthcare costs used in this report for the OECD, which are outlined in Table A.3, are established based on existing studies, as elaborated in Holland (2014[102]). These representative OECD values are then adapted to individual countries, multiplying them by the ratio of each country's income and the average OECD income, for each year.

Table A.3. Unit values used to calculate healthcare costs

USD, 2017 PPP exchange rates

Effect	Value
Chronic bronchitis in adults (new cases)	15,810
Bronchitis in children (cases)	69
Equivalent hospital admissions (respiratory and cardiovascular diseases)	4,149

Note: Values are for the OECD. They are unit values and as such, they refer to costs per statistical life, case of illness, hospital admission and day with restricted activity.
Source: Own evaluation based on Holland (2014[102]).

Changes in ***labour productivity*** are directly implemented in the model as percentage changes in the regional productivity of the labour force. Productivity losses are calculated from lost work days, following the methodology used in Vrontisi et al. (2016[119]). This methodology calculates labour productivity losses as proportional to the number of lost work days, as compared to the average number of work days per year in each region (World Bank, 2014[120]).

Changes in ***crop yields*** are implemented in the model as a combination of changes in the productivity of the land resource in agricultural production, and changes in the total factor productivity of the agricultural sectors. This specification, which is in line with OECD (2015[121]), mimics the idea that agricultural impacts affect not only purely biophysical crop growth rates but also other factors such as management practices. Air pollution affects crop yields heterogeneously in different world regions, depending on the concentrations of ground-level ozone. Overall, the demand for agricultural products, which changes over time in the model even in the baseline scenario, is affected in each region by the air pollution-driven changes in crop yields.

Once the shocks from the air pollution impacts are incorporated in ENV-Linkages, the model finds a new equilibrium that takes into account the impacts of air pollution. Following the adjustment processes that takes place in the model, the direct impacts of air pollution also result in indirect impacts. For instance, an increased demand for healthcare may result in a lower demand for other services, while changes in crop yields for certain crops may result in changes in production of substitute crops or related economic activities (such as food production). These changes in production can then lead to changes in trade patterns.

Annex B. Methodology for calculation of mortality and morbidity endpoints and their valuation

This annex provides a detailed overview of the methodology used to create projections of health impacts of air pollution, including both mortality and morbidity, as well as their valuation in monetary terms. The first part explains the methodology used to calculate air pollution-related deaths linked with high concentrations of fine particulate matter, while the second part focuses on morbidity impacts. Finally, the last part presents the methodology used for the monetary valuation of mortality and morbidity impacts.

Mortality calculations

Following the Global Burden of Disease (GBD, 2018[106]), the total amount of air pollution-related deaths attributable to outdoor air pollution corresponds to the sum of the deaths due to each disease for which there is an increased risk due to outdoor air pollution of fine particulate matter and ground-level ozone. For $PM_{2.5}$, these illnesses are: ischemic heart disease (IHD), strokes, chronic obstructive pulmonary disease (COPD), lung cancer (LC), lower respiratory infection (LRI) and diabetes mellitus type 2 (DM). For ground-level ozone, the Global Burden of Disease (GBD, 2018[106]) indicates that exposure to increases the risk of deaths due to chronic obstructive pulmonary disease (COPD).

The mortality calculations for each disease is based on this formula:

i. $D_t^r = AF \cdot BD_r^t$

ii. $with$

iii. $AF = \left(1 - \frac{1}{RF}\right)$

Where deaths related to air pollution (*D*) are derived as the product between baseline deaths (*BD*) for each disease and the attributable fraction (*AF*), namely the fraction of baseline mortalities that can be associated with air pollution. The attributable fraction (*AF*) is derived as (1-1/*RF*), where *RF* is a disease-specific risk factor, which reflects how, for each disease, the risk of dying because of air pollution increases with higher concentrations of pollutants ($PM_{2.5}$ and ground-level ozone).

The calculations of the health risks (*RF*) linked with exposure to $PM_{2.5}$ used in this report rely on the GBD's Integrated Exposure-Response (IER) functions (Cohen et al., 2018[104]; Burnett et al., 2014[103]). These functions are non-linear and become flat at higher exposures. The formula contains various parameters, one of which is the zero risk threshold, which is set at 2.5 μg/m^3 concentrations of $PM_{2.5}$.

For ground-level ozone, the *RF* is based on the following formula:

$iv.$ $RF = e^{\ln\left(\frac{RR}{10}\right) * (Conc - Conc\ thr)}$

Where *Conc* is the concentration of ground-level ozone measure in part per billions (ppb), *Conc thr* is the zero risk threshold of ozone concentration and *RR* is the Relative Risk associated to ground-level ozone.

Following GBD (2018[106]), this study uses the seasonal average of daily maximum eight hours mean as the metric for ground-level ozone, the concentration threshold is flat at 29.1 ppm and at a relative risk of 1.06.

Baseline mortalities are obtained from the GBD results tool (GBD, 2018[106]). To create the projection for 2020-40 we use GBD foresight, which relies on GBD 2016 data (Institute for Health Metrics and Evaluation (IHME), 2018[107]). To avoid discontinuities between GBD 2016 foresight and GBD 2017 data after 2017, the foresight data were scaled with their respective GBD 2016 value in 2017; this correction factor was applied on all years beyond 2017. Therefore, the final foresight data in the current set differ slightly from the GBD 2016 foresight data because they were tuned to match the 2017 data from GBD 2017. For 2050, base mortalities are assumed equal to 2040 levels.

Baseline mortalities are obtained from the GBD results tool (GBD, 2018[106]). To create the projection for 2020-40 we use GBD foresight, which relies on GBD 2016 data (Institute for Health Metrics and Evaluation (IHME), 2018[107]). To avoid discontinuities between GBD 2016 foresight and GBD 2017 data after 2017, the foresight data were scaled with their respective GBD 2016 value in 2017; this correction factor was applied on all years beyond 2017. Therefore, the final foresight data in the current set differ slightly from the GBD 2016 foresight data because they were tuned to match the 2017 data from GBD 2017. For 2050, base mortalities are assumed equal to 2040 levels.

Morbidity impacts calculations

The morbidity impacts of $PM_{2.5}$ exposure that are quantified in this report are: the effect of chronic exposure on adult and childhood bronchitis, the effect of acute exposure on hospital admissions for respiratory and cardiovascular illness, restricted activity days, lost working days and asthma symptom days for children. The morbidity impacts for ground-level ozone are: the effect of acute exposure on hospital admissions for respiratory and cardiovascular illness and minor restricted activity days.

Quantifying morbidity effects requires detailed data, including the concentration response relationship, the size of population risk, and the prevalence of morbidity. However, this level of information is only available for a small number of countries. To obtain estimates at the global level, the morbidity impacts are extrapolated as a multiplier on mortality from air pollution exposure, based on the EU Clean Air Policy Package studies (Holland, 2014[102]; European Commission, 2013[122]). The advantage of assuming a linear relation between mortality and morbidity is that the calculation of morbidity automatically factors in the non-linearity in response functions that is accounted for in the mortality calculations. The drawback is that non-linearities are missed and that this approach cannot fully capture the connection between exposure to air pollution and illness.

The mortality-to-morbidity ratios are taken from the European Commission's Clean Air Policy Package studies (Holland, 2014[102]; European Commission, 2013[122]). The study by Holland (2014[102]) supplies region-specific morbidity-to-mortality ratios for the 28 European countries in which the package was implemented. To calculate morbidity impacts at the global level, for countries not covered by the Clean Air Policy Package studies, the average of the ratios of the European countries is used. While this extrapolation is not ideal, no data are available at the global level. This assumption is limiting, as it assumes that mortality-to-morbidity ratios throughout the world are similar to those of European countries. Furthermore, it implicitly assumes that healthcare provision is similar in all countries. For hospital admissions, it implies that European admission rates are typical of all other countries, when there is substantial variation around the world with respect to access to healthcare systems. This problem is particularly serious for developing countries, where access to healthcare is much lower. A similar issue arises with respect to lost working days. The European results are based on European rates of absenteeism, reflecting specific social welfare and employment conditions.

There are other limitations of the methodology used to calculate morbidity impacts in this report. Ideally, changes in behaviour (e.g. in diet, smoking habits, etc.), social changes (e.g. healthcare and employment) and medical changes (e.g. changes in healthcare systems and in treatment of diseases) over time and in different world regions should be explicitly factored into the analysis, but this is not possible owing to lack of data at the global level.

Valuation of the welfare costs of mortality and morbidity impacts

The valuation of the welfare costs of the health impacts of outdoor air pollution includes both mortality and morbidity. The total welfare costs are calculated by multiplying each impact considered (e.g. number of hospital admissions, cases of illness, and mortality) by estimates of the unit welfare cost of each impact (e.g. the welfare cost of a hospital admission, a case of illness, and a mortality).

Welfare costs of mortality

The welfare costs of air pollution-related mortality are obtained from a meta-analysis of a large number of studies of individuals' willingness to pay (WTP) for a marginal reduction in their risk of mortality over time. Aggregating the individual results of the various WTPs in the meta-analysis allows us to quantify the so-called Value of a Statistical Life (VSL), a long-established metric that attributes a monetary value to life and, as a consequence, can be used to estimate the welfare costs of mortality (OECD, 2014[101]; OECD, 2012[100]). As a result of this meta-analysis, the base VSL in OECD countries is USD 3 million (2005 PPP) per life lost in 2005.

As this report has global coverage, it was necessary to calculate VSL values for countries outside the OECD. This report relies on the OECD database "Mortality and welfare cost from exposure to environmental risks" (OECD, 2020[99]) for the base year value for each region of the study, since it provides country-specific VSL for OECD countries and emerging economies. Welfare costs in this database are calculated using a methodology adapted from Roy and Braathen (2017[123]).

Furthermore, since the report also considers economic projections, the VSL values need to be adapted over time. A previous OECD study (OECD, 2014[101]) provides a benefit transfer methodology to determine country-specific VSL values from an OECD reference value, based on country income differentials. The benefit transfer methodology is used to adapt VSL to individual countries, but also to estimate its growth over time, as income rises. As argued in OECD (2006[124]), income should be used as the reference variable to adapt WTP over time, so as to avoid situations in which the WTP to save a statistical life rises faster over time than the rate of inflation. Existing studies – such as Costa and Kahn (2004[125]), who calculate the VSL changes in the United States for the period 1940-80 – find that VSL rises over time as income rises. The country-specific income levels over time that are necessary for the calculations are obtained from the International Monetary Fund until 2017 (IMF, 2019[126]) and from the economic projections of the OECD's ENV-Growth model, which are also used for the calibration of the ENV-Linkages model.

The formula used to calculate the VSL is:

$$VSL_r^t = VSL_{OECD}^{2017}\left(\frac{Y_r^t}{Y_{OECD}^t}\right)^{\beta}$$

Where Y is the average income (GDP per capita) of country r in year t expressed in 2017 USD PPP; and β is the income elasticity of VSL. The income elasticity measures the percentage increase in VSL for a percentage increase in income.

The income elasticity used to calculate the country-specific VSL values is a key parameter; choosing different values can alter the results for welfare costs. The income elasticity variable assumes that as incomes rise, the WTP for a marginal reduction in the risk of death also rises, but not quite in proportion to the rise in incomes. The meta-analysis (OECD, 2012[100]) finds that the income elasticity is in the range of 0.7-0.9 for OECD countries, with significantly higher income elasticities for countries in the bottom 40th percentile of income. However the range proposed in OECD (OECD, 2012[100]) was considered to be too low for low-income countries as using such values would imply unrealistically high WTP values for these countries. Existing work on VSL (Hammitt and Robinson, 2011[127]; Roy and Braathen, 2017[123]) supports the assumption that the impact of income elasticity on the WTP does not necessarily hold true for emerging economies. Thus, following previous OECD work (OECD, 2016[8]) this report differentiates elasticity values by income group and uses a slightly higher elasticity for low-income countries. Specifically the income elasticities used are: 0.8 for high-income countries, 0.9 for middle-income countries and 1 for low-income countries (where country groups are distinguished using the World Bank income thresholds).

Given the difficulty in establishing the WTP to reduce the risks of mortality and the high dependency of the results on the key parameter value of income elasticity, the welfare costs results need to be interpreted in the context of the uncertainty surrounding the VSL values. An uncertainty analysis on the parameter values is provided in (OECD, 2016[8]).

While the VLS values are surrounded by uncertainty, a change in methodology would not affect the overall policy results of the analysis, which show high welfare costs associated with the deaths caused by outdoor air pollution.

Welfare costs of morbidity

The analysis of the health impacts of air pollution in this report distinguishes between two types of costs related to illness, as outlined in OECD (2016[8]):

i. The healthcare costs that are used to calculate healthcare expenditures as input to calculate the macroeconomic consequences of air pollution. Healthcare costs reflect the expenditures linked with each case of illness (e.g. the costs of hospital admissions, of going to the doctors or of buying medicines).

ii. Welfare costs of morbidity, which reflect the pain and suffering of each case of illness. In other words, welfare costs of morbidity reflect the disutility of illness.

The welfare costs of morbidity used here rely on previous work by the European Commission (Holland, 2014[102]), which provides unit values for the welfare costs of the morbidity impacts (Table B.1). Morbidity welfare costs are adjusted to specific countries based on income, using the benefit transfer methodology used for mortality. Although there is a bias in transferring estimates of the disutility of morbidity from existing studies, mostly developed in Europe, to the global context, the benefit transfer method is the only available technique in this context, since valuation studies on the welfare impacts of air pollution-related illnesses only exist for a few areas in the world.

Table B.1. Unit values used for the analysis of the welfare costs of morbidity

USD, 2017 PPP exchange rates

Effect	Value
Chronic bronchitis in adults (new cases)	74,526
Bronchitis in children (cases)	817
Equivalent hospital admissions (respiratory and cardiovascular diseases)	695
Restricted activity days	180
Minor restrict activity days (asthma symptom days)	58

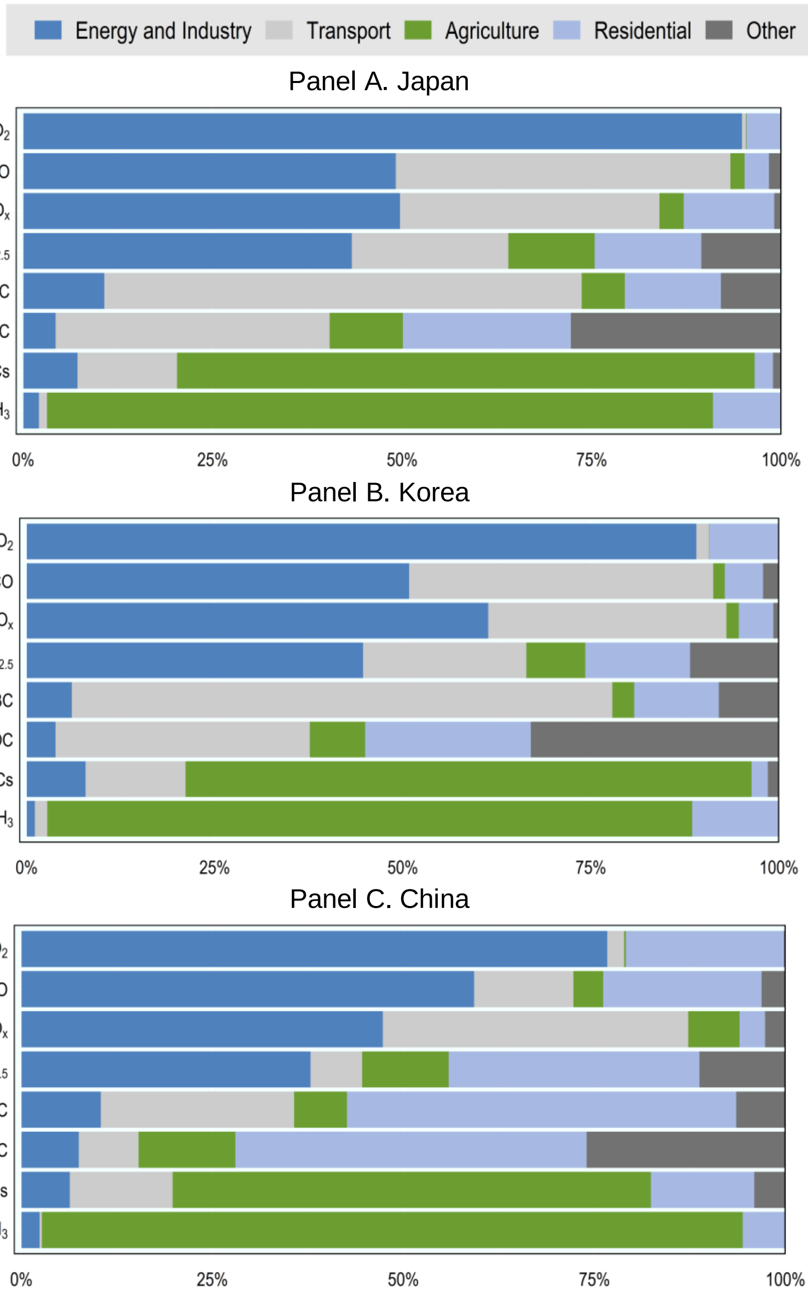
Note: Values are for the OECD. They are unit values and as such, they refer to costs per case of illness, hospital admission and day with restricted activity.
Source: Own evaluation based on Holland (2014[102]).

Annex C. Detailed results

Sectoral share in total emission of air pollutants by countries

Figure C.1. Sectoral share in total emission of air pollutants by Northeast Asian countries

Sectoral share, 2020

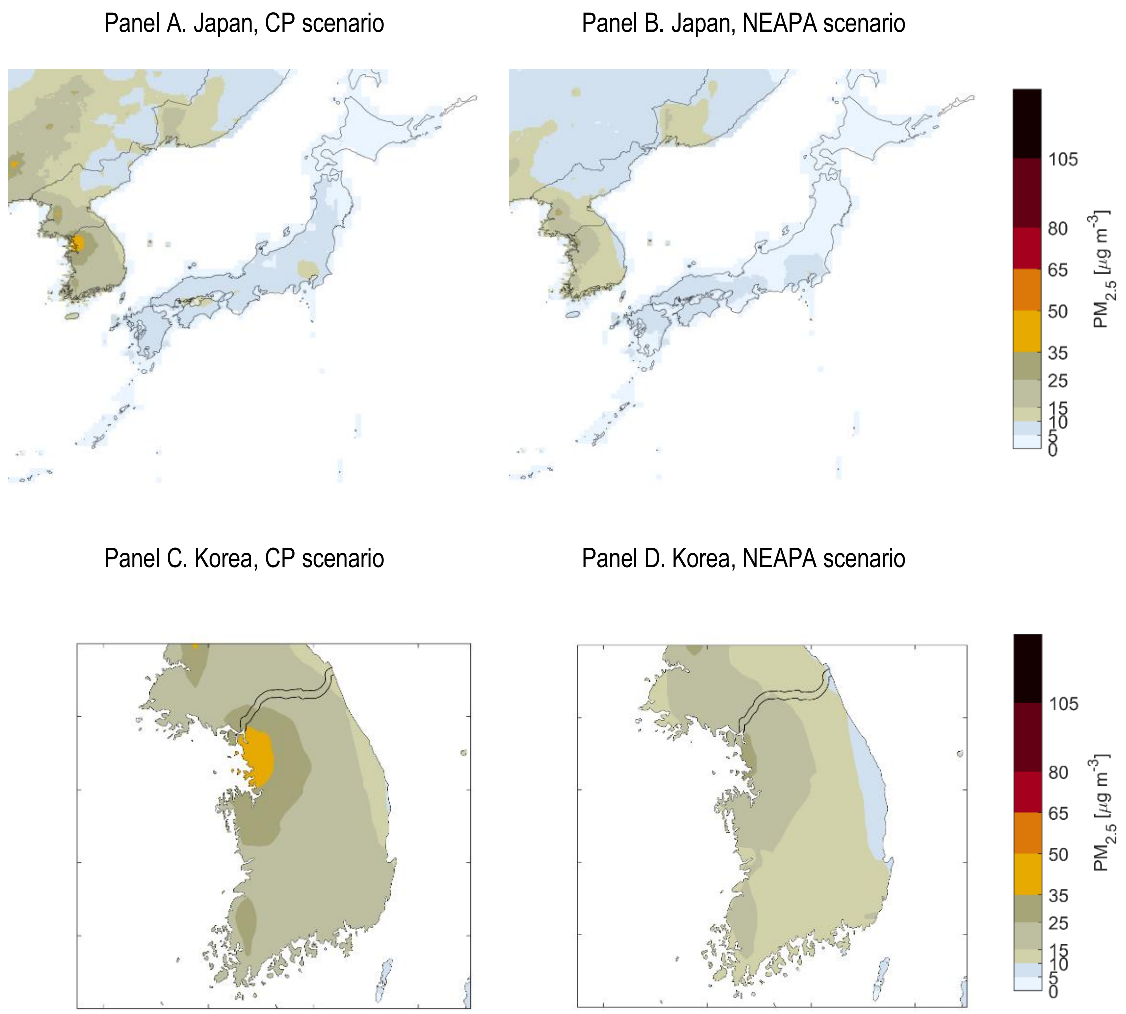


Note: 2020 values are estimates. "Other" includes emissions from the waste sector (except agricultural waste, which is included in "Agriculture".
Source: IIASA's GAINS model.

Concentration maps

Figure C.2. Projected concentrations of PM2.5 in Japan and Korea in the CP and NEAPA scenarios

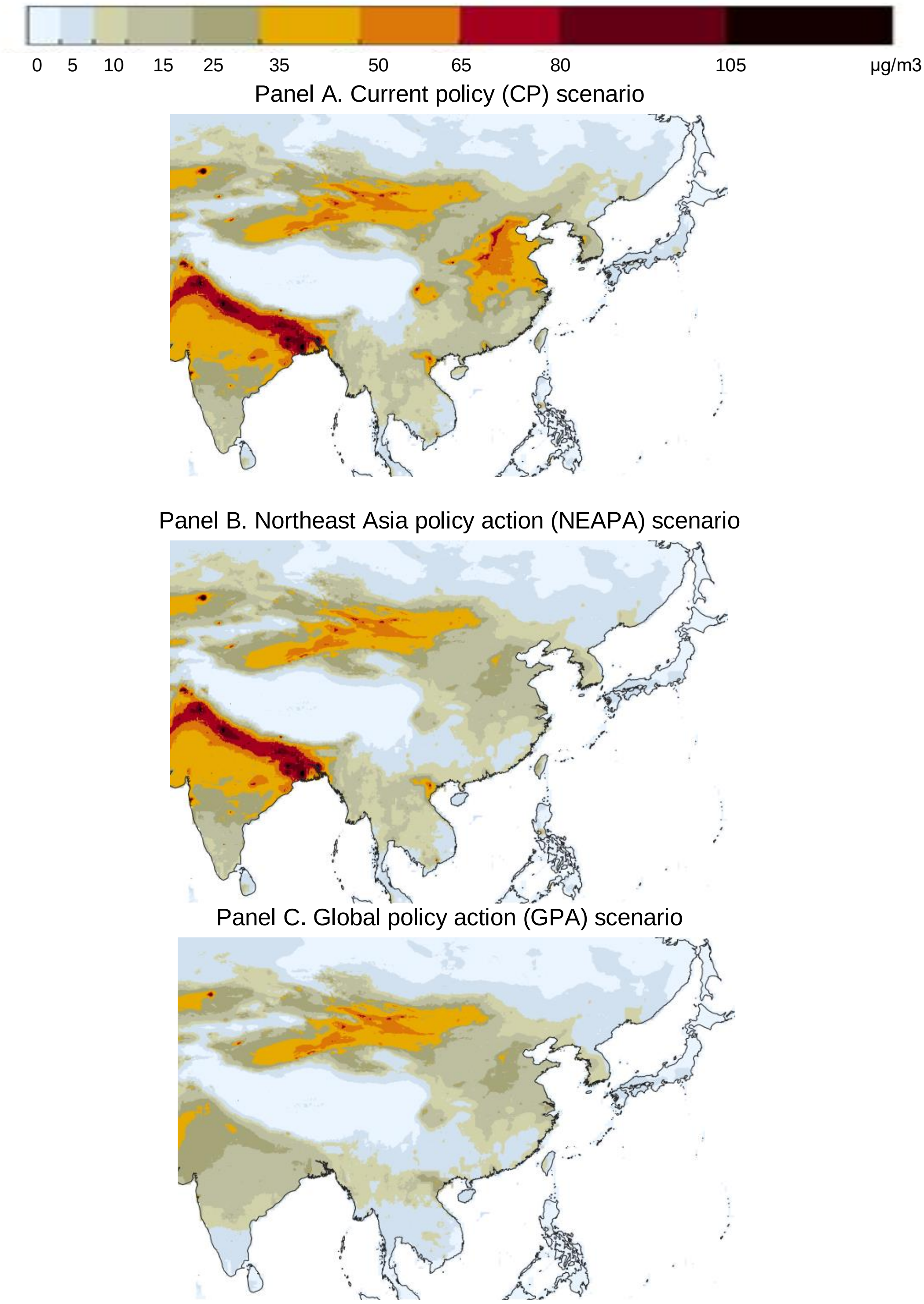
2050, Annual average anthropogenic $PM_{2.5}$ concentrations, µg/m^3



Note: In panel A and B, Eastern data is not presented due to lack of data.
Source: IIASA's GAINS model.

Figure C.3. Projected concentrations of PM2.5 in the extended Asian region

2050, Annual average $PM_{2.5}$ concentrations, µg/m^3



Source: IIASA's GAINS model.