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Achieving **clean air** for blue skies in Seoul, Incheon and Gyeonggi, Republic of Korea

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Abbreviations and acronyms

AMP	alternative maritime power
AP	air pollution
APCAP	Asia Pacific Clean Air Partnership
BC	black carbon
C	centigrade
CAPSS	Clean Air Policy Support System
cc	cubic centimetres
CCAC	Climate and Clean Air Coalition
CFC	chlorofluorocarbon
CH_4	methane
CLRTAP	Convention on Long-Range Transport of Air Pollution
CN	carbon neutrality
CNC	Carbon Neutrality and Green Growth Commission
CNG	compressed natural gas
CO	carbon monoxide
CO_2	carbon dioxide
CO_2eq	carbon dioxide equivalent
EANET	Acid Deposition Monitoring Network in East Asia
EEA	European Environment Agency
e.g.	*exempli gratia* (for example)
EMEP	European Monitoring and Evaluation Programme
ESG	Environmental, Social and Governance
EU	European Union
GDP	gross domestic product
GHG	greenhouse gas
GRDP	gross regional domestic product
GW	gigawatt
HCFC	hydrochlorofluorocarbon
HFC	hydrofluorocarbon
HNO_3	nitric acid
H_2SO_4	sulphuric acid
IBC	Integrated benefits calculator
i.e.	*id est* (that is)
IPCC	Intergovernmental Panel on Climate Change
K-ETS	Korean emissions trading scheme
KAC	Korea Airport Corporation
KEA	Korea Energy Agency
KEPCO	Korea Electric Power Corporation
kg	kilogram
km	kilometre
km^2	square kilometre
KNOC	Korea National Oil Corporation
KOSIS	Korea Statistical Information Service
KOTEMS	Korea Transport Emission Management System
KPX	Korea Power Exchange
KRW	Republic of Korea won
LEAP	Low Emissions Analysis Platform
LNG	liquified natural gas
LPG	liquified petroleum gas
LTO	landing and take-off
m^3	cubic metre
MRV	monitoring, reporting and verification
Mt	million tonnes
MWh	megawatt hour
µm	micrometre
N	nitrogen
NAIRC	National Air Emission Inventory and Research Center
NASA	National Aeronautics and Space Administration
NDC	nationally determined contribution
NEASPEC	Northeast Asian Sub-regional Programme for Environmental Cooperation
NETIS	National Greenhouse Gas Emission Total Information System
NF_3	nitrogen trifluoride

NFR	Nomenclature for Reporting
NH_3	ammonia
NH_4NO_3	ammonium nitrate
$(NH_4)_2SO_4$	ammonium sulphate
$(NH_4)_3PO_4$	ammonium phosphate
NLIC	National Logistics Information Center
NMVOC	non-methane volatile organic compounds
NO	nitrogen oxide
NO_X	nitrogen oxides
N_2O	nitrous oxide
O_3	ozone
P	phosphorus
Pb	lead
PFC	perfluorocarbon
pm	*post meridiem* (after midday)
PM	particulate matter
$PM_{2.5}$	fine particulate matter with a diameter of 2.5 µm or less
PM_{10}	coarse particulate matter with a diameter of 10 µm or less
POP	persistent organic pollutant
ppb	parts per billion (10^9)
ppm	parts per million
RV	recreational vehicle
S	sulphur
SDG	Sustainable Development Goal
SF_6	sulphur hexafluoride
SIG	Seoul, Incheon and Gyeonggi
SLCP	short-lived climate pollutant
SMR	Seoul Metropolitan Region
SMS	seasonal management system (for reductions of particulate matter)
SO_2	sulphur dioxide
SO_X	sulphur oxides
TOE	tonnes of oil equivalent
TSP	trisodium phosphate
TW	terawatt
TWh	terawatt hours
UNEP	United Nations Environment Programme
UNFCCC	United Nations Framework Convention on Climate Change
USD	United States dollars
VOC	volatile organic compounds
WHO	World Health Organization

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Road transport in Seoul.
© Unsplash/MJ Haru

Executive summary

Seoul, Incheon and Gyeonggi (SIG) are three regions covering more than 12 000 square kilometres (km^2) in the northwest of the Republic of Korea with a population of 26 million people, making them collectively one of the largest metropolitan areas in the world. According to the World Bank, the region accounted for 48 per cent of the Republic of Korea's gross domestic product (GDP) in 2016. The large population and economic activity in SIG have driven increases in transport, industry, waste generation, electricity production and other activities that can result in air pollutant emissions. As a result, 15 years ago concentrations of the most health-damaging air pollutants, such as particulate matter (PM), were far in excess of national standards and World Health Organization (WHO) Air Quality Guidelines. Over the last 15 years, air pollution levels in SIG have reduced substantially due to a combination of a robust policy and governance framework for air quality in the regions, the implementation of air pollutant emission reduction measures and through the reductions of emissions in areas from which air pollutants emissions are transported to SIG.

Many other regions of the world are currently grappling with air pollution levels that substantially affect the health of their citizens. Globally, almost everyone is exposed to air pollution levels in excess of WHO Air Quality Guidelines, resulting in both millions of premature deaths and non-fatal health impacts every year. Understanding how regions can put in place robust air quality management systems, understand the magnitude of the air pollution problem, what action should be taken to reduce it, how to pay for this and how its effectiveness can be monitored is crucial if more people are to enjoy clean air. This report, therefore, aims to support efforts to address urban air pollution in Asia and the Pacific by sharing solutions and lessons learned in SIG to tackle air pollution and protect people's health. This will be achieved by documenting the progress that has been made in SIG to reduce air pollution between 2005 and 2020, and how SIG was able to reduce air pollutant concentrations within its boundaries, implement specific mitigation policies and measures, and develop tools and processes to track progress on air pollution. The report will also evaluate how air pollutant emissions within SIG could be further reduced

Scenery of Seoul
© Seoul Metropolitan Government

by 2050. The report outlines key highlights of how SIG has tackled air pollution over the past decades and provides recommendations as to how air quality can continue to improve in the future, including the following.

A robust legal framework governing Seoul, Incheon and Gyeonggi has been put in place and adequately funded for implementation

The first section of this report outlines the status of air pollution between 2005 and 2020. In terms of the regulatory framework, air quality in SIG is governed by three levels of planning and policy making. At the national scale, a **Governing Act** provides an overarching framework for a particular issue. Next, also at the national scale, a **Basic Plan** provides an overview of how the Act will be implemented at the national scale. Finally, at the regional scale, an **Implementation Plan** outlines how the goals of the Act will be implemented in each region, taking the regional priorities and/or contexts into account. This framework has led to substantial action being taken on air pollution in SIG between 2005 and 2020. Firstly, air quality management in the region has been substantially financed, with USD 9 billion invested between 2007 and 2020 across all three regions. This investment has allowed for the effective implementation of mitigation measures in SIG, and 56 per cent of the total investment has been made in the implementation of measures to reduce emissions from the transport sector.

Long-term data on air pollution in Seoul, Incheon and Gyeonggi are publicly available

The investment has resulted in SIG having one of the most studied air quality in the world. A dense monitoring network of air quality stations allows comparison with national air quality standards. There is also an emissions inventory for SIG showing the contributions of different sources that highlights priorities for mitigation. This shows that, as a result of these investments and reductions in air pollutant emissions beyond SIG, there have been substantial improvements in air quality over the past decades, with, for example, annual average coarse particulate matter (PM_{10}) concentrations 30–40 per cent lower in 2021 compared to 2005 levels. Air pollutant emissions in SIG have also substantially reduced, particularly from major sources such as road transport, for which PM_{10} emissions were 73 per cent lower in 2019 compared to 2005 levels. The regular reporting of robust scientific data on air pollutant concentrations and emissions allows these trends to be assessed.

Over the past 15 years, reductions in air pollution have not been achieved alongside reductions in greenhouse gases

There is a substantial opportunity to reduce air pollution and greenhouse gas (GHG) emissions simultaneously, due to their overlapping sources and because there is a suite of mitigation measures which is effective at simultaneously reducing both in SIG. However, reductions in air pollutant emissions between 2005 and 2020 were mainly achieved through the implementation of technical mitigation measures that targeted specific air pollutants but do not also reduce GHGs. This report shows that in the Republic of Korea over the same period (2005–2020) primary fine particulate matter ($PM_{2.5}$) emissions have fallen by 19 per cent but carbon dioxide (CO_2) emissions have increased by 26 per cent. Carbon dioxide emissions have also increased in Incheon, +7 per cent, and Gyeonggi, +11 per cent, in contrast to the trend in the majority of air pollutants. In Seoul, CO_2 emissions have fallen by 14 per cent, but this reduction is far smaller than those for the majority of air pollutants, which have reduced by as much as 89 per cent.

In the future, implementation of climate change plans across regions could also contribute to further reductions in local air pollution

Mitigation measures in the Republic of Korea's carbon neutrality plans, such as the electrification of the vehicle fleet, stringent energy efficiency measures and switching to cleaner fuels in industry, not only reduce GHGs and contribute to achieving the Republic of Korea and SIG's climate change targets but also reduce air pollutant emissions in the three regions. If all carbon neutrality policies and measures modelled for this Assessment were fully implemented by 2050, the national total CO_2 emissions would fall by almost 90 per cent compared to a baseline scenario, with similar emissions reductions for CO_2 estimated for SIG. According to the model, $PM_{2.5}$ emissions would also be reduced by almost 80 per cent in Seoul, more than 85 per cent in Incheon and almost 60 per cent in Gyeonggi in 2050 compared to the baseline scenario. Other

The experience in SIG demonstrates that improving air quality in a densely populated megacity in Asia is possible but requires substantial focus and investment in order for these benefits to be realized.

pollutants, whose major sources overlap even more than CO_2 would be reduced to an even greater extent – the modelling shows that emissions of nitrogen oxides (NO_X) would be reduced by more than 75 per cent in Seoul and over 80 per cent in Incheon and Gyeonggi.

Major air pollutant sources remain; if they are to be reduced additional policies and measures will need to be implemented

The carbon neutrality (CN) scenario evaluated in this assessment focuses on the major sources of CO_2 emissions. Other major sources of air pollutant emissions that remain after the CN measures are implemented include the **non-road transport sector**. This includes machinery used in construction, agriculture and other industries, and while some policies and measures were put forward to reduce emissions, such as the electrification of non-road vehicles, there is potential to identify more measures to further decrease emissions from these sources. Finally, one key contributor to $PM_{2.5}$ concentrations in SIG has not been targeted either by air pollutant mitigation measures historically, or through the CN policies and measures. **Ammonia** (NH_3), which is predominantly emitted from agriculture through the application of synthetic and organic fertilisers, makes a substantial contribution to the formation of $PM_{2.5}$ in the atmosphere, and significantly impacts the magnitude of $PM_{2.5}$ concentrations in SIG. Previous research has emphasized the necessity for NH_3 emissions controls to improve air quality across the Republic of Korea. However, the implementation of the measures included in this Assessment only reduce total national NH_3 emissions by 1.2 per cent in 2050 compared to a baseline scenario. In Gyeonggi, the only region in SIG with significant agriculture, NH_3 emissions are reduced only by around 3 per cent; hence there is a need to identify further air pollution reduction and gender-responsive policies and measures which could reduce this pollutant that is not currently considered within the air quality management frameworks in SIG.

Improving air quality is a key priority for improving human health globally, but currently many countries, cities and regions lack the regulatory framework, scientific underpinning and resourcing necessary to implement mitigation action that leads to reductions in air pollution and benefits human health. The experience in SIG demonstrates that improving air quality in a densely populated megacity in Asia is possible but requires substantial focus and investment in order for these benefits to be realized.

Finally, air pollution in SIG is at a crossroads in terms of the policies and measures that have led to the substantial improvements seen over the past decades, and how it can be further improved in the future. Like many other regions, past improvements in air quality have been achieved through pollutant-specific mitigation measures, and reductions in air pollution have not been achieved alongside reductions in GHGs. For the future, however, policies and measures have been identified which could allow SIG to deal with air pollution and climate change together. As other regions consider how to alleviate their own air quality issues, maximizing the multiple benefits from the action taken can help ensure the broadest possible support for their implementation.

Paldalmun Gate, Hwaseong Fortress, Suwon City, Gyeonggi (UNESCO World Heritage Site).
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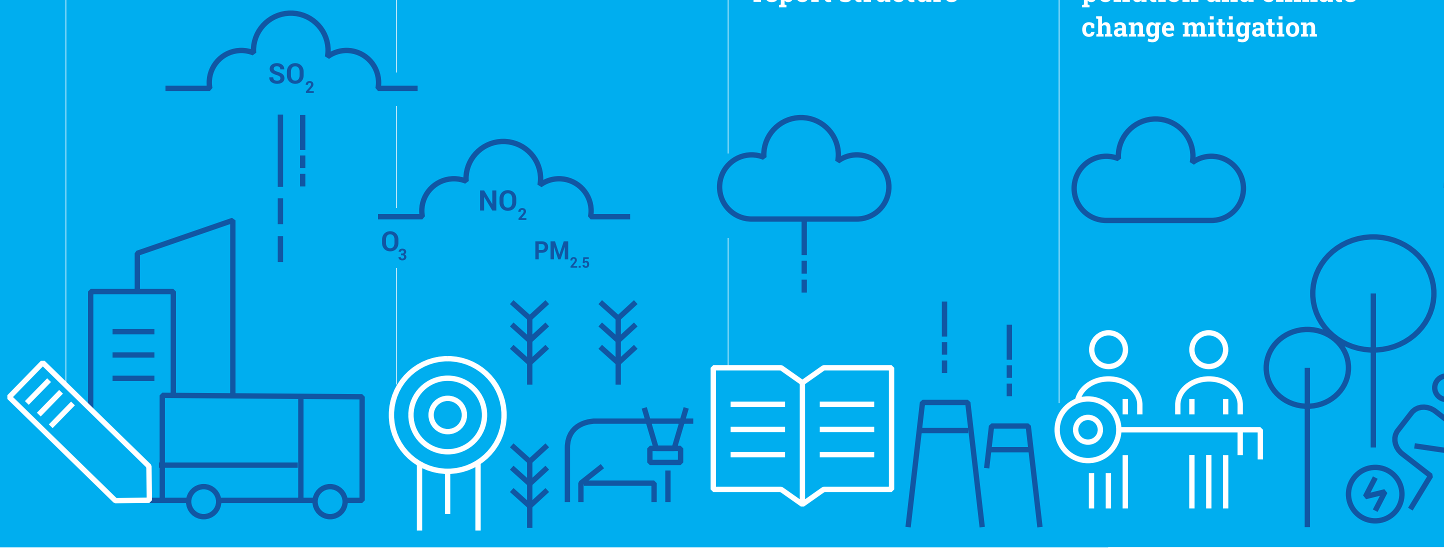
Introduction



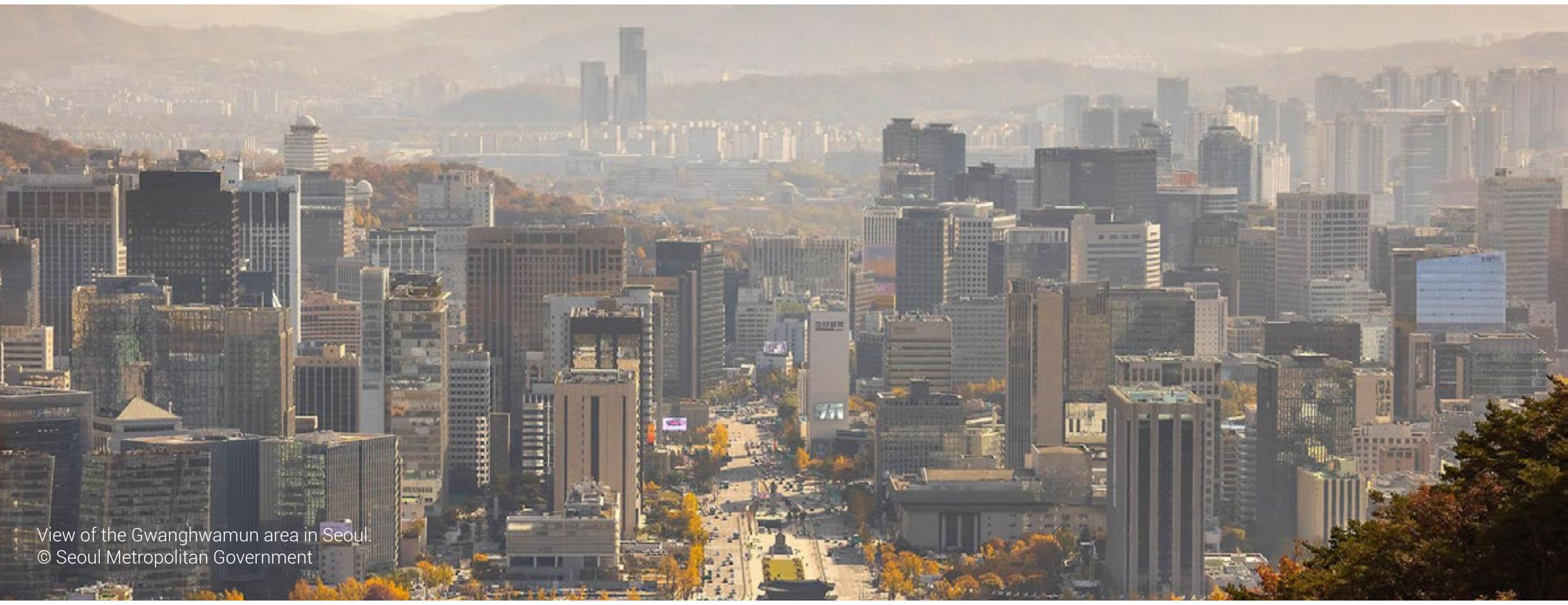
Air pollution is one of the world's largest environmental risk factor for human health and globally contributes to 6.5 million premature deaths per year (Murray *et al.* 2020). This is driven by the increase in the risk of people developing respiratory, cardiovascular and other diseases, including cancers, as a result of exposure to elevated to elevated levels of air pollution (WHO 2021).

1.1 Background

Air pollution is the world's largest environmental risk factor for human health and globally contributes to 6.5 million premature deaths per year (Murray *et al.* 2020). This is driven by the increase in the risk of people developing respiratory, cardiovascular and other diseases, including cancers, as a result of exposure to elevated levels of air pollution (WHO 2021). This exposure can also result in substantial numbers of non-fatal health outcomes, including hospitalizations for respiratory and cardiovascular diseases, the exacerbation of asthma and adverse pregnancy outcomes (Malley *et al*. 2017; Anenberg *et al*. 2018).

Air pollution makes such a substantial contribution to global health burdens because of the near universal exposure of people to levels that are potentially damaging to human health. Unfortunately, 99 per cent of the world's population is exposed to levels of fine particulate matter ($PM_{2.5}$) air pollution that are above the World Health Organization (WHO) Air Quality Guidelines[1] for the protection of human health (WHO 2021). While almost everyone is exposed to health-damaging levels of air pollution, it is often low socioeconomic communities and women who are exposed to the highest levels of air pollution, as a result of their proximity to major air pollution sources, such as industry or cookstoves (Malley *et al*. 2020).

Reducing air pollution exposure, and the negative health effects attributable to it, is complicated by the myriad of sources, sectors and activities that emit health-damaging air pollutants, and the complex physical and chemical processing of pollutants once they are emitted to the atmosphere (Fuzzi *et al*. 2015; Monks *et al*. 2015). This latter consideration means that the air pollution an individual is exposed to in a particular location may result from a combination of pollutants emitted from a nearby source and pollutants emitted a long way away, which have been transported, and may have reacted chemically to form a different pollutant from that which was emitted. The two pollutants most associated with health burdens are $PM_{2.5}$ and ground-level ozone (O_3). They provide two examples of the complexity in the chain of emissions, concentrations, population exposure and associated negative health effects. Particulate matter consists of solid particles suspended in the atmosphere that are made up of multiple chemical constituents, including particles that are directly emitted into the atmosphere (primary PM), and particles that are formed in the atmosphere from



View of the Gwanghwamun area in Seoul.
© Seoul Metropolitan Government

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[1] WHO global air quality guidelines: particulate matter ($PM_{2.5}$ and PM_{10}), ozone, nitrogen dioxide, sulfur dioxide and carbon monoxide. Executive summary 2021. https://apps.who.int/iris/bitstream/handle/10665/345334/9789240034433-eng.pdf?sequence=1&isAllowed=y

gaseous precursor pollutant emissions (secondary PM), including nitrogen oxides (NO_X), sulphur dioxide (SO_2), ammonia (NH_3), and volatile organic compounds (VOC) (Heal *et al.* 2012). Particulate matter has an atmospheric lifetime of a few days, meaning it can be transported hundreds of kilometres and impact air quality in locations that are relatively far from the emissions' source. Ground-level O_3 is formed in the atmosphere from the photochemical reaction of NO_X with VOCs, methane (CH_4) and carbon monoxide (CO). Once formed, O_3 has a lifetime of about three weeks, meaning it can be transported around the globe and impact air quality on different continents (Royal Society 2008; Monks *et al.* 2015).

As there are multiple sources that emit the air pollutants that contribute to $PM_{2.5}$ and O_3 concentrations to which people are exposed, policies and measures need to be implemented across multiple sectors. These include road, rail, air transport and shipping; households; industry; electricity generation; oil, gas and coal production; agriculture including the burning of vegetation; and waste management (IEA 2016). The policies and measures that can and have been implemented to control emissions from these sectors also vary and include technological changes, such as the implementation of emissions control technologies on vehicles, to meet, for example, Euro standards[2]; fuel switching from, for instance, cooking using biomass cookstoves to cleaner fuels such as liquefied petroleum gas (LPG) or electricity; or behavioural change, such as avoiding burning agricultural residues. Many of these policies and measures have low or negative costs and contribute to achieving development priorities, including economic growth, sustainable energy use, sustainable cities, etc. (Haines *et al.* 2017; UNEP 2019a).

Despite progress having been made in improving air quality through the implementation of policies and measures in major source sectors, in many regions, countries and cities, air pollution, and the health impacts resulting from it, have increased over the last decades. In particular, cities in Asia are disproportionally impacted by air pollution. According to an assessment of the impact of air pollution on the world's cities, millions of premature deaths per year occur in major cities in Asia. Indeed, cities in Asia were estimated to have the highest death rates associated with exposure to $PM_{2.5}$ concentrations, with median urban deaths rates of 106, 86 and 78 per 100 000 people in East, South and Central Asia respectively (Anenberg *et al.* 2019).

Therefore, one of the most effective health interventions across Asian cities, and other cities worldwide, is the implementation of policies and measures that reduce exposure to air pollution by reducing emissions from major source sectors.

Seoul, Incheon and Gyeonggi (SIG) are three administrative areas located in the northwest of the Republic of Korea. Seoul and Incheon are designated as Special and Metropolitan cities, while Gyeonggi is a province. While they are separately administrated, SIG together make up a metropolitan area of 26 million people, the fifth largest metropolitan region in the world. Air pollution over the last two decades in SIG has improved substantially, providing a practical example of how the implementation of national and sub-national policies and measures can achieve real improvements in concentrations of and exposure to air pollution. Substantial health burdens in SIG, however, remain due to continued exposure to levels of air pollution that are damaging to human health. According to analysis by the Health Effects Institute, population-weighted $PM_{2.5}$ concentrations in Seoul are 27.16 micrometre per cubic metre ($\mu g/m^3$) and result in 9 000 premature deaths per year, or 40 deaths per 100 000 people (Health Effects Institute 2020; Health Effect Institute 2022).

The metropolitan area that includes SIG, therefore, provides a useful case study of how air quality management can be effective in achieving air pollution reductions, due to the progress made over the past decades. Simultaneously, it also provides an example of a metropolitan area in which further progress in reducing air pollution is needed to protect the health of its citizens.

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[2] European Union emission regulations for new light duty vehicles—including passenger cars and light commercial vehicles (LCV). https://dieselnet.com/standards/eu/ld.php

This report aims to support efforts to address urban air pollution in Asia and the Pacific by sharing solutions and lessons learned in Seoul, Incheon and Gyeonggi to tackle air pollution and protect people's health.

1.2 Aims and goals

Aims

This report aims to support efforts to address urban air pollution in Asia and the Pacific by sharing solutions and lessons learned in SIG to tackle air pollution and protect people's health. This will be achieved by documenting the progress made in reducing air pollution in SIG between 2005 and 2020, evaluating how air pollutant emissions could be further reduced by 2050 and demonstrating how SIG was able to reduce concentrations of air pollutants within its boundaries by implementing specific policies and measures to reduce emissions, and developing a sophisticated set of tools and processes to track progress on air pollution in the region.

To achieve the report's overall goals, it had the following sub-objectives:

- to assess existing information on changes in air pollutant emissions, concentrations and health impacts between 2005 and 2020;
- to present the results of a new integrated assessment of air pollutants, short-lived climate pollutants (SLCPs) and greenhouse gas (GHG) emissions in SIG for 2005–2020 and baseline projections for 2021–2050;
- to evaluate how the implementation of specific policies and measures could reduce air pollutant emissions in SIG in the future, including reductions that could occur through the achievement of the Republic of Korea's CN goal for 2050;
- to provide a concrete set of recommendations on how SIG could further strengthen air quality management in each area and implement the priority mitigation measures that achieve the largest reduction of future emissions.

Target audience

The report aims to inform two specific audiences. Firstly, it provides specific recommendations on how air pollution in SIG could be reduced in the future for local policy and decision makers. The second target audience is policy and decision makers who are working on developing and implementing policies and strategies to address urban air pollution in other cities, regions and countries.

Scope

This assessment of the ability to track progress on air pollution within SIG includes consideration of its air quality monitoring networks and emission inventories that show progress on the magnitude and contribution of emissions from all major source sectors within the three areas and across the Republic of Korea. The assessment's geographic scope is the Seoul Metropolitan Government, the Incheon Metropolitan City and the Gyeonggi Provincial Government, referred to as SIG.

The area of the National Assembly Building in Yeouido, Seoul.
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Directly reducing emissions from their sources is the most widely adopted and most beneficial to the population way of achieving air quality goals.

1.3 Assessment framework and report structure

Multiple frameworks have been put forward for the assessment of air pollution in particular geographic locations, some of which focus on a subset of air pollutant characteristics, such as emissions, concentrations or impacts. To provide the most comprehensive overview of historic changes in air pollution and future opportunities to reduce it further, the framework for assessing air pollution in SIG in this report encompasses a four-part air pollution chain (Figure 1).

The components of the chain starts with **emissions**, that is, the initial release of air pollutants into the atmosphere from human and natural sources. Once released, these pollutants are present in the atmosphere in varying **concentrations** at different locations, determined by atmospheric transport, chemical reactivity and physical processes. After concentrations, **exposure** is the concentration of air pollutants that people breathe over a period of time, which, finally, can result in negative health **impacts**. These four components of the air pollution chain are relevant for different facets of air quality management and, therefore, provide a variety of perspectives on how air pollution has changed and could change further in SIG in the future.

The health impacts of air pollution are often the driving force and underlying reason behind decisions to implement action to reduce it, thereby protecting and enhancing people's health. The health impacts may also have an economic impact which also motivate policy makers to take action. It is, however, often most practical to measure the concentrations of air pollutants in the atmosphere, rather than health impacts directly. Overarching air quality goals are, therefore, often expressed as limits on the concentrations of air pollutants in the atmosphere, as these can be monitored and tracked over time, to assess, for example, compliance with legal air quality standards. Finally, while interventions can be implemented which reduce exposure to air pollution without reducing it, such as wearing a mask, installing indoor air filters or changing travel routes away from major roads, directly reducing emissions from their sources is the most widely adopted, and most beneficial to the population approach to achieving air quality goals. Policies and measures to reduce emissions are, therefore, the activities that decision makers can take to achieve air pollution goals. The emission sources and the geographic location of emission reductions play important roles in determining the impacts of policies and measures in reducing air pollutant concentrations and health impacts.

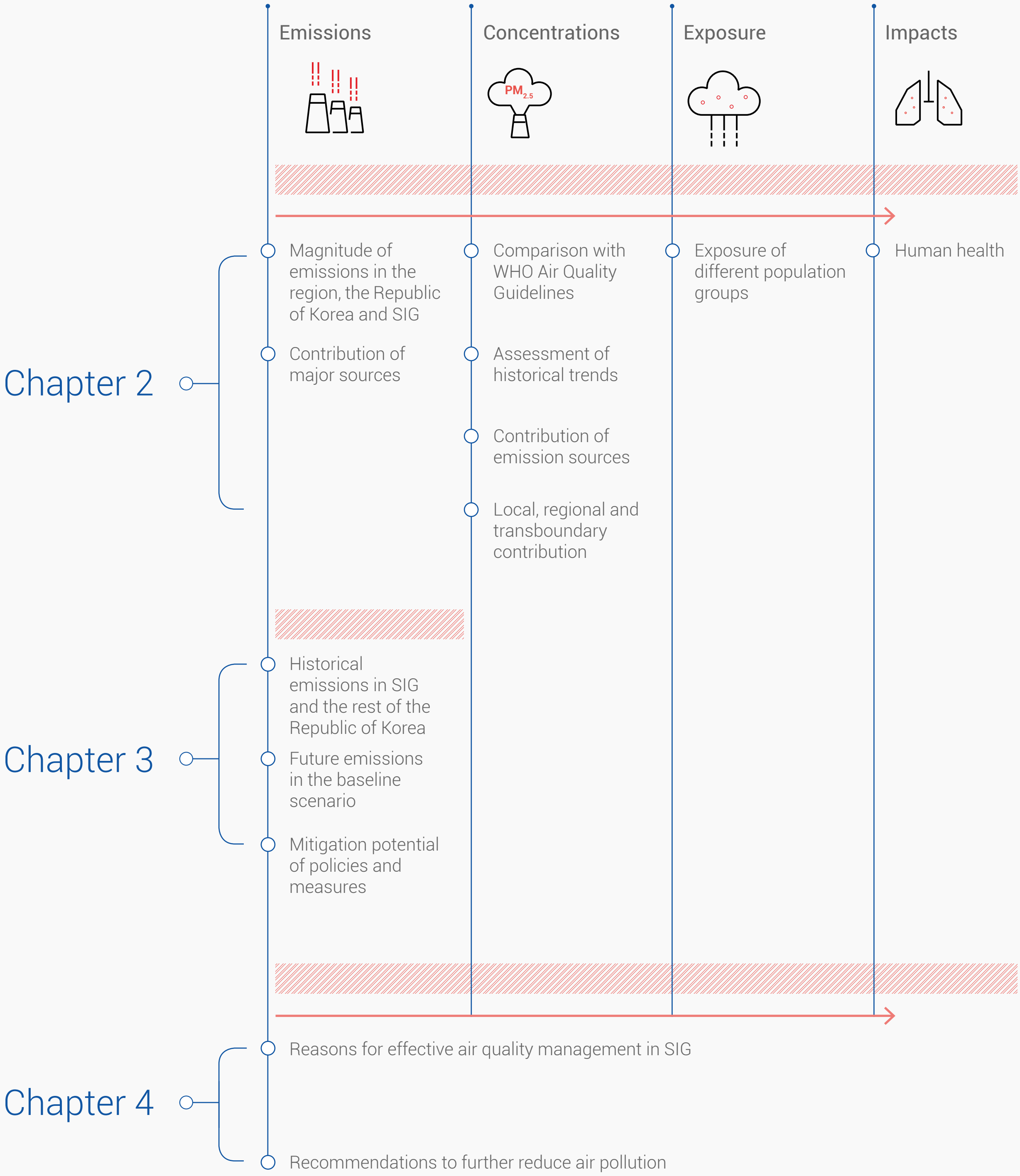
Sihwa Lake Tidal Power Plant, Ansan City, Gyeonggi.
© Gyeonggi Provincial Government

The report attempts to achieve its goal of documenting progress in SIG in reducing air pollution and evaluating future strategies for further reductions through the lens of the four components of the air pollution chain Figure 1.1.

As a whole, the report aims to provide an assessment of changes in health impacts, atmospheric concentrations and emissions. The three main chapters of this report are distinguished by the methods used to assess air pollution, and focus on particular facets of the air pollution chain in SIG.

Chapter 2: The state of air pollution in Seoul, Incheon and Gyeonggi has been developed through a review of existing information from reports, scientific papers, etc. that focus on particular aspects of air quality within SIG. This chapter is focused on past changes and the current status of air pollution within SIG, rather than future changes, which are included in subsequent chapters. Chapter 2 assesses the current status of air pollution in SIG through three aspects of the air pollution chain. First, the current status of air pollutant concentrations, focusing on $PM_{2.5}$, is provided based on data collected from a large number of monitoring networks throughout SIG. The $PM_{2.5}$ concentrations across SIG are compared with WHO Air Quality Guidelines for the protection of human health. The contribution to $PM_{2.5}$ concentrations in SIG from different emission sources and different geographic locations, i.e. from emissions emitted within SIG itself, from the rest of the Republic of Korea and from transboundary transport of emissions originating outside of the Republic of Korea, are evaluated. Secondly, the chapter reviews the impact that $PM_{2.5}$ concentrations in SIG have on human health. The magnitude of the these, and their relative importance compared to other risks to human health in SIG are reviewed. Chapter 2 also reviews the magnitude of emissions that are emitted within SIG to identify the major sources emitting health-damaging air pollutants within the three areas themselves. While a substantial proportion of the $PM_{2.5}$ concentrations in SIG result from emissions from outside of the area, including the rest of the Republic of Korea or other countries, this report focuses on the emissions from sources within SIG as these are within the control of the local governments that administer each area. Finally,

Figure 1.1
Content of the report mapped across the four components of air pollution chain from emissions to impacts



Chapter 2 also reviews the air quality management framework within Republic of Korea and SIG and describes how each stage of the air pollution chain is regulated and monitored.

Chapter 3: Integrated air pollution and climate change mitigation assessment for Seoul, Incheon and Gyeonggi presents the results from a new assessment conducted in preparation of this report that assess past and future air pollutant, SLCP, and GHG emissions in SIG. It estimates emissions of these pollutants between 2005 and 2020 and assesses how they changed over these 15 years. Emissions in SIG are also projected to 2050 under different scenarios, reflecting varied levels of action to tackle emissions of air pollutants. These future scenarios include a baseline projection in which no new policies or measures are implemented, and mitigation scenarios that reflect the introduction of specific policies and measures. These include policies and measures identified to be implemented in SIG that will contribute to the Republic of Korea achieving carbon neutrality (CN) by 2050. This allows the assessment of the extent to which climate change mitigation can yield air pollution benefits alongside reducing the Republic of Korea's contribution to climate change. Additional measures that target other major air pollution source sectors are also modelled to assess the emissions reduction potential from their implementation. Chapter 3, therefore, focuses on the emissions part of the air pollution chain, as it is this component where action can be taken that reduces emissions, and consequentially also air pollutant concentrations, exposure and health impacts. The chapter identifies a set of concrete, specific mitigation measures that could reduce air pollutant emissions from their current levels.

Chapter 4: Achieving clean air for blue skies in Seoul, Incheon and Gyeonggi provides a set of recommendations based on the previous chapters on how further action can be taken to improve air quality in SIG. The recommendations cover specific action that can be taken to implement priority policies and measures identified in Chapter 3 as being effective in reducing air pollution between 2021 and 2050. It also includes recommendations on how air quality management processes, tools and mechanisms could be strengthened to facilitate a better understanding of air quality in SIG.

A water taxi in Songdo, Incheon
© Incheon Metropolitan City

> **Global and regional studies have shown that there are a variety of strategies and action that can target major sources of SLCPs and simultaneously improve air pollution locally and reduce a country's contribution to global climate change.**

1.4 Key consideration: links between air pollution and climate change mitigation

As outlined above, this report aims to assess the historical trend in air pollution in SIG and future action that could further reduce air pollution. As outlined in the following chapters, past reductions in air pollution in SIG have not been accompanied by simultaneous reductions in GHGs (Chapter 3). Looking forward, however, the achievement of CN in the Republic of Korea, because of the specific mitigation measures identified to achieve this, can contribute to both Republic of Korea's internationally communicated climate change goal of meeting the Paris Agreement[3] and contribute to air pollution reductions in SIG. A key consideration in this report is therefore the links between air pollution and climate change and how connected these issues are both physically and politically within SIG. The issues of climate change and air pollution are closely linked because:

- in many cases GHGs and air pollutants are emitted from the same sources; and
- some of the same substances contribute to climate change and air pollution, such as methane (CH_4), black carbon (BC) and tropospheric ozone O_3, all SLCPs (Figure 1.2) (Shindell *et al.* 2012).

These links provide substantial opportunities to design strategies and identify mitigation measures that can simultaneously reduce air pollution and mitigate climate change. Global and regional studies have shown that there are a variety of strategies and action that can be taken to target major sources of SLCPs and simultaneously improve air pollution locally and reduce a country's contribution to global climate change (UNEP/WMO 2011; UNEP 2018; CCAC SNAP 2019; Kuylenstierna *et al.* 2020; Nakarmi *et al.* 2020).

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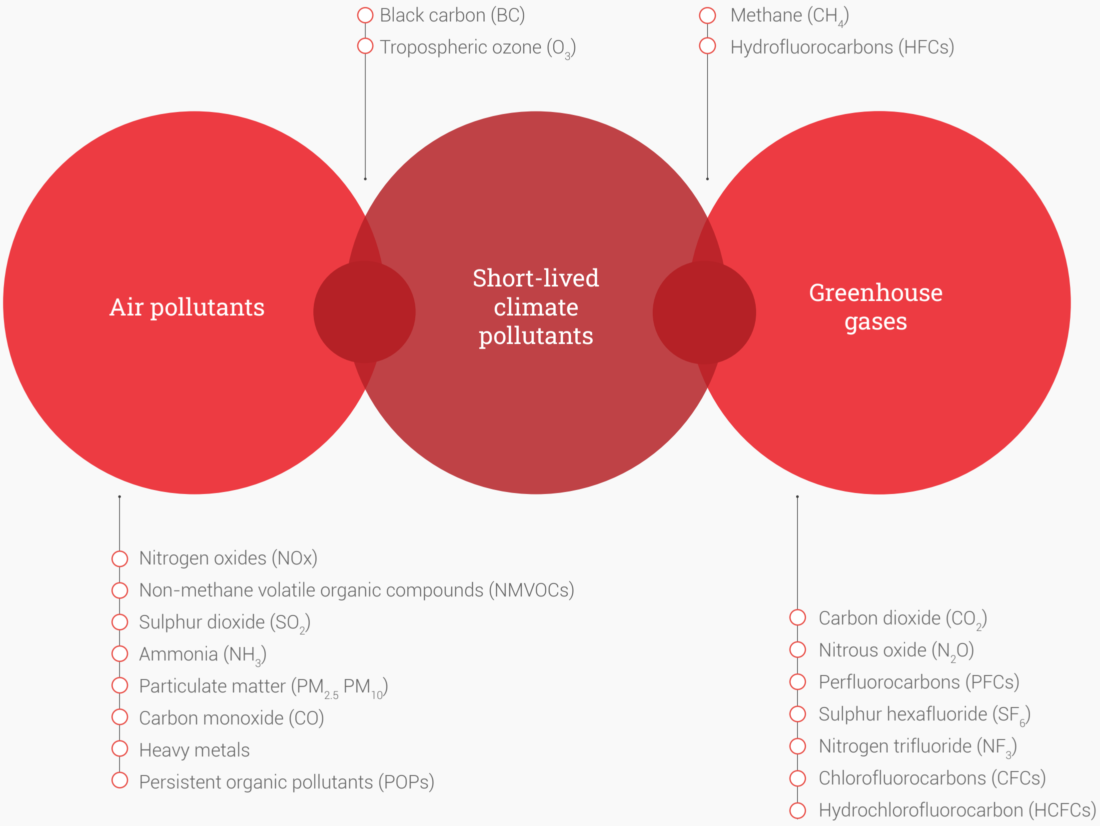
[3] The UNFCCC Paris Agreement. https://unfccc.int/process-and-meetings/the-paris-agreement?gclid=CjwKCAiAlp2fBhBPEiwA2Q10D6e8LfOB0ikIoOAyWyWvrMr0flP3bKW96UGFXKfA71Q2tpEvtfGZ0BoCtqIQAvD_BwE

Figure 1.2
Summary of pollutants that are classified as air pollutants, short-lived climate pollutants and greenhouse gases



Globally, for example, it was estimated that implementation of the 16 most effective measures to reduce SLCPs – BC and CH_4 – could avoid 2.4 million premature deaths by 2030 compared to the baseline, as well as providing 52 million additional tonnes of four staple crops – maize, rice, soy and wheat – due to less crop damage from exposure to O_3. These air quality benefits are disproportionately achieved locally in those countries and regions where the emissions reductions occur.

At the same time, implementation of these measures would also avoid 0.5° C of global temperature increase, making an important contribution to limiting global temperature rises when combined with fast and ambitious CO_2 mitigation. Black carbon, CH_4 and tropospheric O_3, together with hydrofluorocarbons (HFCs), are called short-lived climate pollutants (SLCPs) because of the relatively short time they spend in the atmosphere once emitted – from days to two decades – and their impacts on climate and air quality, except for HFCs, which just impact the climate.

It is important to note that the benefits of the measures that target SLCP source sectors are delivered for two reasons. Firstly, they reduce SLCPs themselves, which, in the case of BC and CH_4, have direct impacts on both air quality and climate and secondly, because many of the SLCP source sectors are also major sources of GHGs, such as CO_2 and other air pollutants. The implementation of mitigation measures in these sectors can, therefore, reduce emissions of GHGs and other air pollutants in addition to reducing SLCPs.

The Republic of Korea has committed to climate change mitigation targets that could also reduce air pollutants. In 2021, it submitted its updated nationally determined contribution (NDC) to the United Nations Framework Convention on Climate Change (UNFCCC) Secretariat. The updated and enhanced target is to reduce total national GHG emissions by 40 per cent from the 2018 level of 727.6 million tonnes of carbon dioxide equivalent ($MtCO_2eq$) by 2030. The NDC focuses on mitigation in power generation, industry, buildings, transport, agriculture and waste management, all of which can be substantial sources of air pollution.

In 2016, the Republic of Korea introduced the 2030 Basic Roadmap for Achieving the National Greenhouse Gas Reduction Target (2030 Roadmap). This lays out intended annual GHG reductions, relative to 2016, in particular sectors and has nine specific goals to be achieved by 2030:

01 Allocating emissions reductions of 219 $MtCO_2eq$, out of a total of 315 Mt, to eight areas, including power generation, industry, and construction;

02 Emissions reductions from power generation of 64.5 $MtCO_2eq$ through the adoption of low-carbon power sources, the management of electricity demand, and higher electricity transmission and supply efficiency;

03 Emissions reductions from the building sector of 35.8 $MtCO_2eq$;

04 Emissions reductions of 3.6 $MtCO_2eq$ by decreasing waste generation and improving its management;

05 The industrial sector, which includes steel, petrochemicals and 20 other business types, is to reduce emissions by 56.4 $MtCO_2eq$ through energy efficiency improvements, refrigerant replacement, innovative technologies and use of waste as a resource;

06 Emissions reductions by the public and other sectors of 3.6 $MtCO_2eq$;

07 Emissions reductions by the agricultural and livestock industries of 1 $MtCO_2eq$;

08 Emissions reductions from the new energy industries of 28.2 $MtCO_2eq$;

09 Emissions reductions from transport of 25.9 $MtCO_2eq$.

The Republic of Korea is pushing policies forward that will accelerate the achievement of its updated 2030 target and 2050 goal in accordance with the Carbon Neutrality Act.

The Republic of Korea is pushing policies forward that will accelerate the achievement of its updated 2030 target and 2050 goal in accordance with the Carbon Neutrality Act. This was enacted in September 2021 with the aim of strengthening both mitigation and adaptation measures, and addressing inequality that could arise in the societal transition to CN. The Act clearly defines 2050 CN as the Republic of Korea's national vision and stipulates the minimum level of its NDC target for 2030. Other key pillars of the Act include climate impact assessment, climate-responsive budgeting, an emissions trading scheme (K-ETS), adaptation measures for the climate crisis, and designation of special zones and establishment of support centres for the just transition. The Act serves as a legislative basis for the economic and social transition that will ultimately enable the Republic of Korea to achieve its NDC. The impact of climate change mitigation strategies on air quality can be significant and this is explored within Chapter 4, within which the impact of mitigation measures in the Republic of Korea's carbon neutrality scenario is evaluated to identify their air pollutant emission reductions.

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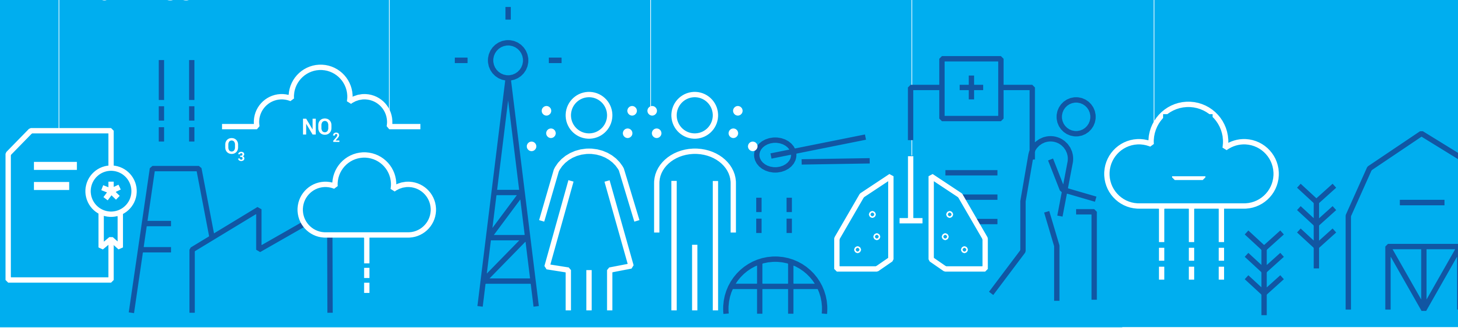
02

Status and impacts of air pollution in Seoul, Incheon and Gyeonggi



Key Findings

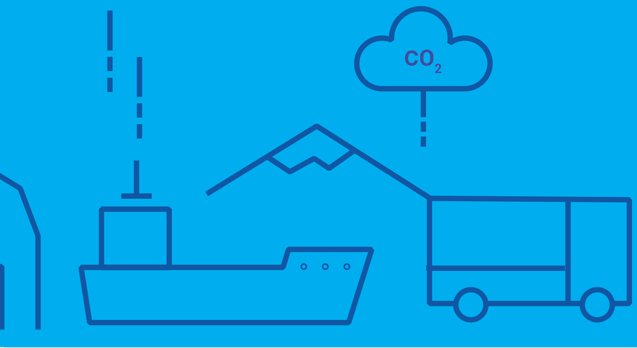
01 There is a robust legal framework for air quality management in the Republic of Korea, and Seoul, Incheon and Gyeonggi, which establishes air quality goals, identifies specific mitigation measures to achieve these goals, and outlines roles and responsibilities in the implementation and monitoring of air quality in each region.

02 Over the past decades, funding totalling approximately USD 9 billion has been invested in air quality management in Seoul, Incheon and Gyeonggi, targeted at implementing mitigation action as well as science and public communication.

03 Over the past 15 years, concentrations of the most health-damaging air pollutants, including particulate matter and nitrogen oxides, have decreased in Seoul, Incheon and Gyeonggi. In contrast, ozone concentrations have increased.

04 Air pollution levels in Seoul, Incheon and Gyeonggi are highly impacted by the transboundary transport of air pollution, and emission reductions in Seoul, Incheon and Gyeonggi and beyond have contributed to a decrease in air pollutant concentrations over the past two decades.

05 There is a substantial body of scientific evidence demonstrating the role of exposure to air pollution in negative health outcomes from epidemiological studies in Seoul, Incheon and Gyeonggi.



More than 1 000 scientific journal articles on air pollution in SIG were found when air pollution in Seoul, Incheon and Gyeonggi was searched in the Scopus scientific citation dataset.

2.1 Air quality management in the Republic of Korea and Seoul, Incheon and Gyeonggi

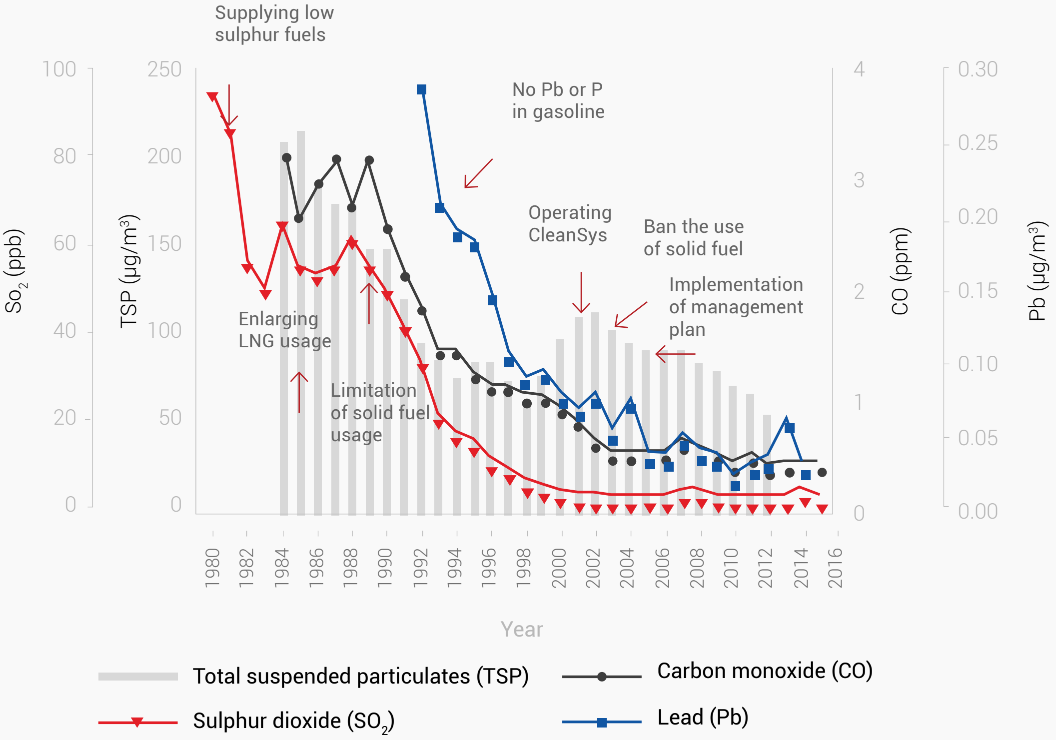
The regions of Seoul, Incheon and Gyeonggi are some of the most studied globally in terms of the status of air pollution within them. More than 1 000 scientific journal articles on air pollution in SIG were found when air pollution in Seoul, Incheon and Gyeonggi was searched in the Scopus scientific citation dataset. In addition to these scientific studies, non-academic information on air pollution in SIG includes air quality measurements from a dense atmospheric monitoring network and a national emission inventory. The following sections provide an overview of air pollution from academic and other information gathered in SIG. It is ordered according to the four components of the air pollution chain (Figure 1.1), i.e. air pollution concentrations in SIG (Section 2.2), air pollution exposure (Section 2.3), air pollution health impacts (Section 2.4), and air pollutant emissions (Section 2.5).

2.1.1 Legal Framework

Since the 1960s, by prioritizing economic development, Republic of Korea has industrialized and urbanized rapidly. As a result, several environmental problems, including air pollution, have arisen since the 1980's.

Korea's air quality management policy began in the 1980s with fuel conversion and stricter emission standards. The conversion from coal and heavy oil to diesel and gas, and the strengthening of air pollutant emissions standards for workplaces and cars drastically reduced concentrations of primary air pollutants, as shown for Seoul in Figure 2.1. Since the early 2000s, however, the concentrations of primary air pollutants have not changed significantly. This is because, although the emissions of individual pollutants decreased, the overall number of pollutants increased. To overcome this, the **Special Act on Air Quality Improvement in the Seoul Metropolitan Region (SMR)** was enacted in 2003 and the **Basic Plan for Air Quality Management in the Seoul Metropolitan Region** implemented in 2005 (Figure 2.4). The Plan aimed to regulate the total amount of emissions, not their concentrations, and its main measure was the reduction of fine dust emissions from diesel vehicles. As a result, the concentration of elemental carbon (soot), mainly emitted from diesel vehicles, decreased, alongside other pollutants such as sulphur dioxide (SO_2). Section 2.2 provides further information on emission trends.

Figure 2.1
Trends in air pollutant concentrations, Seoul, 1980–2016



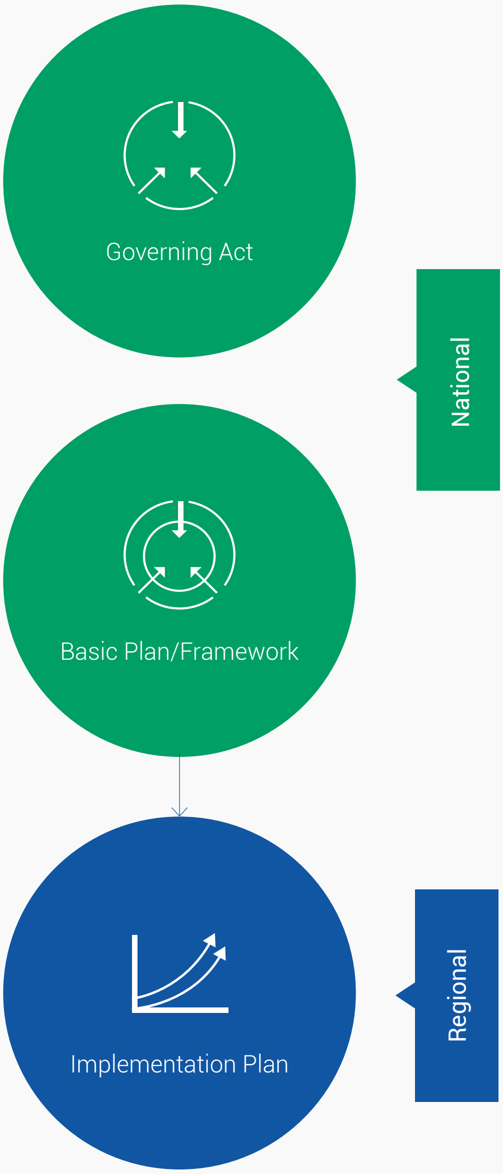
Source: Korean Academy of Engineering 2018

The government implemented tight measures to control air pollution in the 1990s. In 2003, the Special Act on Air Quality Improvement in the Seoul Metropolitan Region (SMR) was established, and the 1st Basic Plan for Air Quality Management in the SMR in 2005, after which air quality improved. In 2013, however, WHO designated fine dust as a first-class carcinogen, amplifying public anxiety and igniting a strong demand for responses.

In 2017, the government prioritized air pollution management and announced the **Comprehensive Plan for Particulate Matter (PM) Control**. In 2018, the **Measure for Enhanced Emergency and Regular PM Control** was developed and followed by the establishment of the **Special Act on the Reduction and Management of Fine Dust** and a revision of the **eight PM Control Acts** by 2019. Since 2020, efforts have been made to build a carbon neutral society. The government announced its **Carbon Neutrality 2050** policy in December 2020 and the NDC was revised with a raised reduction target for GHG emissions in line with global responses to the climate crisis.

Currently, the large volume of information regarding air pollution in SIG has resulted from, and informed, the development of a legal framework for the management of air quality in the three regions, and more broadly throughout the Republic of Korea. Across policy areas, including on air pollution, there are three levels within the framework that links national policy making to regional-level planning and implementation (Figure 2.2). At the national scale, a **Governing Act** provides the overarching framework for a particular issue. Next, also at the national scale, a **Basic Plan**, provides an overview of how the Act will be implemented at the national scale. Finally, at the regional scale, an **Implementation Plan** outlines how the goals of the Act will be implemented in each region, taking account of regional priorities and/or contexts.

Figure 2.2
Relationship between national and regional laws and plans for air quality management, Republic of Korea



Within this structure, the current legal framework relevant to air pollution control in the Republic of Korea and SIG (Figure 2.3) includes the Framework Act on Environmental Policy (Act. Number 17797). This overall purpose of this Act is to:

"ensure that all citizens enjoy a healthy and pleasant life by preventing environmental pollution and environmental damage and by managing and preserving the environment in an appropriate and sustainable manner through defining the rights and duties of citizens and the obligations of the state with regard to environmental preservation and determining the fundamental matters for environmental policies".

This Act includes provisions that apply not only to air pollution management but other types of environmental pollution, including water quality. The Act establishes important requirements that are fundamental to successful air quality management, including that the state should set environmental standards. This provision has resulted in the establishment of national ambient air quality standards in the Republic of Korea for seven pollutants. The current standards, as of 2022, are shown in Table 2.1.

The responsibility for the enforcement and achievement of environmental standards within the Framework Act on Environmental Policy rests with both national and sub-national governments. It states, for example, that the development of projects or statutes undertaken at state or local levels should ensure that environmental standards are maintained. It also requires that the national government will develop and implement a Comprehensive National Environmental Plan, which is required to include information on setting targets and identifying measures and projects to achieve targets on "*matters concerning the preservation of the air environment*". In addition, the Framework Act also requires local governments to develop environmental plans that are in line with the Comprehensive National Environmental Plan, but which take the specific characteristics of the region for which they are being developed into account. It also specifies that targets can be set by the Special Metropolitan City, Seoul; Metropolitan Cities, such as Incheon; and Self-Governing Provinces, such as Gyeonggi, that are more stringent than the national environmental standards. Finally, as well as establishing targets and setting out plans, the Framework Act also requires annual public reporting on the status of the environment.

Table 2.1

Ambient air quality standards, Republic of Korea, 2022

Pollutant	Average period	Standard
Sulphur dioxide	Annual	20 ppb
Sulphur dioxide	24 hours	50 ppb
Sulphur dioxide	1 hour	150 ppb
Carbon monoxide	8 hours	9 ppm
Carbon monoxide	1 hour	25 ppm
Nitrogen dioxide	Annual	30 ppb
Nitrogen dioxide	24 hours	60 ppb
Nitrogen dioxide	1 hour	100 ppb
PM_{10}	Annual	50 µg/m^3
PM_{10}	24 hours	100 µg/m^3
$PM_{2.5}$	Annual	15 µg/m^3
$PM_{2.5}$	24 hours	35 µg/m^3
Ozone	8 hours	0.06 ppm
Ozone	1 hour	0.1 ppm
Lead	Annual	0.5 µg/m^3
Benzene	Annual	5 µg/m^3

Note: ppb: parts per billion[4]; ppm: parts per million

Figure 2.3 shows that within the air quality management framework, the Republic of Korea has a basic law to govern air quality, the Clean Air Conservation Act, and legislated and revised related laws to better respond to PM and define severe PM situations as social disasters. The legislated laws include the Special Act on the Improvement of Air Quality in Atmospheric Control Areas and the Special Act on the Improvement of Air Quality in Port Areas. The Clean Air Conservation Act's stated purpose is to:

"prevent air pollution which causes harm to people and the environment, and manage and preserve the atmospheric environment in a proper and sustainable manner, thereby to enable all people to live in the health and comfortable environment".

The Clean Air Conservation Act divides responsibility for the management of air quality between the Ministry of Environment at the national level and mayors or provincial governors at the sub-national level. The Clean Air Conservation Act has substantially more detailed provisions for air quality management specifically compared with the Framework Act on Environmental Policy, including:

- **Air Quality Monitoring Networks:** the Clean Air Conservation Acts requires that *both* the national and sub-national governments establish networks which measure the levels of air pollutants in the atmosphere. A plan for the installation of monitoring stations is to be developed and financial assistance provided to achieve these plans. The data produced from these measurement sites are available in a publicly accessible data repository at https://www.airkorea.or.kr/eng/.
- **Air Pollution Alerts:** where acute levels of air pollution are expected to seriously damage human health, a mayor or governor is given the power within the Clean Air Conservation Act to issue air pollution alerts. They are also empowered to restrict the operation of vehicles and business hours or implement other measures to attempt to reduce air pollution levels in areas where alerts have been issued.

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[4] Billion = 10^9

- **Regulation of emissions:** the Clean Air Conservation Act empowers the Ministry of Environment to set permissible emissions levels from facilities which emit air pollutants through ordinances. Sub-national governments may set more stringent emissions levels where necessary to achieve air quality standards. For new facilities that will emit air pollutants, the Ministry of Environment must grant permission for their establishment. Specific emission sources are also covered within the Clean Air Conservation Act. For example, the Ministry of Environment is empowered to set permissible levels of sulphur content within fuels and is required under the Act to undertake inspection of vehicles to ensure they meet vehicle emission standards.

- **Emission inventory development:** in addition to the regulation of emissions, the Act also requires that the Ministry of Environment conduct "*a survey of the emission sources and emission quantities of air pollutants nationwide*". The development of this for the whole country is the responsibility of the Ministry of Environment, but mayors and governors are required to conduct surveys of emissions quantities within their jurisdictions.

- **Air Pollution Planning:** the Act requires the Ministry of Environment to develop a Comprehensive Plan for the Improvement of Atmospheric Environment every 10 years. This must include information on the current status of air pollutant emissions, air pollutant reduction goals and measures to achieve them. This Plan also has to link to climate change mitigation as it is required to include information on GHG emission levels, goals for their reduction and measures to be taken to achieve the goals.

- **Financial support:** the Act also provides provisions to ensure that financial support is provided for its implementation at national and local scales.

- **Regional air pollution prevention:** much of the air pollution experienced in SIG does not originate from emission sources. The Clean Air Conservation Act requires that the Ministry of Environment develop a Comprehensive Measure for Prevention of Damage Caused by Yellow Dust – transboundary air pollution caused by desert dust from Northeast Asia. The measure will be developed by the Ministry of Environment, but a Yellow Dust Committee is also established by the Act to deliberate and provide guidance on matters related to transboundary dust pollution. The measure is required to include information on the current status of yellow dust, and the domestic and international initiatives that are being taken to reduce the damage caused by it.

Finally, there is a Special Act that specifically outlines additional criteria for air quality management in SIG, within the Special Act on the Improvement of Air Quality in Atmospheric Control Areas. The stated purpose of this is to:

> ***"to protect residents' health, and create a decent living environment in the metropolitan area by implementing comprehensive policies and systematically controlling air pollutants in order to improve the air quality of the metropolitan area".***

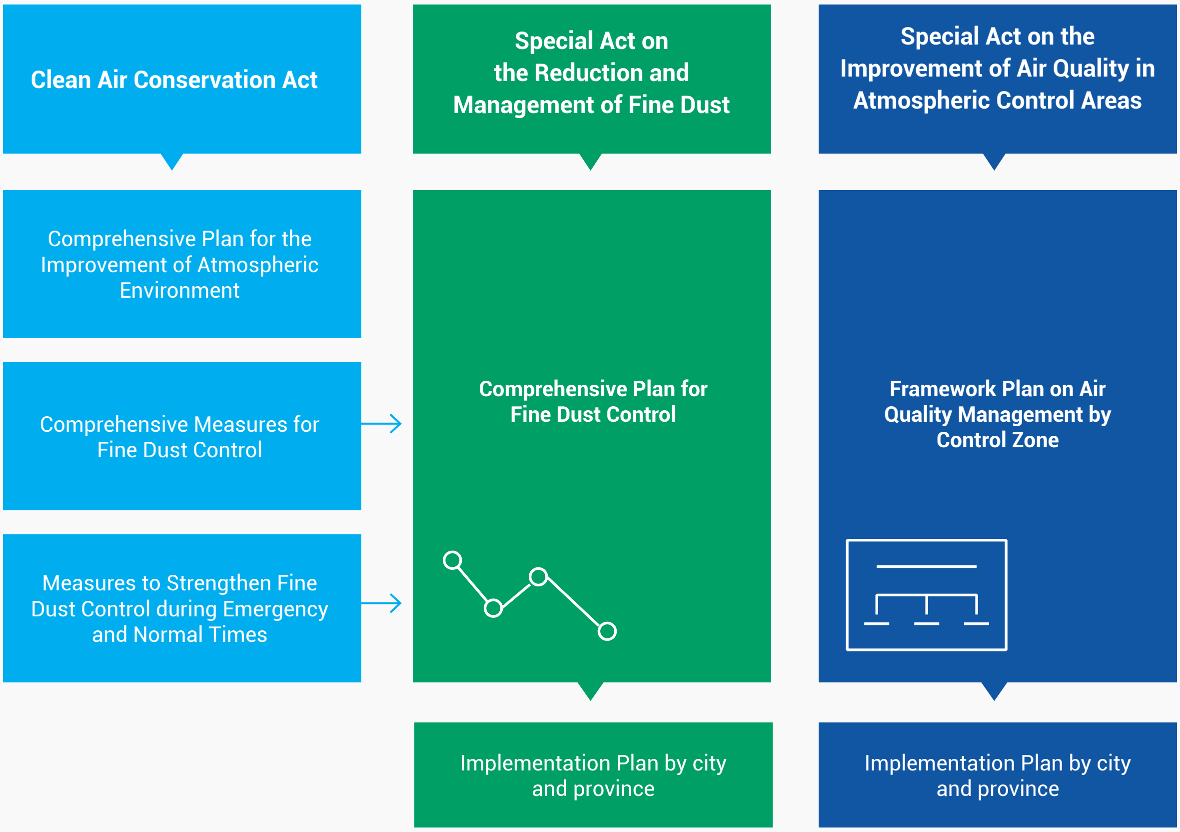
This Special Act takes precedence over the Clean Air Conservation Act in those areas covered by it. It requires the Ministry of Environment to develop a Basic Plan to improve air quality across SIG and specifically outlines the contents of the Plan. This includes the pollutants that should be covered – nitrogen oxides (NO_X), sulphur oxides (SO_X), volatile organic compounds (VOCs), dust, coarse and fine particulate matter (PM_{10} and $PM_{2.5}$) and ozone (O_3) – as well as the current status of air pollution and mitigation plans. The Basic Plan is to be developed, in principle, for every 10 years but can be revised or updated depending on policy changes. While the responsibility for updating it lies with the Ministry of Environment, local governments are given a consultative role in its development. In addition, the Seoul Metropolitan Government and other local governments are required to develop implementation plans which outline how the Master Plan will be implemented within their jurisdictions. These plans require approval from the Ministry of Environment and progress is required to be reported annually. The Special Act also contains specific provisions for the introduction and implementation of the allocation of total permissible emissions for business sites, the emissions trading system, incentives for early scraping of rundown diesel vehicles, the revision of the acquisition and holding tax systems for diesel vehicles and the reduction of non-road PM emissions, including from ships. Finally, the Special Act also specifies that funding

> **Seoul, Incheon, Gyeonggi and other local governments in the Republic of Korea are required to develop their implementation plans under the Basic Plan of the central government to achieve the goals envisaged by each Governing Act.**

support or cheap loans for financing environmental improvements can be provided to local governments for the implementation of specific action to reduce air pollution in particular areas, where necessary.

As shown in Figure 2.3, under each of these Governing Acts is a national plan for their achievement. Seoul, Incheon and Gyeonggi and other regions of the Republic of Korea then develop their own implementation plan within their area to achieve the goals of the Acts. There is a large degree of cooperation between the governments of Seoul, Incheon and Gyeonggi in the implementation of their plans. Section 2.1.2 provides further information on the policies and measures included within the implementation plans for each region.

Figure 2.3
Overview of the air quality management framework, Republic of Korea and Seoul, Incheon and Gyeonggi, 2022



2.1.2 Policies and measures to reduce emissions

During the 20th century, various efforts have been made to manage air quality in the Republic of Korea, including by the legal system. This sections details some of the major laws and policies that took effect, especially in the period 2005–2020 in SIG and nationwide. As outlined above, the framework for air quality management in the Republic of Korea specifies targets for air pollution levels, air quality monitoring requirements and responsibilities, and also provides some guidance on national policies and measures that should be implemented to improve air quality. This latter component of air quality management is fundamental to achieving reductions that lower atmospheric concentrations of key air pollutants, thereby decreasing both exposure and health impacts.

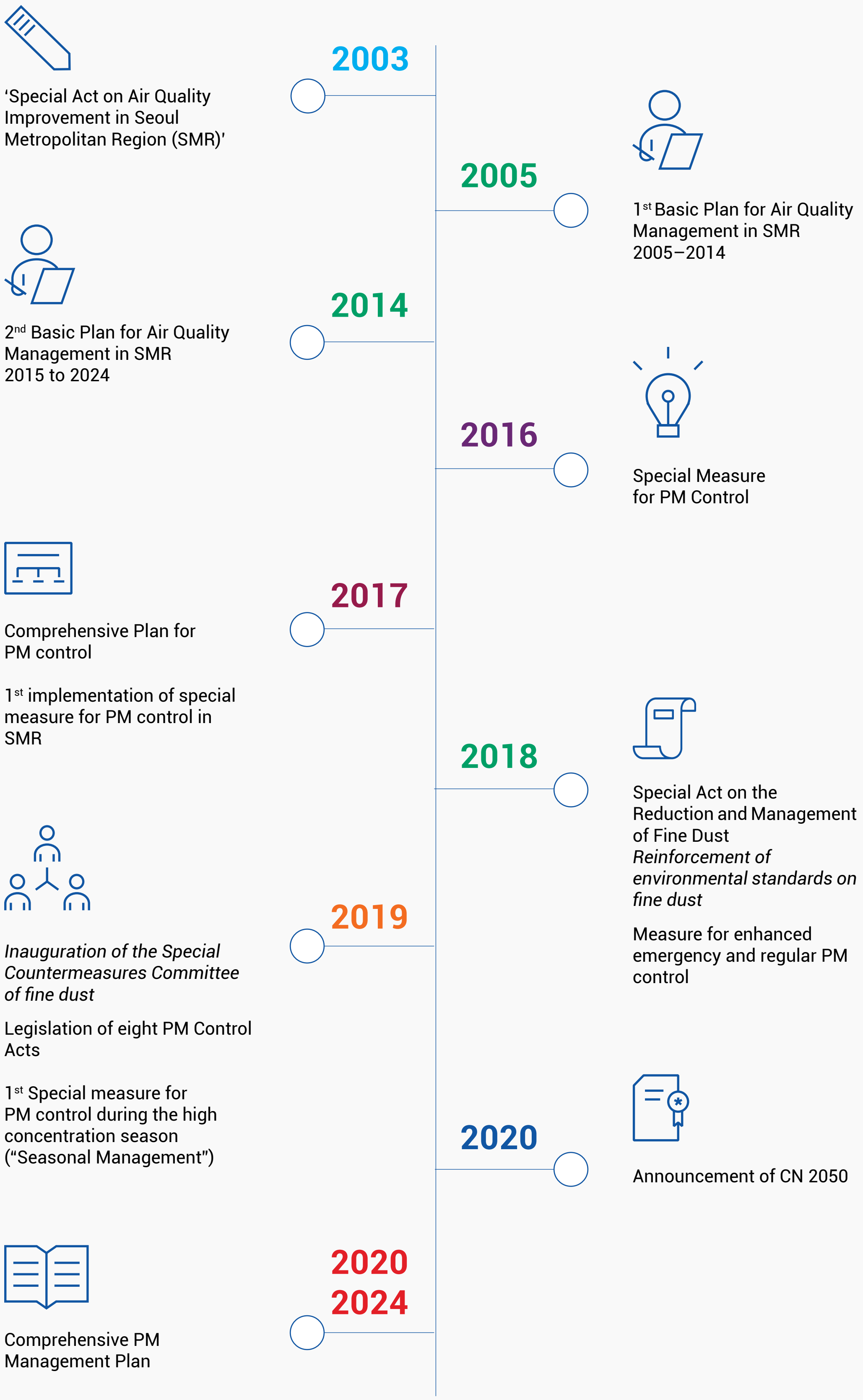
As outlined in Chapter 1, air pollution is a multi-faceted issue that ultimately results from the emission of pollutants into the atmosphere from a wide variety of human and natural activities. These sources include fuel combustion, industry, electricity generation, transport, households and the service sector. They also include emissions from industrial processes, solid and liquid waste management and agriculture. Each of these sources has the potential to emit multiple pollutants that contribute to $PM_{2.5}$ and O_3 concentrations, which have the largest impacts on human health. Globally, therefore, a large number of different mitigation measures have been identified to control emissions from all major sources of air pollution. These can be classified into different types based on how each measure reduces emissions. They include the following.

+ **Business:** a total pollution load control system has been introduced for businesses within the SIG air quality management jurisdiction. Small-sized businesses will be supported to install pollution prevention facilities. Additionally, low-interest loans will be available to help finance businesses' endeavours to contribute to improving air quality.

+ **Transport:** a subsidy system for the early scrapping of vehicles and the acquisition and holding tax systems for diesel vehicles were revised to incentivize the early scrapping of rundown diesel vehicles and curb the sale of new ones. In addition, measures to curb the demand for diesel-powered vehicles included relative price adjustments for fuel, stricter emissions standards for new vehicles and strengthened producer liabilities. Furthermore, small and mid-sized diesel vehicles are subject to as strict nitric oxide (NO) emission standards as in the European Union (EU) regulations, while children's school buses and the parcel delivery service are banned from using new diesel vehicles. For the sake of PM abatement in the non-road sector, the ship fuel quality standard was strengthened in 2020, and an emissions control area was announced around large ports, to which only ships powered by quality fuels with a sulphur (S) content of 0.1 per cent are allowed to enter. Furthermore, the vessel speed-reduction programme has established restrictions around large ports, while the alternative maritime power (AMP) system is being expanded (i.e. using electricity generated on land to power ships while in port).

A subsidized zero-emission battery-powered electric 'e-bus' in Seoul.
© Seoul Metropolitan Government

Figure 2.4
Timeline of key milestones in the development of the air quality management framework, the Republic of Korea and Seoul, Incheon and Gyeonggi, 2003-2021



2003

'Special Act on Air Quality Improvement in Seoul Metropolitan Region (SMR)'

2005

1st Basic Plan for Air Quality Management in SMR 2005–2014

2014

2nd Basic Plan for Air Quality Management in SMR 2015 to 2024

2016

Special Measure for PM Control

2017

Comprehensive Plan for PM control

1st implementation of special measure for PM control in SMR

2018

Special Act on the Reduction and Management of Fine Dust
Reinforcement of environmental standards on fine dust

Measure for enhanced emergency and regular PM control

2019

Inauguration of the Special Countermeasures Committee of fine dust

Legislation of eight PM Control Acts

1st Special measure for PM control during the high concentration season ("Seasonal Management")

2020

Announcement of CN 2050

2020
2024

Comprehensive PM Management Plan

- **Power generation and households:** the retirement of 30+ year-old coal-fired power plants was moved up to 2021. Furthermore, while preserving a stable power supply, coal power plants are subject to a diminishing operation policy that includes shutdowns, a cap on power generation capacity and the improvement of the facilities and their equipment. Additionally, NH_3 generation in agriculture and VOCs from households are also controlled.
- **Public health projection:** public health protection measures have been strengthened for when the concentration of PM goes up. As the concentration level goes up from December to March, a seasonal PM management system has been adopted with stricter implementation of emissions reduction and public health promotion measures.
- **Science-based policy and public communication:** three-dimensional measurements linking ground, vehicles, vessels, planes, and satellites were launched in 2020 to improve the accuracy of PM forecasts, based on enhanced equipment and human resources. In addition, the National Air Emission Inventory and Research Center has enhanced its policy support features to improve statistical accuracy and provide transparent and objective information.

In SIG, examples of all of these measures have been included within the plans developed to achieve the goals of Republic of Korea's legislation on air pollution. As Figure 2.5 shows, there is a large degree of overlap in the policies and measures implemented SIG to improve air quality. The Basic Plan for SIG has established a set of common mitigation measures across all regions that have been implemented to reduce air pollutant emissions and achieve the goal of the Basic Plan, i.e. reaching the air quality levels in the Special Act on Air Quality Improvement in Atmospheric Control Areas by 2024 (Figure 2.5).

These measures include action in the major emission source sectors (Section 2.5). In the road transport sector, mitigation measures included within the Basic Plan for SIG includes the phasing out of old diesel vehicles. Generally, diesel vehicles are more polluting than gasoline vehicles in terms of their PM emissions and older diesel ones may not be fitted with the particle filters that newer ones have. The phasing out of older diesel vehicles can therefore have a disproportionate effect, relative to other vehicle categories, on reducing air pollutant emissions.

Other measures in the transport sector include increasing the penetration of zero-emission vehicles, such as electric vehicles, within the vehicle fleet. To achieve this, various measures have been taken, including encouraging the procurement of electric vehicles within the public sector and the expansion of the charging infrastructure within SIG. Emission standards have also been put in place for non-road mobile sources, such as construction and agricultural machinery (Figure 2.5).

For industrial sources of emissions, a **cap-and-trade system** has been put in place that limits the emissions from large point sources and incentivizes emissions reductions. In addition, while for large point sources the polluter pays principle has been in place in SIG, for small businesses that may be emission sources but unable to pay for the control technologies, finance is available within the Basic Plan to ensure that small businesses can also afford to pay for their emissions. The funding available to small businesses can cover some of the costs of emissions control equipment. Other measures cover community sources, including those within homes, agriculture and waste (Figure 2.5).

Various measures have been taken, including encouraging the procurement of electric vehicles within the public sector and the expansion of the charging infrastructure, to increase the penetration of zero-emission vehicles within the vehicle fleet in SIG.

Figure 2.5
Overview of current Basic Plan for air quality improvement including key mitigation measures to reduce emissions from major sources, Seoul, Incheon and Gyeonggi

Vision

Clean air Korea without concern for PM

Goal

Meet the SMR clean air improvement target by 2024
PM$_{2.5}$ 17μg/m^3; PM$_{10}$ 30μg/m^3; NO$_2$ 0.021ppm; O$_3$ 0.06 ppm

↑

Control strategies

Road mobile pollution sources

1 Phase-out old diesel vehicles
2 Deployment of zero-emission vehicles
3 Stronger control of transport demand

Non-road mobile pollution sources

1 Strong control of construction and agricultural machinery
2 Focused control of ship and port sources
3 Airport air quality management

Emission facilities

1 Strengthen cap-and-trade system
2 Strengthen emissions standards for facility
3 Emissions reductions in coal-burning power plants

Community sources

1 Stronger management of community sources
2 Stronger management of PM in communities

Strengthen policy base and encourage civil participation

In addition to the Basic Plan, which outlines a common set of mitigation measures implemented across SIG, there are also policies and measures that are specific to each region, which form part of the suite of policies and measures implemented to achieve air quality targets in the regions. In 2007, for example, the Seoul Metropolitan Government announced the Clean Seoul 2010 policy and has implemented further policies to improve its air quality. As a result, annual average PM concentration in Seoul dropped by 22 per cent in 2010 to 47 micrometres per cubic metre (μg/m^3) from 60 μg/m^3 in 2006, and in 2020 and 2021 the city consecutively recorded its lowest ever $PM_{2.5}$ concentrations. The annual average concentrations of $PM_{2.5}$ in Seoul were, however, 20 μg/m^3 in 2021, which still fell short of the national air quality standards, and thus the Seoul Metropolitan government announced the Cleaner Seoul 2030 policy with the aim of reducing annual average concentration to 13 μg/m^3 by 2030 so that it becomes one of the global top 10 cities, on a par with London and Paris. The main strategies of Cleaner Seoul 2030 are:

+ early conversion of diesel vehicles, which are high emitters, to low-emission vehicles;

+ gradual expansion of restrictions on the operation of polluting vehicles throughout Seoul; and

+ establishment of a regular management system for air pollutant emissions sources.

The policy consists of 11 key tasks and 50 sub-tasks in five areas: vehicle management, home/workplace management, construction site management, living area management and strengthening response capabilities.

In addition, Incheon has a major international airport and a large port area, both of which are significant sources of air pollution. Emission control measures for these large facilities are part of the set of measures to achieve air quality improvements in Incheon. In 2020, for example, an air quality improvement plan for Incheon International Airport was developed covering the period 2020–2024. Provisions within the plan include the supply of low emissions vehicles operating at the airport and the use of ground power systems (i.e. electricity from the power grid) for aircraft when they are at the airport terminal. At the port in Incheon, measures include stricter standards for the sulphur content of fuels at the port, reducing the sulphur content from 3.5 per cent to 0.5 per cent for ocean-going vessels in 2020 and domestic vessels in 2021. The measures also include the installation of diesel particle filters in cargo handling equipment.

In Gyeonggi, where regional characteristics include a large number of small-scale industrial facilities that emit air pollutants, mitigation efforts are focused on promoting emissions reduction technologies using subsidies for the installation and operating costs of treatment facilities. Between 2017 and 2020, KRW 91 billion (approximately USD 65 million) was provided to 1 640 facilities and emissions are estimated to have been reduced by about 60 per cent on average (Kim 2021).

The implementation of these policies and measures required substantial funding to be allocated to air quality management in SIG. Table 2.2 shows the funding for air quality management in SIG between 2007 and 2020. The funding is disaggregated into four categories: implementation of mitigation measures in the road transport sector, implementation of mitigation measures in industrial facilities and businesses, implementation of mitigation in other sectors, and providing a scientific basis for air quality management and communications with the public. Between 2007 and 2020, a total investment of KRW 12.5 trillion[5] (approximately USD 8.9 billion) has been made in air quality management. Approximately 56 per cent of this, KRW 7 trillion or around USD 5 billion, has been for the implementation of policies and measures to reduce emissions in the transport sector. To control emissions from industrial facilities and businesses, KRW 198 billion or approximately USD 140 million have been invested, while KRW 850 billion or just more than USD 600 million have been invested in scientific studies and public communication. Over time, there has been a shift in the share of funding for air quality management that has been invested in scientific and communication activities compared to the implementation of mitigation measures. In earlier years, for example 2008–2010, a majority of the total funds for air quality management were used for scientific studies and public communication. In more recent years, the funding for this component was substantially lower, and the funding for the implementation of mitigation measures, particularly in the transport sector, increased. In particular, funding for the purchase of low-carbon vehicles including the subsidy of electric and hydrogen fuel-cell vehicles has been expanded in place of the emissions reduction measures for diesel-powered vehicles.

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[5] Trillion = 10^{12}

The implementation of these policies and measures requires substantial funding to be allocated to air quality management in SIG.

In summary, through the Governing Acts, Basic Plans and regional implementation plans, SIG and the Republic of Korea have established clear targets for the improvement of air quality. These targets have been supplemented by plans that identify key mitigation measures to reduce emissions that have been implemented in key sectors, and which have been provided with substantial funding and investment to achieve their application on the ground. The following sections outline, for different components of the air pollution chain – from emissions to atmospheric concentrations, exposure and health impacts – the current status of air quality in SIG, and how it changed between 2005 and 2020 in response to the efforts made to reduce it.

Table 2.2

Funding allocated for air quality management in Seoul, Incheon and Gyeonggi, 2007–2020, KRW million

Year	Total	Automobile management measures (non-road mobile pollution sources)	Measures for emission facilities' management	Measures for management of emissions from household pollution sources	Establishing a scientific management base and promoting it to the public
2007	874 092	481 420 (-)	6 092	3 774	382 806
2008	1 496 459	499 868 (-)	6 020	6 582	983 989
2009	1 349 533	384 431 (-)	13 566	16 322	935 214
2010	1 011 612	363 684 (-)	8 930	3 565	635 433
2011	843 831	507 768 (199)	10 698	10 791	314 574
2012	874 711	561 913 (380)	8 501	12 948	291 349
2013	869 853	495 496 (91)	8 120	5 598	360 639
2014	889 711	497 005 (2 330)	8 132	8 370	376 204
2015	508 607	427 153 (3 408)	12 224	66 688	5 950
2016	521 340	234 061 (14 556)	11 814	285 251	4 770
2017	309 382	285 577 (21 224)	6 146	27 380	11 505
2018	549 870	432 146 (33 587)	13 651	81 633	22 440
2019	982 863	836 257	19 592	107 725	19 289
2020	1 438 519	1 048 480 (55 121)	64 540	214 217	56 161
2007-2020	12 520 383	6 219 002	198 026	850 844	4 400 323

Note: Total investment of KRW 12 520 trillion in 2007~2020, 50% for automobile management measures
Source: Evaluation report on the performance of the Implementation Plan for Air Quality Management in SMR

< Box 2.1 >

Tackling high fine particulate matter concentration episodes: the seasonal management system

Seasonally customized management: emergency mitigation measures and a seasonal management system (SMS) are used in the Republic of Korea to minimize damage to citizens' health and contribute to reducing pollution by reflecting seasonal concentration characteristics. The emergency mitigation measures, put into practice since 2017, are designed to reduce air pollution through prompt responses when concentration levels are high. The seasonal management system, established in 2019, works to lower the frequency, intensity and effects of high concentrations episodes from December to March, using stronger mitigation policies than in other seasons affecting transport, heating, workplaces and the reduction of exposures. The aim of the SMS, which is in place from December to March when high $PM_{2.5}$ concentration episodes are most likely to occur, is to limit the number of high $PM_{2.5}$ concentration episodes within SIG. The SMS includes pre-emptive measures taken to reduce the likelihood of high $PM_{2.5}$ concentration episodes, as well as putting in place procedures to inform the public when such episodes are forecasted or do occur.

For the pre-emptive measures, action is taken across four areas.

+ **Transport:** there is a phased expansion of traffic restrictions for all vehicles with internal combustion engines. During the SMS time period, these restrictions apply initially to vehicles of Grade 4 and 5 (equivalent to Euro emission standard 3) and are gradually expanded to other vehicle grades which meet more stringent vehicle emission standards. There is also an incentive programme designed to reduce the distance travelled by cars. Points, which can be used like money, are provided if car mileage is reduced by a certain amount. During the SMS season, more points are provided for not using passenger cars.

+ **Heating:** heating is a major source of air pollution during winter as demand peaks. Pre-emptive measures within the heating sector include the promotion of switching to eco-friendly boilers by expanding those eligible for subsidies to cover the cost of conversion.

+ **Workplaces:** within industry and other workplaces pre-emptive measures include restrictions on the use of construction equipment and requirements for workplaces to put in place air pollution reduction measures and operate monitoring systems to ensure emissions are reduced.

+ **Exposure reduction:** in addition to action to reduce emissions from key sectors, the SMS also contains action to minimize population exposure to $PM_{2.5}$ during high concentration episodes. The action includes the enforcement of indoor air quality maintenance standards in subways, which have historically been a source of high exposure in SIG, and the more intensive cleaning of roads to reduce exposure to road dust.

In addition to these measures, an air quality forecasting system has been developed for high $PM_{2.5}$ episodes. This system, in combination with the air quality monitoring network, provides the information which prompts the mayor or governor to issue alerts, if the following conditions are met in two of the three regions, i.e. Seoul, Incheon or Gyeonggi: i) $PM_{2.5}$ exceeded 50 µg/m^{-3} on one day and is forecast to exceed 50 µg/m^3 on the next; ii) a $PM_{2.5}$ warning is issued on one day and concentrations are forecast to exceed 50 µg/m^3 on the following day; and iii) concentrations are forecast to exceed 75 µg/m^3 on the next day.

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At the end of 2021, across the Republic of Korea, there were 636 air quality monitoring sites, including 50 in Seoul, 37 in Incheon, and 123 in Gyeonggi.

2.2 Air pollution concentrations

Comprehensive air quality monitoring network

As outlined above, the Governing Acts for air quality in the Republic of Korea require that there is a comprehensive air quality monitoring network which measures the atmospheric concentration of key air pollutants. To assess compliance with the Acts' standards, there is a substantial and dense network of monitoring sites across SIG. While the local governments in each region are responsible for the operation of these monitoring sites, the data are stored and made publicly available through the centralized Air Korea data repository and public information website (https://www.airkorea.or.kr/eng/). At the end of 2021, across the Republic of Korea, there were 636 monitoring sites, including 50 in Seoul, 37 in Incheon and 123 in Gyeonggi (Table 2.3). Within SIG, the majority of these sites are urban background sites, with others located at roadsides. In Incheon and Gyeonggi, several sites are located in other environments, including rural areas and seaports (Table 2.3).

This comprehensive network provides the basis for understanding current levels of air pollution across SIG, and assessing how this has changed over time, as described in the following sub-sections.

Current levels of air pollution in Seoul, Incheon and Gyeonggi exceed national standards and international guidelines

As outlined in Section 2.1, the overarching air quality goals governing air pollution in SIG and the rest of the Republic of Korea are defined based on atmospheric concentrations of air pollutants, i.e., ambient air quality standards (Table 2.1). Using data from the monitoring networks in each region, the annual average PM_{10} and $PM_{2.5}$ concentrations for SIG and Republic of Korea are shown in Figures 2.6 and 2.7. Annual average $PM_{2.5}$ concentrations in 2021 in SIG were approximately 21 $\mu g/m^3$, approximately 25 per cent higher than the ambient air quality standards of the Republic of Korea and substantially higher than the WHO Air Quality Guidelines.

Table 2.3

Number of air quality monitoring sites classified according to their location, the Republic of Korea, 2021

Region	Urban	Roadside	Rural	Seaport	National background	Total
Seoul	25	15	0	0	10	50
Incheon	24	6	2	2	3	37
Gyeonggi	108	11	4	0	0	123
Gangwon	24	1	8	2	0	35
Chungnam	39	3	2	4	2	50
Daejeon	11	2	0	0	0	13
Chungbuk	30	1	2	0	0	33
Sejong	4	1	0	0	0	5
Busan	28	3	0	4	0	35
Ulsan	18	2	0	1	0	21
Daegu	19	2	0	0	0	21
Gyeongbuk	46	1	3	1	1	52
Gyeongnam	38	2	3	1	0	44
Jeonnam	39	0	1	5	3	48
Gwangju	11	2	0	0	0	13
Jeonbuk	38	2	2	1	1	44
Jeju	10	1	0	0	1	12
Total	512	55	27	21	21	636

Note: new installation of urban monitoring site in 2022: Incheon (1), Gyeonggi (2), Ulsan (1), Gyeongbuk (1), Jeonbuk (2)
Source: Air Korea

Figure 2.6

Annual average coarse + fine particulate matter (PM_{10}) concentrations in the Republic of Korea, Seoul, Incheon and Gyeonggi, 2005-2021, microgrammes per cubic metre

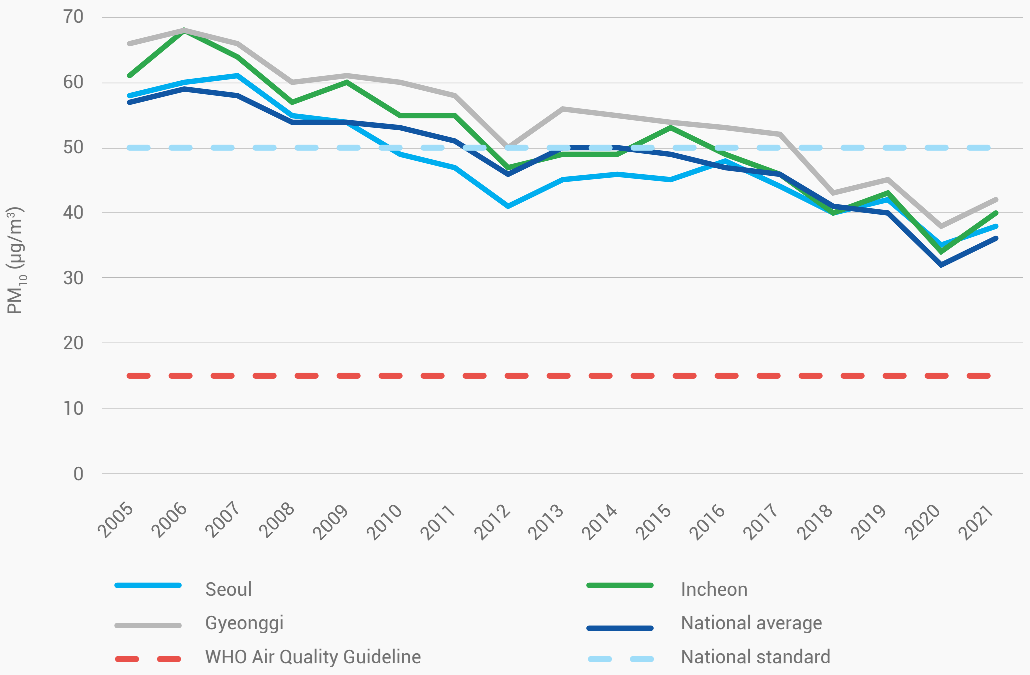


Figure 2.7
Annual average fine particulate matter concentrations $PM_{2.5}$, the Republic of Korea and Seoul, Incheon and Gyeonggi, 2015–2021, microgrammes per cubic metre

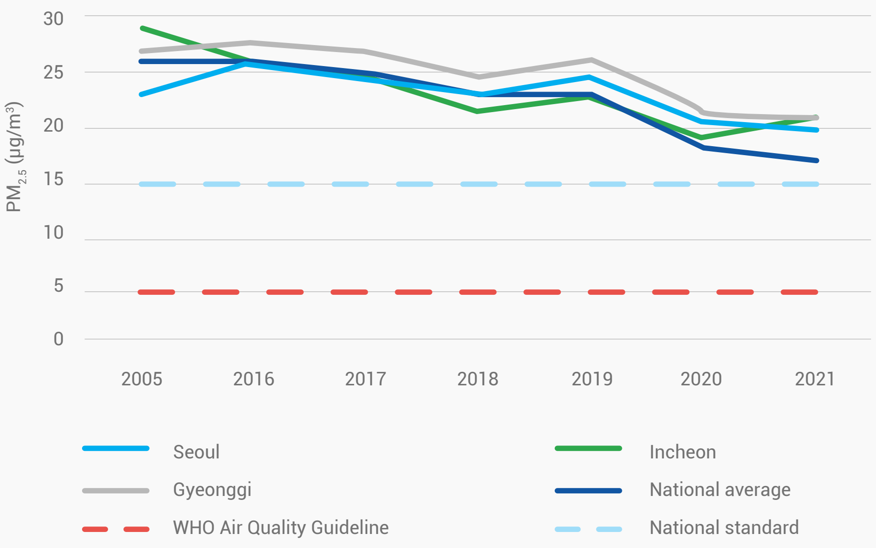


Figure 2.8
Annual average nitrogen dioxide concentrations, the Republic of Korea and Seoul, Incheon and Gyeonggi, 2005–2021, parts per billion

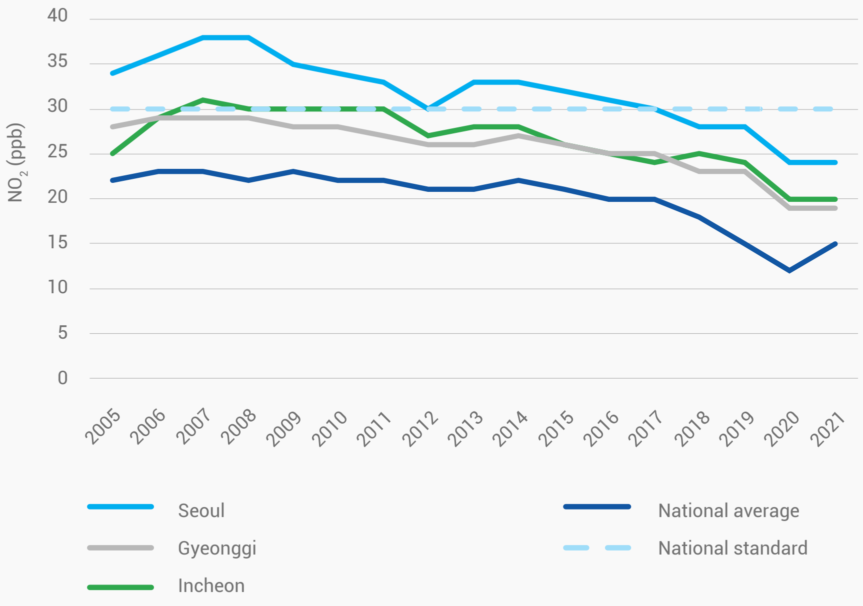
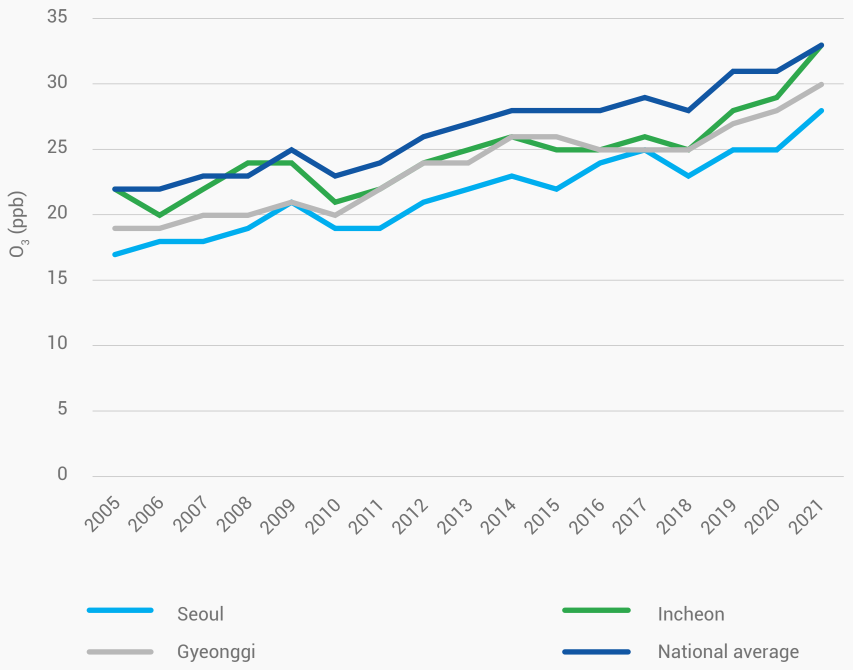


Figure 2.9
Annual average ozone concentrations, the Republic of Korea and Seoul, Incheon and Gyeonggi between 2005 and 2021, parts per billion



Current levels of air pollution differ in different locations. A detailed assessment of the correlation between land use, i.e. residential, commercial, industrial and greenbelt (rural) areas, across the Republic of Korea and concentrations of PM and gaseous pollutants showed clear differences. The highest PM_{10} concentrations were estimated to be in industrial land-use zones, with average annual concentrations of 56 $\mu g/m^3$. Commercial and residential areas had slightly lower PM_{10} concentrations, respectively 55 and 53 $\mu g/m^3$ on average, while PM_{10} concentrations were lowest in greenbelt areas at 49 $\mu g/m^3$. These elevated PM_{10} concentrations, even in greenbelt areas far from major emissions sources, emphasize the large contribution of transboundary PM across SIG and Republic of Korea in general (Yoo *et al.* 2015).

For gaseous air pollutants, such as nitrogen dioxide (NO_2), highest concentrations were in commercial, industrial and residential areas, respectively 25, 23 and 21 ppb, with substantially lower concentrations of 12 ppb in greenbelt area, reflecting the more local contribution to NO_2 concentrations. In contrast, annual average O_3 concentrations were higher, at 31 ppb, in greenbelt areas than in other land-use types, 20–24 ppb. This is consistent with O_3 concentrations being higher in areas downwind of sources of major O_3 precursors compared to those closer to emission sources, and the impact of high NO_X concentrations resulting in the titration of O_3, and lower O_3 concentrations in more polluted urban areas (Yoo *et al.* 2015).

There are multiple components that contribute to the levels of PM air pollution in Seoul, Incheon and Gyeonggi. In 2014–2015, 2 215 samples of $PM_{2.5}$ were taken from a monitoring site in the centre of Seoul. Average $PM_{2.5}$ concentrations from these samples were 42.6 $\mu g/m^3$, with highest concentrations in winter and spring, and the lowest in summer. Secondary inorganic aerosols made the largest contribution to $PM_{2.5}$ concentrations with nitrates, 6.9 $\mu g/m^3$; sulphates, 6.7 $\mu g/m^3$; and ammonium, 4.4 $\mu g/m^3$ contributing 42 per cent of the $PM_{2.5}$ mass. Organic carbon, 6.4 $\mu g/m^3$, also made a substantial contribution, with smaller ones from elemental carbon, 1 $\mu g/m^3$, and other trace metals (Park *et al.* 2020).

Air pollutant concentrations have decreased substantially over the past decades in Seoul, Incheon and Gyeonggi

Despite PM concentrations exceeding national and international standards/guidelines, substantial progress has been made in reducing them over the past decades. Long-term trends in PM concentrations have decreased due to the implementation of policies and measures designed to reduce emissions. In 2001, for example, PM_{10} concentrations in SIG were on average approximately 70 μg/m^3, approximately double current levels (Kim *et al.* 2017). Many studies have assessed trends in PM and gaseous air pollutants at monitoring sites across SIG between the 2000s and 2010s. At a residential site in Seoul, $PM_{2.5}$ concentrations were estimated to have fallen by 2 per cent per year between 2003 and 2017, dropping from 38 μg/m^3 in 2003 to 31 μg/m^3 in 2017 (Kim *et al.* 2020). At a monitoring site in Yongsan, annual average $PM_{2.5}$ concentrations fell from 33 μg/m^3 in 2004 to 25 μg/m^3 in 2013 (Ahmed *et al.* 2015).

More recently, there was also a reduction in $PM_{2.5}$ concentrations in SIG driven by measures implemented during the COVID-19 pandemic. In 2020, $PM_{2.5}$ concentrations in Seoul were on average 16 per cent lower than in 2019. This was attributed to emissions reductions occurring locally as a result of Republic of Korea's COVID-19 measures, reductions in emissions of PM and PM-precursors in Northeast Asia and a resultant reduction in the transboundary transport of pollution to SIG (Uhm *et al.* 2021).

Different components of $PM_{2.5}$ have shown decreasing trends

At a residential site where trends in $PM_{2.5}$ were assessed between 2003 and 2017, for example, larger decreasing trends in organic carbon and elemental carbon were calculated, with 3 and 6 per cent reductions, respectively, in their annual average concentrations between 2003 and 2017 (Kim *et al.* 2020). A broader assessment of the chemical constituents of PM indicate that reductions in mobile source emissions are responsible for some of this decrease. An assessment of $PM_{2.5}$ samples from across Seoul taken in 2003–2007 and 2014–2015 indicate that the average concentration in $PM_{2.5}$ of organic carbon, 9.9 μg/m^3 in 2003–2007 and 6.4 μg/m^3 in 2014–2015; elemental carbon, 3.2 μg/m^3 and 1.0 μg/m^3 respectively; nitrate, 7.2 μg/m^3 and 6.9 μg/m^3; sulphate, 8.6 μg/m^3 and 6.7 μg/m^3 and ammonium, 5.6 μg/m^3 and 4.3 μg/m^3 all decreased over that time period. In contrast, the concentration of the crustal component of $PM_{2.5}$ increased from 2.0 μg/m^3 in 2003–2007 to 4.3 μg/m^3 in 2014–2015. The reduction in these components was attributed to a fall in mobile source emissions, while the increased crustal contribution was attributed to a rise in the frequency of Asian dust events (Park *et al.* 2020). Reductions in PM_{10} concentrations across Republic of Korea, including SIG, were similar across residential, commercial, industrial and rural areas and were approximately -1 μg/m^3 per year between 2002 and 2013.

Gaseous air pollutants have also reduced substantially in areas across Seoul, Incheon and Gyeonggi over the last decades

Across Republic of Korea, including SIG, $PM_{2.5}$ concentrations and NO_2 concentrations were shown to be highly correlated. Annual average NO_2 concentrations across Korea fell on average by 24 per cent between 2001 and 2018, including in SIG (Yeo and Kim 2022). At a central urban site in Seoul, between 2004 and 2013, annual average NO concentrations decreased from 38 to 21 ppb and NO_2 concentrations from 40 to 36 ppb, respectively (Vellingiri *et al.* 2015). The implementation of policies and measures to reduce NO_X emissions from road transport, such as the natural gas vehicle supply programme, have been attributed as reasons for the reductions in NO_2 concentrations in SIG (Yeo and Kim, 2022). According to an assessment of the trends in air pollutant concentrations across different land use types, the trend in NO_2 concentrations between 2002 and 2013 was strongest at residential locations, -0.295 ppb per year, probably reflecting the heavy use of vehicles in these areas (Yoo *et al.* 2015).

Annual average concentrations of CO and SO_2 have also decreased substantially – by 39 per cent across Republic of Korea between 2001 and 2018 according to one study (Yeo and Kim, 2022). Concentrations of SO_2 in Seoul fell by approximately 95 per cent between 1980 and 2000 from up to 20 μg/m^3 in 1980. Volatile organic compound concentrations have also decreased substantially, by more than 50 per cent between 2004 and 2016 (Kim and Lee 2018).

While other pollutants have decreased, ozone concentrations have increased in Seoul, Incheon and Gyeonggi

While the atmospheric concentrations of the majority of air pollutants have decreased over the past decades, one pollutant, ground-level O_3 has been increasing (Figures 2.6–2.9). Ground-level O_3 is not directly emitted but is formed through the photochemical reaction of NO_x, VOCs, methane (CH_4), and CO in the atmosphere. Ozone has an atmospheric lifetime of three weeks, meaning that it can be transported over long distances. The time required for O_3 formation after the emission of NO_x, VOCs, CH_4 and CO means that O_3 concentrations often occur further downwind of major sources rather than in the immediate vicinity. The photochemical nature of O_3 formation also means that concentrations are typically highest during the summer months and lowest in the winter.

While NO_x contributes to the formation of O_3 in the atmosphere, it also contributes to its destruction. The three-week atmospheric lifetime of O_3 means that in SIG, background O_3, i.e. transported O_3, can be transported from other Asian countries and even other continents. In areas with relatively high NO_x concentrations, this background O_3 can be destroyed (titrated), leading to lower O_3 concentrations in the centre of major cities compared to surrounding ones with lower NO_x concentrations. This feature of O_3 chemistry has been observed over decades globally, including in SIG. Over the past decades, however, as NO_x emissions and atmospheric concentrations in SIG have fallen, O_3 concentrations have simultaneously increased. At an urban site in Seoul, for example, between 2004 and 2013, NO_x concentrations decreased from 78 ppb to 61 ppb. At the same time, average O_3 concentrations increased from 13 ppb in 2004 to 18 ppb (Vellingiri *et al.* 2015). Across SIG, average daily maximum 8-hour O_3 concentrations were about 25 ppb in 2005 but by 2016, had risen to around 60 ppb.

Ozone is an air pollutant that has negative impacts on the respiratory system. In 2019, 1 500 premature deaths in the Republic of Korea were estimated to be attributable to O_3 exposure (Murray *et al.* 2020). While not toxic as PM, both short- and long-term O_3 exposure can damage human health. Therefore, while the dominant trend of air pollutant concentrations in SIG over the last 20 years has been downward, a consequence of the emissions reduction policies has been an increase in O_3 concentrations due to a reduction in the destruction of O_3 transported into SIG.

Emissions from outside Seoul, Incheon and Gyeonggi make substantial contribution to air pollution, especially during high concentration episodes

The health impacts of air pollution result from both short-term exposure to elevated concentrations and from long-term exposure. The majority of the health burden results from long-term, chronic exposure, but short-term episodes can prompt emergency responses to reduce concentrations. As a result of these two timescales, the Republic of Korea has established air quality standards for short (daily) and long (annual) time periods.

Multiple studies have shown that emissions from outside SIG make a substantial contribution on both timescales. Therefore, while significant reductions in concentrations have and could be made through action taken to reduce emissions in SIG, it is not possible for this action to fully mitigate the emissions that result in degraded air quality.

The contribution of long-range, transboundary transport to $PM_{2.5}$ levels in SIG has been assessed using a variety of different observational and modelling techniques. These studies show that for short-term episodic periods of high PM concentrations, long-range transport plays a substantial role in driving their elevated levels. Based on 11 years of observations in Seoul between 2008 and 2019, for example, the contribution of long-range transport and local pollution to high PM_{10} episodes, more than 50 $\mu g/m^3$, were estimated to vary across the year. On average, long-range transport of emissions from outside SIG were estimated to contribute around 30 per cent of PM_{10} pollution during high concentration episodes, with local sources contributing about 45 per cent and the remainder being unclassified. High winter PM_{10} episodes had, however, higher long-range PM_{10} contributions of around 40 per cent during episodes in October–January (Park *et al.* 2021). This suggests that although substantial contributions could be made through emissions reductions implemented locally, emissions reductions in other regions will be necessary to fully alleviate high PM_{10} episodes in SIG.

Other studies assessing the determinants of specific high $PM_{2.5}$ concentration periods have estimated larger contributions from long-range transport. The contribution of emissions from different regions to $PM_{2.5}$ concentrations in May 2009–2013 in Seoul were assessed and more than 70 per cent of the organic carbon, elemental carbon, sulphate and nitrate components of $PM_{2.5}$ during these periods were estimated to result from transboundary transport (Lee *et al.* 2017).

Other studies assessing meteorological conditions have identified the presence of strong high-pressure weather systems over Northeast Asia during times when PM_{10} concentrations in Seoul are elevated. They identify these conditions as being particularly conducive to producing elevated PM concentrations in SIG because emissions from beyond the Republic of Korea are trapped within the boundary layer and disperse over the Republic of Korea, but cannot escape and be ventilated (Oh *et al.* 2015). In January 2019, hourly $PM_{2.5}$ concentrations were as high as 188 $\mu g/m^3$, among the highest concentrations ever recorded. When $PM_{2.5}$ concentrations at monitoring stations in the Yellow Sea were assessed, their concentrations were also elevated, indicating the westerly transboundary transport of pollution to the Korean peninsula. Atmospheric modelling of the pollution episodes, which occurred in the Republic of Korea in January 2019 indicates that 60–70 per cent of $PM_{2.5}$ concentrations in Seoul in January 2019 resulted from transboundary transport of emissions (Oh and Park, 2022).

In addition to the large contribution that long-range transboundary transport of emissions originating beyond the Republic of Korea make to high PM concentration episodes in SIG, studies have also assessed the contribution of transboundary transport of emissions to long-term (annual) concentrations and estimate that they make a substantial contribution to annual average PM concentrations. In 2015 and 2016, emissions originating beyond the Republic of Korea were estimated to contribute 47 per cent and 43 per cent of annual average $PM_{2.5}$ concentrations in Seoul, respectively (Kumar *et al.* 2021). The contributions of emissions originating outside the Republic of Korea are highest in winter and spring, and lowest in summer. In March 2015, for example, the contribution from emissions originating outside the Republic of Korea was as high as 57 per cent of total monthly average $PM_{2.5}$ emissions (Kumar *et al.* 2021).

While the peak and annual average contributions of long-range transport to $PM_{2.5}$ concentrations are substantial, over the past few years efforts taken by neighbouring countries to reduce their emissions have been shown to have reduced $PM_{2.5}$ concentrations across the Republic of Korea. Geostationary satellite observations of aerosol concentrations have been combined with ground-based measurements and back-trajectory analysis to assess the contribution of long-range transport to $PM_{2.5}$ concentrations in SIG (Bae *et al.* 2021; Lee *et al.* 2021). Between 2015 and 2018, the contribution of long-range transport was estimated to contribute 33 per cent to annual average $PM_{2.5}$ concentrations. During long-range transport events, however, $PM_{2.5}$ concentrations in SIG were estimated to be 52 per cent higher than the 2015–2018 annual average (Lee *et al.* 2021). The reduction in $PM_{2.5}$ concentrations observed between 2015 and 2018 was evaluated using similar approaches to understand the contribution of emissions reductions compared to changes in meteorology. It was shown that approximately half the reductions of $PM_{2.5}$ concentrations across the Republic of Korea were due to changes in meteorology between 2015 and 2018, and half due to reductions in emissions. This included reductions in emissions in upwind countries that have contributed to reductions in $PM_{2.5}$ concentrations across the Republic of Korea (Bae *et al.* 2021).

Multiple different sectors contribute to air pollution levels in Seoul, Incheon and Gyeonggi

In addition to the complexity of multiple geographic emissions sources contributing to $PM_{2.5}$ pollution in SIG, there are also a myriad of sectors which determine air pollution levels in the city. Reducing concentrations in SIG, therefore, requires that emissions from multiple source sectors, both within and out of the area, are reduced. The range of sources contributing to $PM_{2.5}$ concentrations in SIG varies across the year and location, for example, proximity to particular sources. At one urban site in Seoul in 2014 and 2015, approximately 40 per cent of the measured $PM_{2.5}$

concentrations were made up of secondary inorganic aerosols, i.e., ammonium nitrate and ammonium sulphate. Secondary inorganic aerosols are formed in the atmosphere by chemical reactions following the primary emission of gaseous pollutants such as NO_X, SO_2 and NH_3. The largest sources of NO_X typically include transport, but industry, households and electricity generation are other possible substantial sources. Sulphur dioxide is emitted by the combustion high sulphur fuels, including solid fuels, such as coal and liquid fuels, such as high-sulphur diesel. Ammonia is primarily emitted from the agricultural sector, including from synthetic fertilizers, manure management and organic fertilizer application (Park *et al.* 2020).

A further 23 per cent of $PM_{2.5}$ measured at the site was estimated to be primary particles directly emitted from mobile sources, underlining the large contribution of the transport sector in determining the levels of $PM_{2.5}$ in SIG. The burning of fossil fuels in industry was estimated to make a significant contribution with 9 per cent of the $PM_{2.5}$ mass concentration from oil combustion and 4 per cent from coal combustion. Biomass burning was estimated to contribute 12 per cent of $PM_{2.5}$ annual mass concentrations, and soil dust contributed 8 per cent. Aerosols derived from sea salt contributed 1 per cent of the $PM_{2.5}$ mass concentration (Park *et al.* 2020).

Previous studies, which have quantified the contribution of different sources to $PM_{2.5}$ concentrations at other sites across SIG, have estimated similar contributions of different emission sources (Park 2004). In 2019, further measurements of $PM_{2.5}$ concentrations in Seoul indicated that secondary nitrate and secondary sulphate contributed 25.5 and 20.5 per cent to annual $PM_{2.5}$ mass at the site. The contribution from mobile sources was lower than at the site measured in 2014/2015, less than 10 per cent of the $PM_{2.5}$ mass. There were, however, large contributions from oil combustion and biomass burning. Incineration of waste was an additional source identified at this site, which made a similar contribution of about 8 per cent to mobile sources (Park *et al.* 2022).

Other major sources have been shown to have a significant impact on air quality in their locality. The emission associated with aircraft take-off and landing cycles, for example, as well as on ground operations at Incheon International Airport, and other airports in SIG, negatively affect air quality around them. Specifically, at Incheon airport, O_3 and NO_X concentrations were significantly higher than at other locations due to airport emissions (Song *et al.* 2015).

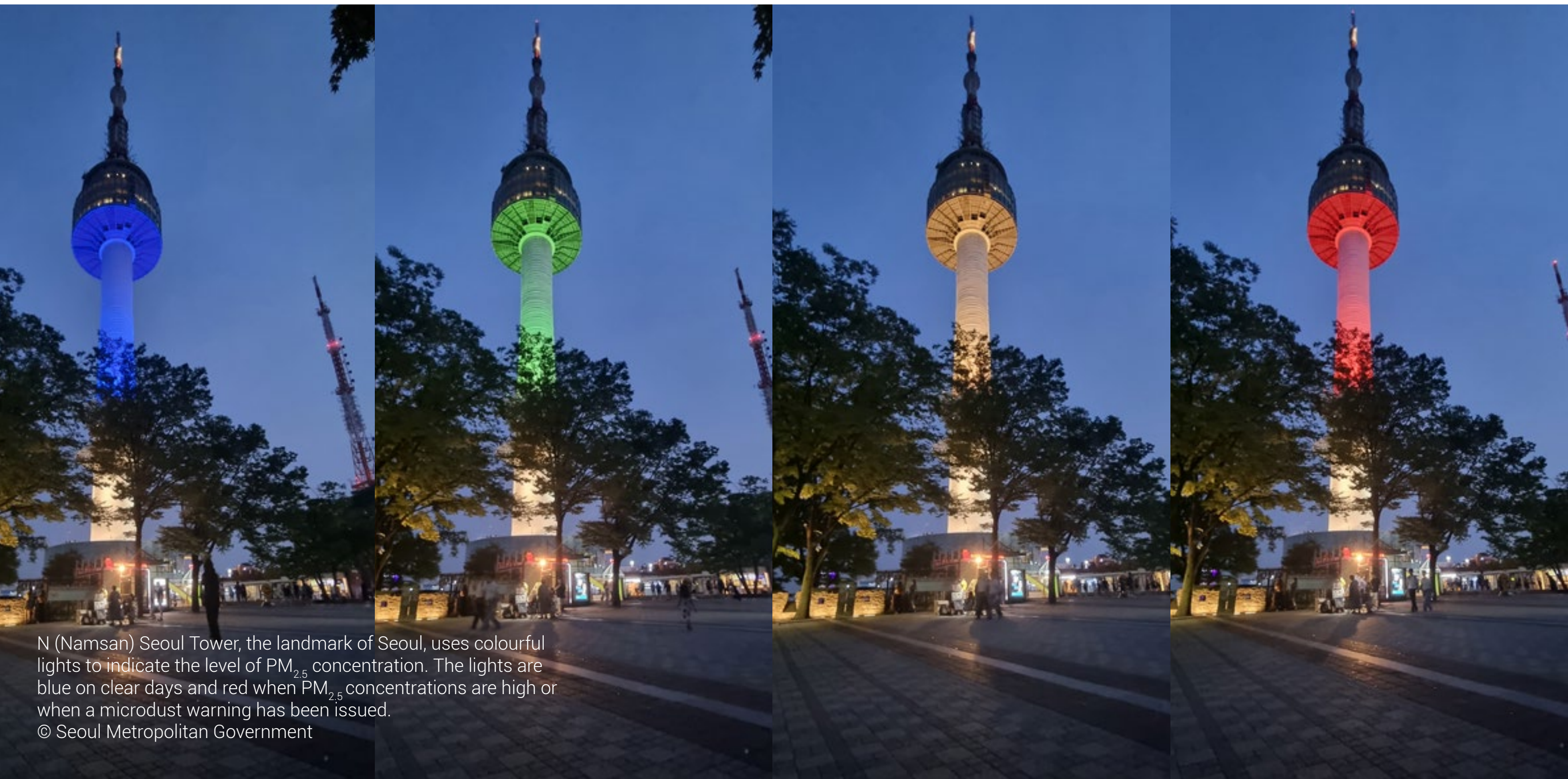
COVID-19 measures contributed to lower air pollution levels in 2020

Air quality globally was impacted by measures put in place to reduce the spread of COVID-19. In many locations, concentrations of air pollutants decreased substantially due to reductions in transport demand and lower industrial activity. In Seoul, the implementation of COVID-19 reduction measures also resulted in substantial falls in air pollutant concentrations. Thirty days after social distancing was imposed in the Republic of Korea, for example, $PM_{2.5}$ concentrations were 10.4 per cent lower than in the 30 days prior to the introduction of these measures. Nitrogen dioxide and CO concentrations also decreased substantially, by 16 and 17 per cent respectively (Han and Hong 2020). Other studies have shown even larger reductions in $PM_{2.5}$ concentrations in Seoul during the COVID-19 pandemic. Compared to previous years, concentrations in Seoul in January–April 2020 of 25.6 $\mu g/m^3$ were more than 4 $\mu g/m^3$ lower than for the same period during the previous four years (Han *et al.* 2020). March 2020 $PM_{2.5}$ concentrations were estimated to be 36 per cent lower than March 2017–2019 concentrations (Seo *et al.* 2020). The lower $PM_{2.5}$ concentrations during the period of pandemic were also helped by more frequent northerly winds, which resulted in relatively lower transboundary contributions to air pollution in SIG.

2.3 Air pollution exposure

Section 2.1 shows that a large number of studies have assessed the atmospheric concentrations of air pollutants in SIG. There have, however, been fewer studies that have assessed how citizens of SIG are exposed to these concentrations. Previous studies in other locations have demonstrated that measurements of ambient concentrations are imperfect proxies for population exposure to $PM_{2.5}$. Firstly, people spend a majority of time indoors, including in SIG where people are on average estimated to spend 90 per cent of their time indoors (Lim *et al.* 2012). The infiltration of outdoor air indoors and the deposition of PM on surfaces can result in lower $PM_{2.5}$ concentrations indoors (Dimitroulopoulou *et al.* 2006). Alternatively, the presence of indoor emissions sources can elevate indoor $PM_{2.5}$ concentrations beyond those that are measured outside (Malley *et al.* 2020). Secondly, people spend different amounts of time in different places where $PM_{2.5}$ concentrations vary. This can result in substantial differences in exposure to $PM_{2.5}$ for population groups who have different jobs, who live in different areas and who travel by different transport modes. This often results in disparities in exposure to air pollution across genders, ages and socioeconomic status.

There are limited studies on the exposure of different population groups to air pollutants in SIG. The most comprehensive one simulated the daily activities of 10 representative population groups in Seoul, based on more than 2 000 time-activity patterns of people within the city. The representative population groups, whose daily activities were undertaken while monitoring $PM_{2.5}$ concentrations, included housewives, 20-40-year-old workers, teenage students, university students, senior citizens, male and female service workers and 20-40-year-old unemployed people. These population groups spend different amounts of time at home, in buildings that are not their homes, outdoors and using transport. Although the overall average daily $PM_{2.5}$ exposure was about 20 $\mu g/m^3$, it varied between population groups. Both the lowest and highest daily $PM_{2.5}$ exposure was estimated for different groups of office workers, the lowest was 9.8 $\mu g/m^3$; the highest was 43.1 $\mu g/m^3$. The primary distinction between groups of office workers was that those with highest exposures visited restaurants after work, whereas those with lowest exposure went home. The restaurants concerned cooked using charcoal directly on the table where customers were eating, leading to average $PM_{2.5}$ concentrations in those restaurants of



N (Namsan) Seoul Tower, the landmark of Seoul, uses colourful lights to indicate the level of $PM_{2.5}$ concentration. The lights are blue on clear days and red when $PM_{2.5}$ concentrations are high or when a microdust warning has been issued.
© Seoul Metropolitan Government

388 µg/m^3. In contrast, those restaurants where food was cooked in the kitchen had substantially lower average $PM_{2.5}$ concentrations of 22 µg/m^3. Housewives and teenage students also had relatively lower $PM_{2.5}$ exposure compared to other population groups, while university students and senior citizens had relatively higher ones.

A second study assessed almost 4 000 time-activity patterns of Seoul residents and $PM_{2.5}$ concentrations in seven microenvironments to assess population exposure. Average population $PM_{2.5}$ exposure varied seasonally, peaking in winter at around 30 µg/m^3, and reaching a minimum in autumn at 9.8 µg/m^3. The population in Seoul was disaggregated into high-mean $PM_{2.5}$ exposure of 45 µg/m^3; medium, 28 µg/m^3; and low, 20 µg/m^3 exposure groups. The association between different socioeconomic characteristics and membership of these exposure groups was assessed, and age, gender, working status, working hours, monthly income and health conditions were significantly associated with membership of each group. More men were identified as being part of the high-exposure group, and the average age of people in this group was substantially higher than the other exposure groups. The higher exposure group had higher monthly incomes and on average worked longer hours than the lower exposure groups. The low-exposure group on average spent about 80 per cent of their time at home, compared to around 60 per cent for the high-exposure group, who spent a substantially larger fraction of time at other indoor locations such as offices (Guak *et al.* 2021).

These studies underline the importance of considering both the $PM_{2.5}$ concentrations in different microenvironments, which might be substantially different from measured ambient $PM_{2.5}$ concentrations, and the amount of time that people spend in each microenvironment to determine a population's exposure to $PM_{2.5.}$ Several other studies have highlighted microenvironments across SIG in which $PM_{2.5}$ concentrations are elevated, particularly public transport systems. Several studies have assessed concentrations in SIG's subway system, in which stations and train carriages have low levels of ventilation, while $PM_{2.5}$ emissions from brake abrasion add to concentrations. Assessments of concentrations of $PM_{2.5}$ across the subway network found particularly high values on platforms, 129 µg/m^3; drivers' seats, 129 µg/m^3; passenger carriages, 126 µg/m^3, with concentrations lower but elevated in stations, 88 µg/m^3, and ticket offices, 65 µg/m^3 (Kim *et al.* 2012). Hence, when determining $PM_{2.5}$ exposure, commuters or workers on Seoul's subway may be exposed to elevated $PM_{2.5}$ concentrations compared to people who use other transport modes. Public buses, for example, have been measured to have lower $PM_{2.5}$ concentrations than the subway (Lee *et al.* 2022).

Since the 2008 study of $PM_{2.5}$ in Seoul's subway system, however, there have been interventions that have resulted in lower $PM_{2.5}$ concentrations in previously high areas. In 2007, a screen door system was installed at subway station platforms, potentially reducing the infiltration of $PM_{2.5}$ emissions from trains into platform areas (Kim *et al.* 2012). The installation of this system was estimated to reduce $PM_{2.5}$ concentrations on station platforms by 16 per cent. In addition, the public bus system has been fitted with air purification systems that can reduce the $PM_{2.5}$ concentrations substantially. Across three buses with the air purification systems in Gyeonggi, their installation lowered $PM_{2.5}$ concentrations inside the buses by 34–60 per cent. These studies demonstrate that a targeted approach to lessening exposure in specific microenvironments can lead to substantial $PM_{2.5}$ reductions and contribute to decreasing the exposure of people who regularly use these services or spend time within these microenvironments.

Multiple epidemiological studies conducted in SIG have identified a direct link between air pollution levels and a range of negative health impacts.

2.4 Air pollution health impacts

There is a wealth of evidence globally of the negative effects of air pollution on human health. This evidence has been regularly synthesized and has led to global organizations, such as WHO, establishing air quality guideline values for the protection of human health. The literature on air pollution's health burden shows that it impacts human health through multiple mechanisms, including through incidences and exacerbation of respiratory and cardiovascular disease, lung cancer, Type II diabetes, low birth weight and preterm birth. The negative health impacts of air pollution include excess mortality and morbidity, and result from both long-term (annual) air pollution exposure and exposure to short-term high concentration episodes. Multiple pollutants have been identified as being toxic and their concentrations in the atmosphere are determined by emissions from multiple sources across different geographic scales.

The level of PM, NO_x and O_3 concentrations in the atmosphere of SIG are above WHO Air Quality Guidelines for the protection of human health and in some cases exceed the national ambient air quality standards of the Republic of Korea.

Multiple epidemiological studies conducted in SIG have identified a direct link between air pollution levels in the region and a range of negative health impacts. Levels of $PM_{2.5}$ in SIG have been associated with increased risks of mortality and morbidity – $PM_{2.5}$ and PM_{10} exposure, for example, has been associated with acute stroke mortality (Hong *et al.* 2002), lung cancer incidence (Yang *et al.* 2021), heart disease (Kang *et al.* 2016), circulatory diseases (Choi and Kim 2021), respiratory diseases (Park 2019) and cardiovascular disease (Choi *et al.* 2019). One study in Seoul assessed the association of specific $PM_{2.5}$ components and PM from specific sources with overall mortality. While overall $PM_{2.5}$ mass was significantly associated with mortality, other components, particularly organic carbon, elemental carbon and lead (Pb) were also associated with mortality. Particulate matter from mobile sources and biomass burning were the sources of $PM_{2.5}$ most associated with mortality (Heo *et al.* 2014).

Other pollutants, particularly O_3, have also been associated with negative health impacts in SIG. Daily mean O_3 concentrations were compared with daily mortality rates between 2001 and 2009 in Seoul, and a significant negative association was calculated (Bae *et al.* 2020).

Air pollution disproportionately affects women, especially pregnant women, and young children and are more at risk due to structural and biological differences, including low wages, in decent jobs, and cultural and gender roles. Air pollution can further increase the risk of certain diseases among children and elderly persons causing long-term health problems.

Direct evidence of the negative impact of air pollution on human health in Seoul demonstrates the necessity to implement policies designed to reduce emissions and exposure. Health impact assessment studies have also been conducted in SIG to understand the magnitude of the health burden associated with the negative impacts of exposure to air pollution on human health. Health burdens have been estimated for $PM_{2.5}$ exposure for mortality from ischemic heart disease, chronic obstructive pulmonary disease, lung cancer and strokes. In Seoul, Incheon and Gyeonggi, population-weighted annual $PM_{2.5}$ concentrations were estimated to be 24.2 μg/m^3, 27.6 μg/m^3 and 25.0 μg/m^3 respectively in 2015. This level of exposure was estimated to be associated with 1 763 premature deaths in Seoul, 309 in Incheon and 2 352 in Gyeonggi in 2015. These 4 424 premature deaths per year associated with air pollution in SIG were 37 per cent of the total estimated air pollution health burden in the Republic of Korea. The majority of these premature deaths resulted from strokes, with heart disease and lung cancer being the second and third major causes. Between 2006 and 2015, the number of premature deaths associated with air pollution exposure was estimated to have decreased substantially in all three regions (Han *et al.* 2018). In Seoul, there were almost 1 000 fewer premature deaths per year in 2015 compared to 2006, while in Gyeonggi and Incheon, there were around 600 and 100 fewer respectively.

The health impacts outlined above typically affect adults, predominantly older people and/or people with underlying health conditions. Studies conducted in SIG, however, show that air pollution in the region also impacts children. In Seoul, an assessment of 360 000 births showed a significant association between infant exposure to PM_{10} and infant mortality (Son *et al.* 2011). Exposure to $PM_{2.5}$ has been associated with reduced peak expired flow in asthmatic children in Incheon, and with increased incidence of attacks in asthmatic children in Seoul (Kim *et al.* 2020). Maternal exposure to PM_{10} has also been significantly associated with low birth weight. In Seoul and Incheon, 7 and 11 per cent of all low birth weight births were estimated to be the result of maternal PM_{10} exposure (Seo *et al.* 2010).

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2.5 Air pollutant emissions

The concentrations of air pollutants in SIG are determined both by local air pollutant emissions and the transport of air pollution from other regions. Estimates of air pollutant emissions for SIG, therefore, represent a subset of the totality of emissions that contribute to the ambient concentrations measured and experienced in SIG. There is, however, a possibility that the magnitude of emissions emitted in SIG has been underestimated as these are the emissions which are within the control of local or national governments to reduce through air pollution reduction and gender-responsive policies and measures.

Section 2.1 highlights that within the Republic of Korea's legal framework to tackle air pollution, and it is the responsibility of the Ministry of Environment to develop and maintain a national emission inventory. The National Air Emission Inventory and Research Center (NAIR) estimates annual emissions of CO, NO_X, SO_X, TSP, PM_{10}, $PM_{2.5}$, BC, VOCs, and NH_3, through the Clean Air Policy Support System (CAPSS). Emissions are calculated by applying the emissions factors and control efficiency for each emission source/fuel to the appropriate activity level for each source. Note that emissions from fugitive dust and biomass burning were only included in the CAPSS inventory from 2015.


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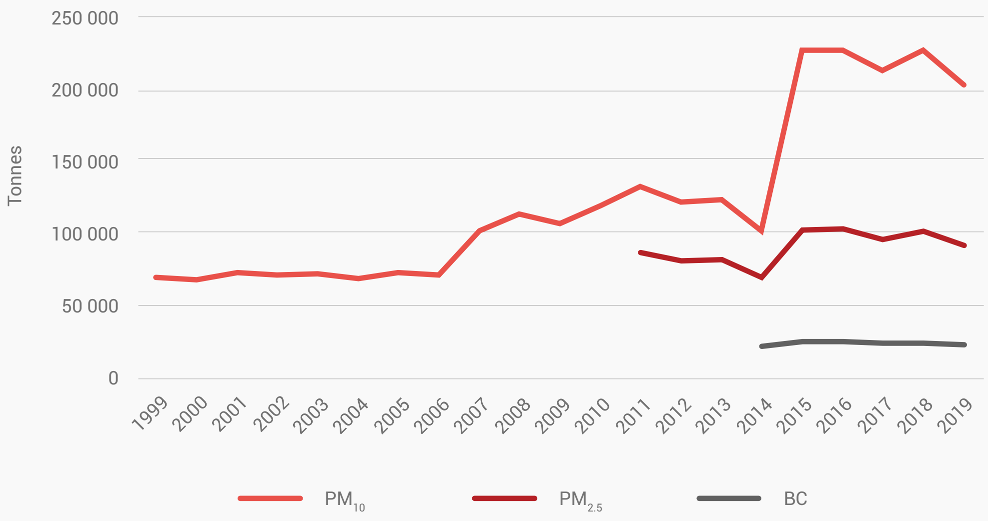
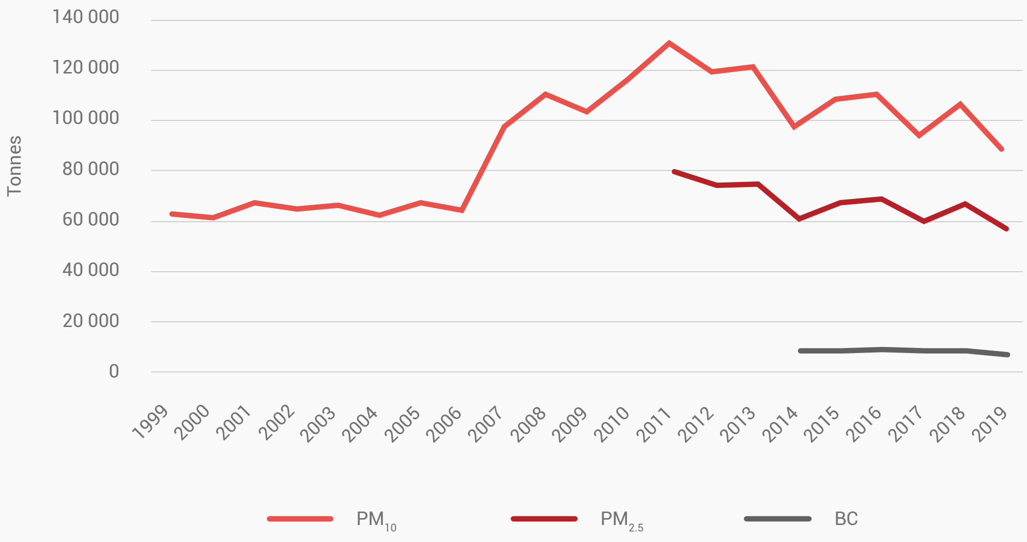
Figure 2.10
Air pollutant emissions of coarse and fine particulate matter (PM_{10}), fine particulate matter ($PM_{2.5}$), and black carbon, including emissions of fugitive dust and biomass burning, the Republic of Korea, 1999–2019, tonnes



Source: National Air Emission Inventory and Research Center

Figure 2.11
Air pollutant emissions of coarse and fine particulate matter (PM_{10}), fine particulate matter ($PM_{2.5}$), and black carbon, including emissions of fugitive dust and biomass burning, the Republic of Korea, 1999–2019, tonnes



Source: National Air Emission Inventory and Research Center

The contribution of different sources to air pollutant emissions in the Republic of Korea are shown for 2005 in Table 2.4 and Figure 2.12, and for 2019 in Table 2.5 and Figure 2.13 from the emission inventory developed by the National Air Emission Inventory and Research Center. Across the Republic of Korea, manufacturing industry makes the largest contribution to primary $PM_{2.5}$ emissions, 37 per cent of total emissions in 2019. Fugitive dust and non-road transport were the second largest sources. For NO_X, road and non-road transport were the dominant sources, contributing 60 per cent of national total NO_X emissions, with manufacturing industry the next largest source, responsible for 14 per cent. Sulphur dioxide is emitted mostly from industrial processes, 31 per cent, and energy production, 26 per cent. Ammonia is emitted predominantly from agriculture. Figures 2.10 and 2.11 show particulate emissions with and without the inclusion of fugitive dust and biomass burning. Figure 2.10, which includes these sources of emissions after their first estimation in 2015, shows a large increase in emissions between 2014 and 2015 as a result of their inclusion. This reflects the methodological update to the emission inventory rather than actual changes in the magnitude of emissions between these years. Figure 2.11 shows the time-series of particulate emissions excluding fugitive dust and biomass burning to show the trend in emissions without the increase resulting from the inclusion of these sources, and highlights that, for other sources, emissions of $PM_{2.5}$ fell between 2010 and 2019.

Between 2005 and 2019, the emissions of most pollutants decreased, in particular from the road transport sector, from which PM_{10} emissions decreased by 73 per cent, and NO_X emissions fell by 19 per cent. Several other sectors had increases in emissions between 2005 and 2019, including the manufacturing industry, non-road transport and agriculture.

Several studies have presented summaries of the National Air Pollutant Emission Inventory. As shown in Tables 2.4 and 2.5 and Figures 2.12 and 2.13, these highlight the contribution of different source sectors, and temporal trends in emission magnitudes across different years. Choi *et al.* (2021) presented an assessment of the 2017 National Air Pollutant Emission Inventory (CAPSS 2017), which showed a broadly similar contribution by sectors as described above. For $PM_{2.5}$, manufacturing industry made the largest contribution, 31 per cent, to emissions in 2017, followed by fugitive dust, 19 per cent; non-road transport, 16 per cent; biomass burning, 13 per cent and road transport, 10 per cent. For BC, however, a component of $PM_{2.5}$ that has been identified as being particularly toxic, 43 per cent of total national emissions came from non-road transport and 34 per cent from road transport. These categories also contributed the majority of NO_X emissions, 37 per cent from road transport and 26 per cent from non-road transport. For SO_2, 34 per cent was emitted from industrial processes, 25 per cent from energy production and 23 per cent from manufacturing industry. For VOC emissions, 54 per cent came from solvent use and industrial processes contribute 18 per cent. Finally, 79 per cent of NH_3 emissions came from agriculture. Compared to 2016, emissions from some key sources decreased in 2017, with emissions from the energy sector falling by 3–23 per cent for different pollutants. This includes reductions in public power generation and manufacturing industry. Road transport emissions also decreased, with a 4 per cent reduction in NO_X emissions, and a 10 per cent fall in $PM_{2.5}$ emissions compared to 2016. Emissions from the non-road sector increased between 2016 and 2017 mainly due to increases in shipping, except for SO_2, which also decreased from non-road sources.

Choi *et al.* (2021) also breaks down total national emissions by different regions (Table 2.6). In 2019, Seoul, Incheon and Gyeonggi together emitted less than 20 per cent of national total $PM_{2.5}$ emissions, but substantially larger fractions of other pollutants. For example, approximately 33 per cent of national BC and VOC emissions originated in SIG together with around 27 per cent of NO_x emissions. This reflects the different contributions of major sources to emissions of these pollutants, and where those major sources are located in the Republic of Korea. Black carbon and NO_X are mainly emitted from transport, which is highly concentrated in SIG but $PM_{2.5}$ has multiple sources including industry, much of which is located outside of SIG. A relatively small component of NH_3 emissions originate in Seoul and Incheon, but 15 per cent of its total national emissions originate in Gyeonggi, the second largest contribution by a single province.

Table 2.4

Air pollutant emissions by emission source, the Republic of Korea, 2005, tonnes

Emission Source	PM_{10}	SO_X	NO_X	VOCs	NH_3	CO
Energy production	8 229	139 064	390 895	5 326	1 335	35 889
Non-industry	2 978	58 706	93 658	3 041	1 706	79 759
Manufacturing industry	16 000	68 181	108 186	2 426	1 048	14 342
Industrial process	6 888	82 371	55 327	134 493	44 701	22 882
Energy transport and storage				25 933		
Solvent use				432 828		
Road transport	25 312	5 190	455 217	102 198	10 946	584 485
Non-road transport	7 870	53 506	188 631	18 461	481	49 613
Waste disposal	64	1 444	14 811	31 715		1 948
Agriculture					174 738	
Other surface-pollutant source					12 196	
Total	67 341	408 462	1 306 725	756 421	247 151	788 918

Source: Korea Environment Corporation (KeCO), National Air Emission Inventory and Research Center

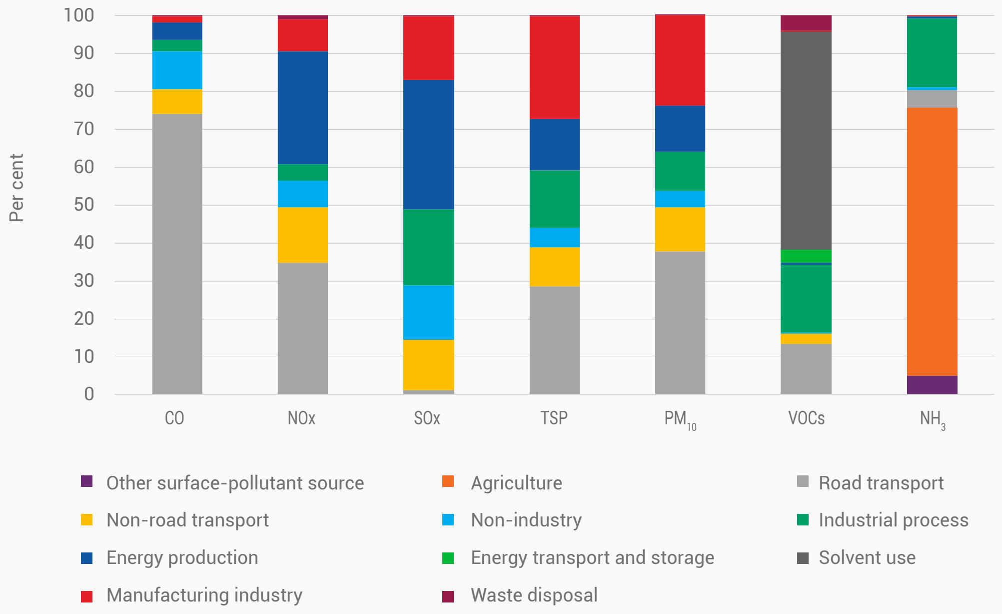
Table 2.5

Air pollutant emissions and by emission source, the Republic of Korea, 2019, tonnes

Emission Source	CO	NO_X	SO_X	PM_{10}	$PM_{2.5}$	VOCs	NH_3	BC
Energy production	64 327	75 513	45 297	3 365	2 813	8 434	1 422	372
Non-industry	47 629	85 814	15 869	1 177	857	2 828	1 350	180
Manufacturing industry	19 737	169 221	65 730	52 932	27 118	3 404	717	623
Industrial process	26 766	51 705	105 699	6 699	5 139	186 292	44 630	15
Energy transport and storage						29 062		
Solvent use						545 244		
Road transport	180 489	371 851	308	6 719	6 182	36 663	2 615	3 801
Non-road transport	187 565	311 748	37 555	17 265	15 989	63 951	122	6 904
Waste disposal	2 140	12 332	2 326	267	228	59 537	22	3
Agriculture							252 444	
Other surface-pollutant source	10 552	271		599	539	1 281	12 962	40
Fugitive dust				105 037	17 272			122
Biomass burning	218 642	8 407	75	13 806	11 482	83 521	15	2 151
Total	757 847	1 086 862	272 859	207 866	87 619	1 020 217	316 299	14 211

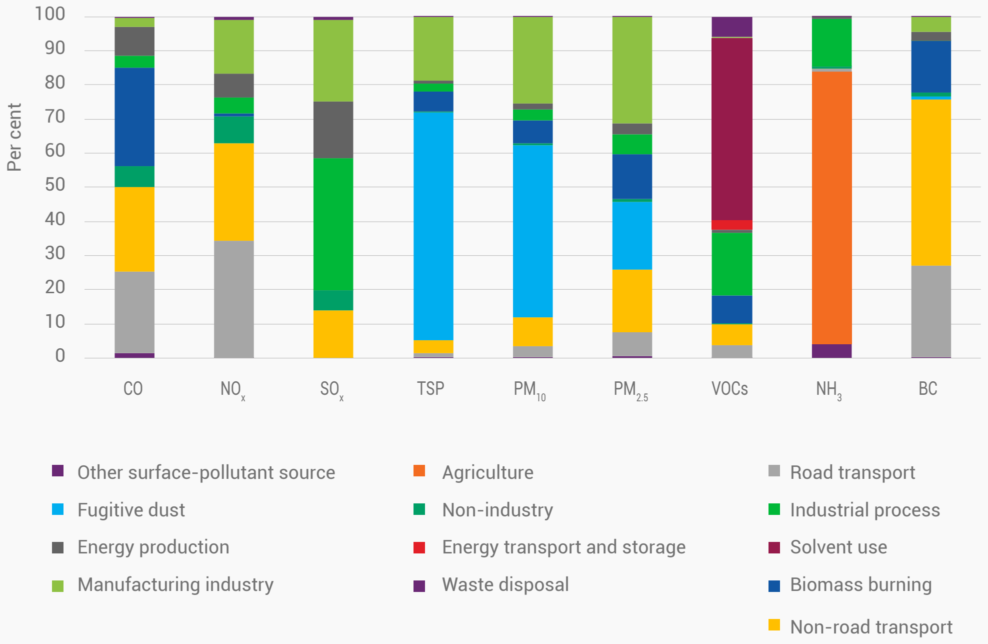
Source: Korea Environment Corporation (KeCO), National Air Emission Inventory and Research Center

Figure 2.12
Contribution of different sources to short-lived climate pollutants and air pollutants, the Republic of Korea, 2005, per cent



Source: Korea Environment Corporation (KeCO), National Air Emission Inventory and Research Center

Figure 2.13
Contribution of different sources to short-lived climate pollutants and air pollutants, the Republic of Korea, 2019, per cent



Source: Korea Environment Corporation (KeCO), National Air Emission Inventory and Research Center

The concentrations of air pollutants in SIG are determined both by local air pollutant emissions and the transport of air pollution from other regions.

Table 2.6

Total emissions of air pollutants from Seoul, Incheon, Gyeonggi and the Republic of Korea, 2019, thousand tonnes

	CO_2	CO	CH_4	NMVOC	NO_X	PM_{10}	SO_2	NH_3	$PM_{2.5}$
Republic of Korea	643 767.2	757.8	1 297.6	1 020.2	1 086.9	207.9	272.9	316.3	87.6
Seoul	41 812.5	46.6	125.2	63.7	71.0	9.7	1.0	3.5	2.7
Incheon	52 989.6	39.2	-1.5*	52.9	52.9	7.2	11.3	6.7	2.5
Gyeonggi	71 096.3	125.0	205.2	188.4	170.7	29.9	9.0	47.4	9.9

Source: Korea Environment Corporation (KeCO), National Air Emission Inventory and Research Center
(*): This negative CH_4 value for Incheon is because of methodology which subtracts emissions from wastes generated in other cities but is landfilled in Incheon. Incheon has a huge landfill site to which wastes generated in SIG are transported and treated.

Table 2.7

Contribution to national total emissions of different air pollutants from Seoul, Incheon and Gyeonggi, 2019, per cent

	CO_2	CO	CH_4	NMVOC	NO_X	PM_{10}	SO_2	NH_3	$PM_{2.5}$
Seoul	6.5	6.1	9.6	6.2	6.5	4.7	0.4	1.1	3.1
Incheon	8.2	5.2	-0.1*	5.2	4.9	3.5	4.1	2.1	2.9
Gyeonggi	11.0	16.5	15.8	18.5	15.7	14.4	3.3	15.0	11.3

Source: Korea Environment Corporation (KeCO), National Air Emission Inventory and Research Center
(*): This negative CH_4 value for Incheon is because of methodology which subtracts emissions from wastes generated in other cities but is landfilled in Incheon. Incheon has a huge landfill site to which wastes generated in SIG are transported and treated.

03

Developing emission inventories, baseline and mitigation scenarios for Seoul, Incheon and Gyeonggi

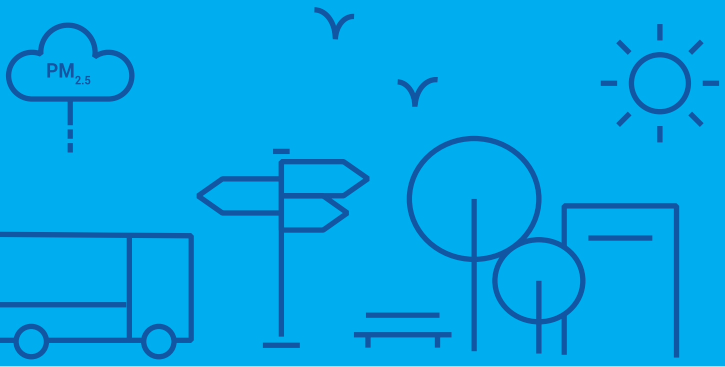
Key Findings

01 To build on the progress on air pollution in Seoul, Incheon and Gyeonggi achieved over the past two decades, it is necessary to assess what policies and measures would be most effective in reducing air pollution over the next decades.

02 An air pollution mitigation assessment was conducted that estimated historic emissions and projected emissions into the future for a baseline scenario with no new policies and measures, and for mitigation scenarios which evaluated the effectiveness of new policies and measures.

03 The key difference in the outlook for air quality management in Seoul, Incheon and Gyeonggi over the next 20 years is the ability to further reduce air pollution alongside decreases in greenhouse gases such as carbon dioxide. Historically, air pollutant emissions have fallen in Seoul, Incheon and Gyeonggi, but carbon dioxide emissions have increased over the past 15 years.

04 The implementation of measures in the Republic of Korea's carbon neutrality scenario, such as the expansion of electricity generation from renewable sources, the introduction of zero-emission vehicles and improving energy efficiency can both reduce air pollution and achieve net zero carbon dioxide emissions by 2050, to which the Republic of Korea is committed.



Air pollutant emissions within Seoul, Incheon and Gyeonggi are produced by multiple sectors, including transport, households, industry, agriculture and waste management.

3.1 Estimating emissions in Seoul, Incheon and Gyeonggi

Chapter 2 reviewed the existing state of knowledge of air pollution in SIG and highlights that current air pollutant concentrations exceed national standards and WHO guidelines for the protection of human health. The research summarized in Chapter 2 shows that the reasons for the elevated fine $PM_{2.5}$ concentrations are due to emissions within SIG, emissions from the rest of the Republic of Korea and in other countries that are then transported to SIG. Despite current levels of air pollutant concentrations being higher than standards and guidelines, substantial progress has been made through the implementation of policies and measures to diminish emissions in SIG, as well as through reductions in emissions in those regions from which pollution is transported to SIG.

This chapter aims to extend the analysis of the current state of air pollution in SIG presented in Chapter 2 to assess how air pollution in SIG could change in the future as a result of socioeconomic development and the implementation of new policies and measures. The focus of this chapter is on the emissions in SIG because, while not the only determinant of air pollution and associated health impacts, it is the component of air pollution that it is possible to directly control within the boundary of each of SIG's local governments. This assessment, therefore, evaluates the extent to which the emissions within these boundaries could be reduced, knowing that reductions elsewhere, i.e. in the rest of the Republic of Korea, the emissions reduction of which are quantified in this assessment, and other Asian countries are necessary to fully reduce air pollutant concentrations in SIG below health-based guidelines. Recommendations on regional cooperation to achieve these emissions reductions are outlined in Chapter 4.

Therefore, the main aims of this chapter and the air pollutant emissions mitigation assessment for SIG are to:

+ estimate historical emissions of air pollutants in SIG and the rest of the Republic of Korea, and assess their trends between 2005 and 2020;

+ project air pollutant emissions from 2021 to 2050 in each region for a baseline scenario, which does not include the implementation of any further policies and measures designed to reduce air pollutant emissions;

- assess the emissions reduction potential in SIG of policies and measures designed to reduce emissions, and specifically to:
    - evaluate how achieving the Republic of Korea's carbon neutrality commitment can reduce air pollutant emissions alongside GHG reductions;
    - identify those sectors that will remain substantial sources of emissions even after the implementation of future policies and measures to identify where future air quality management plans should focus.

The following sections describe the methods and key features of the assessment, and Section 3.2 outlines the results in terms of historical and projected air pollutant emissions in SIG and the rest of the Republic of Korea.

3.1.1 Context for this air pollution mitigation assessment for Seoul, Incheon and Gyeonggi

Air pollutant emissions within SIG are produced by multiple sectors, including transport, households, industry, agriculture and waste management. Before describing the mitigation assessment itself, this section aims to provide the necessary context to understand why these sectors make contributions to air pollution and what are the ultimate drivers in these sectors.

This section presents an overview of key data from each of the sectors that contributes to air pollutant emissions in SIG. The data presented, while providing the context of each major air source sector, are also the basis for estimating air pollutant emissions in SIG and the Republic of Korea in 2005–2020. The methods which use these data to undertake the air pollution mitigation assessment are presented in the following sections.

Demographic and economic variables

The Republic of Korea had a population of almost 52 million people in 2020. Just over half of them, approximately 26 million people, lived in SIG, making it one of the largest metropolitan areas in the world. The Republic of Korea's economy was approximately KRW 1 800 trillion in 2020, equivalent to approximately USD 1.4 trillion. The services and public administration sector contributed approximately 57 per cent to the Republic of Korea's economy, followed by industry, with agriculture making a small contribution. Overall, 48 per cent of the Republic of Korea's economy in 2020 was due to activities within SIG. In Seoul, services and public administration is the large majority of the economy, while in Incheon and Gyeonggi industry makes a larger contribution, even though services contribute the majority of the value added gross domestic product (GDP) in these regions (Table 3.1). The contribution of different industries to industrial GDP is described below under the industry sector.

Table 3.1
Key demographic and macroeconomic variables, the Republic of Korea, Seoul, Incheon and Gyeonggi, 2020

	Republic of Korea	Seoul	Incheon	Gyeonggi
Population (million people)	51.8	9.6	3.0	13.5
Households (million)	20.3	3.9	1.1	4.9
GDP (trillion KRW)	1 839	377	77.9	434
Value added GDP industry, manufacturing, mining and construction	575	26.5	26.2	195
Value added GDP agriculture, forestry and fishing	31.8	0.38	0.28	3.14
Value added GDP services and public administration	1 044	348	47.4	230

Between 2005 and 2020, a significant shift has been made in the replacement of gas devices for cooking and heating with electric devices in SIG.

Households

The 52 million people in the Republic of Korea live in 20 million households (Table 3.1, Figure 3.1). The average household size of 2.55 people per household across the Republic of Korea is lower in Seoul, 2.46 people per household, but higher in Incheon, 2.7 people, and in Gyeonggi, 2.8 people. In terms of energy consumption, which is the main contributor to air pollutant emissions from the households, electricity and natural gas are the two main energy carriers used in households. Electricity consumption is slightly higher in households in Incheon and Gyeonggi, on average, compared to Seoul, and increased in these two regions between 2005 and 2020, but has been flatter in Seoul. Natural gas consumption per household decreased across all three regions between 2005 and 2020 (Table 3.2). This could be attributed to electrification and energy efficiency improvements. Between 2005 and 2020, a significant shift has been made in the replacement of gas devices for cooking and heating with electric ones in SIG. There have also been significant increases in the energy efficiency of key devices such as boilers.

Houses in Jamsil area in Seoul.
© Seoul Metropolitan Government

Table 3.2

Electricity and natural gas consumption per household, the Republic of Korea, Seoul, Incheon and Gyeonggi, 2005–2020, electricity: megawatt[6] hours; gas: tonnes of oil equivalent

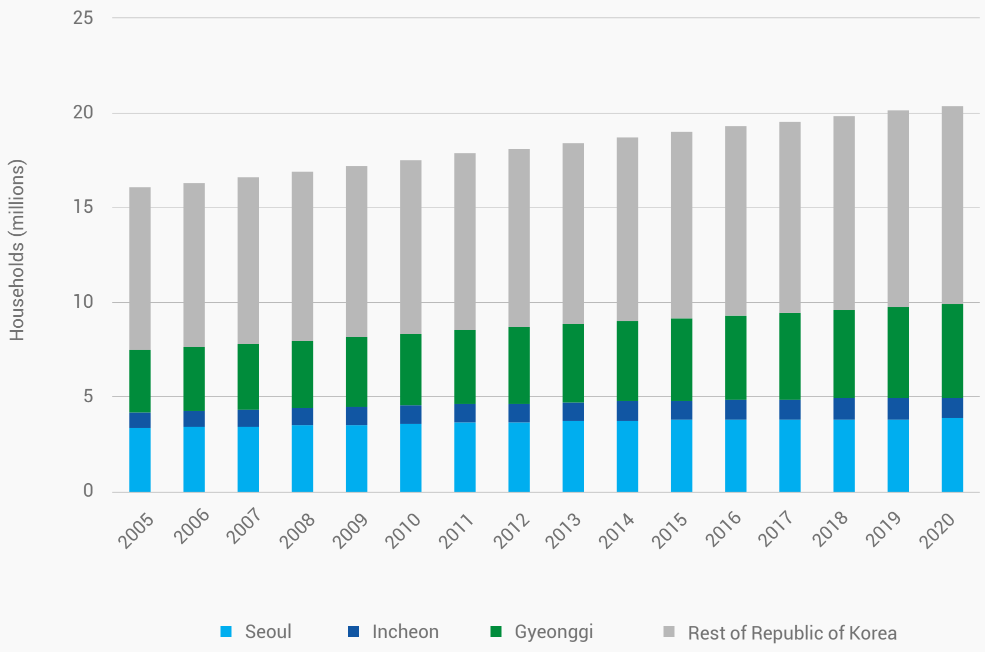
Electricity consumption per household (MWh)	2005	2010	2015	2020
Republic of Korea	3.17	3.50	3.36	3.65
Seoul	3.46	3.66	3.43	3.65
Incheon	3.15	3.51	3.53	3.85
Gyeonggi	3.51	3.81	3.58	3.92

Gas consumption per household (TOE)	2005	2010	2015	2020
Republic of Korea	0.52	0.52	0.44	0.51
Seoul	0.87	0.77	0.59	0.65
Incheon	0.77	0.66	0.50	0.53
Gyeonggi	0.65	0.58	0.45	0.46

Note: MWh: megawatt hour; TOE: tonnes of oil equivalent

Figure 3.1

Households, Republic of Korea disaggregated by region, 2005–2020, millions



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[6] Megawatt = 1 million watts

There has been a large increase in vehicle ownership, but at the same time, more vehicles meet the stringent vehicle emission standards.

Transport

The transport sector has shown substantial changes between 2005 and 2020. For road transport, the total number of vehicles in the Republic of Korea increased by 56 per cent, almost 4 per cent per year (Figure 3.2). Vehicles in SIG made up 44 per cent of the 24 million vehicles on the road in the Republic of Korea in 2020, but the increase has varied between the three regions. In Seoul, there has been a modest increase in the number of vehicles, 14 per cent, between 2005 and 2020, while in Incheon the number of vehicles has more than doubled. In Gyeonggi, there has been a 65 per cent increase (Figure 3.2).

Private passenger cars make up more than half of the vehicles in the Republic of Korea, with recreational vehicles[7] (RVs) and trucks the second and third largest categories. In Seoul, a larger proportion of total vehicles, 62 per cent, are passenger cars, with proportionally fewer trucks. In Incheon and Gyeonggi, the split between vehicle type is more in line with the national average.

The increase in the number of vehicles across the Republic of Korea and SIG has resulted from a large increase in vehicle ownership. Compared to 2005, there has been a substantial increase in the number of passenger cars per person in all regions, with the largest increase in Incheon (Figure 3.3). At the same time, the size of vehicles has also increased, with a smaller number of small passenger cars and an increasing number of medium and large passenger cars[8] (Figure 3.4).

Rush hour traffic in Gangbyeon Expressway, Seoul.
© Seoul Metropolitan Government

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[7] A recreational vehicle (RV) is a motor vehicle or trailer that includes living quarters designed for accommodation.

[8] Vehicle categories according to the Republic of Korea's Motor Vehicle Management Act: light: 1 000 cubic centimetres (cc) or less; small: less than 1 600 cc; medium: less than 2 000 cc and large: greater than 2000 cc.

Figure 3.2

Number of vehicles in the Republic of Korea, a) by vehicle type and b) by region, 2005–2020, thousands

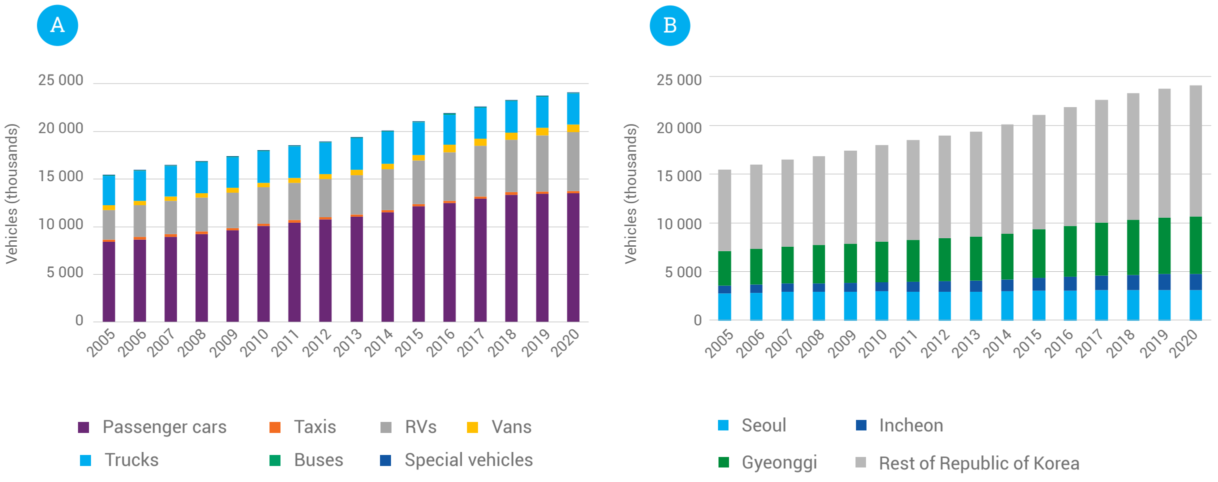


Figure 3.3

Number of vehicles in the Republic of Korea, Seoul, Incheon and Gyeonggi, A) all vehicle types and B) passenger cars, 2005–2020, per thousand people

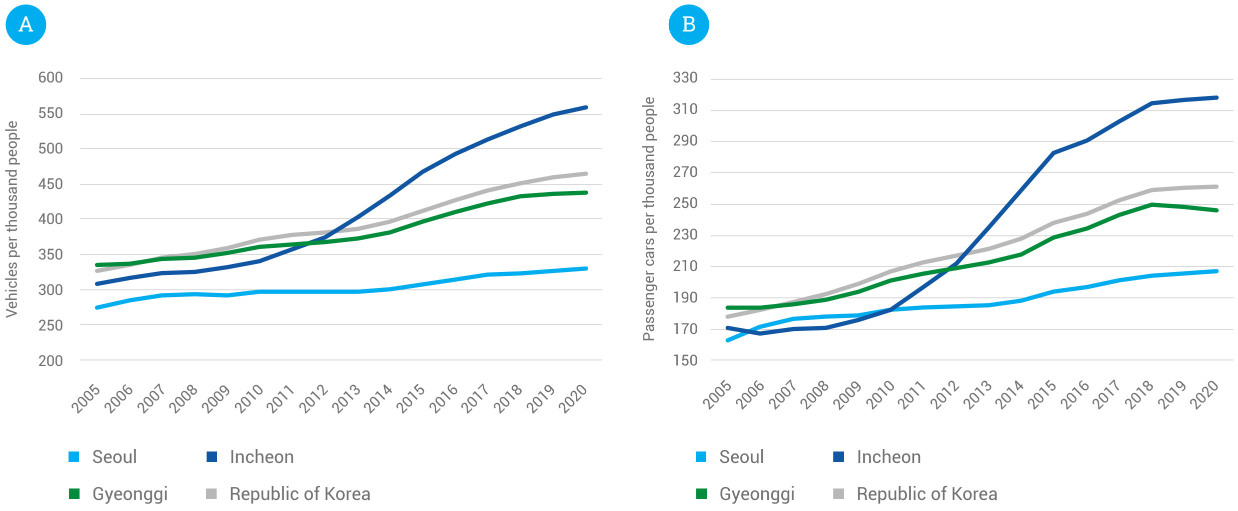
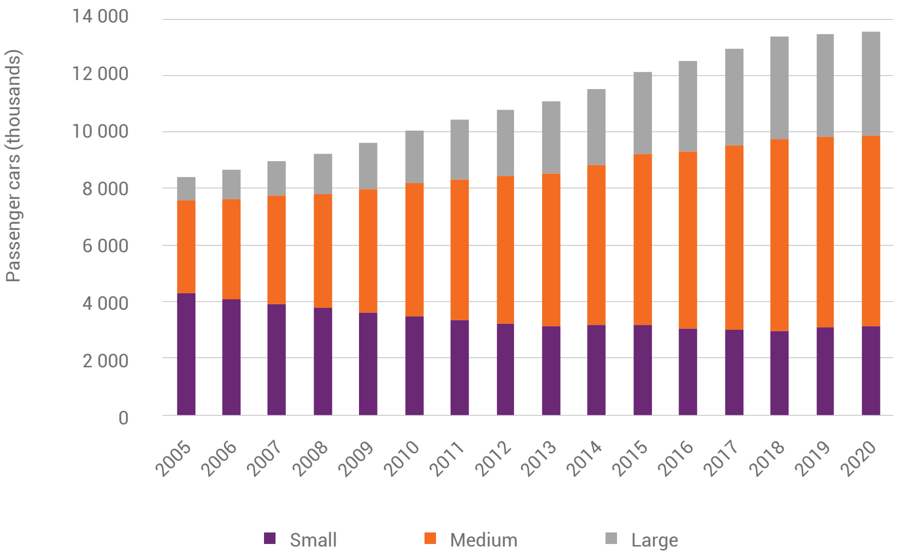


Figure 3.4
Passenger cars disaggregated by size, Republic of Korea, 2005–2020, under the Automobile Management Act, small-sized cars with 1 000 cc or less displacement, medium-sized cars with 1 600 cc or less displacement, and large-sized cars with 2 000 cc or more, thousands



While the vehicle fleet has increased and the average higher weight of vehicles could have driven up air pollutant emissions from road transport in SIG, between 2005 and 2020 increasingly stringent vehicle emissions standards have been introduced which have reduced emissions per vehicle. Over the past few decades, the Republic of Korea has regulated the emission of air pollutants from vehicles – Section 3.2 provides further information on vehicle emissions standards and the funding allocated to this. These emissions standards apply to new vehicles and follow similar examples of regulations in Europe and North America. Over the past 15 years, there has been a substantial increase in the proportion of vehicles that meet more stringent vehicle emissions standards (Figures 3.4 and 3.5). For light-duty vehicles, the Republic of Korea's emissions standards for gasoline vehicles reflect California's[9], and for diesel vehicles, they follow the Euro standards[2] (Park *et al.* 2021).

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[9] United States vehicle emission standards. https://en.wikipedia.org/wiki/United_States_vehicle_emission_standards

Figure 3.5
Medium-sized passenger cars meeting different vehicle emissions standards, Republic of Korea, 2005–2020, per cent

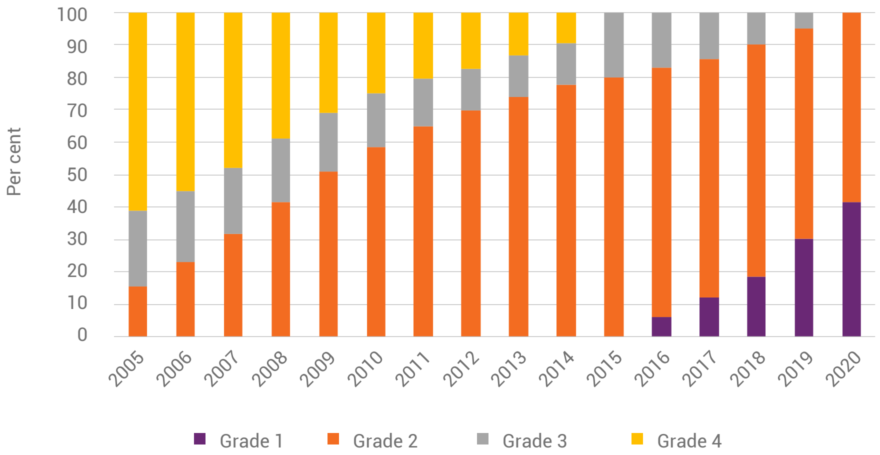
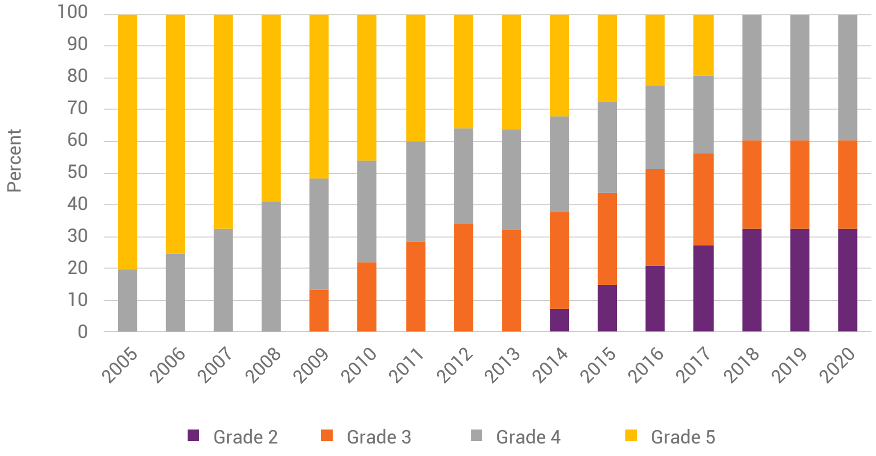


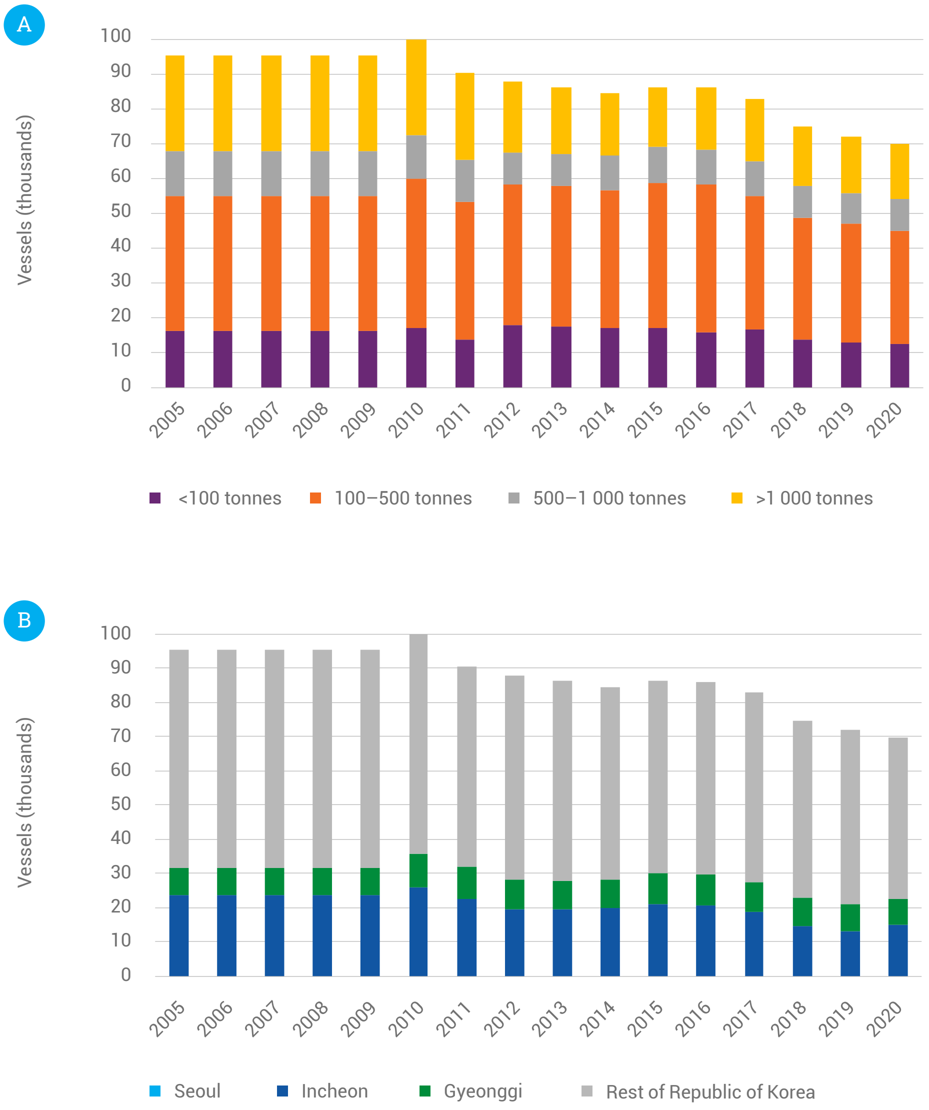
Figure 3.6
Large heavy-duty vehicles meeting different vehicle emissions standards, Republic of Korea, 2005-2020, per cent



While the road transport sector has the largest share of journeys, there are also substantial, and potentially large emissions, from the non-road transport. Rail transport includes passenger transport on trains, which use a combination of electric and diesel engines, and metros, including in SIG and other cities in the Republic of Korea (Figure 3.7). Rail is also for a substantial volume of freight transport. For shipping, the Port of Incheon is the second largest in the Republic of Korea, at which approximately 20 per cent of the cargo ships in the Republic of Korea's dock (Figure 3.8).

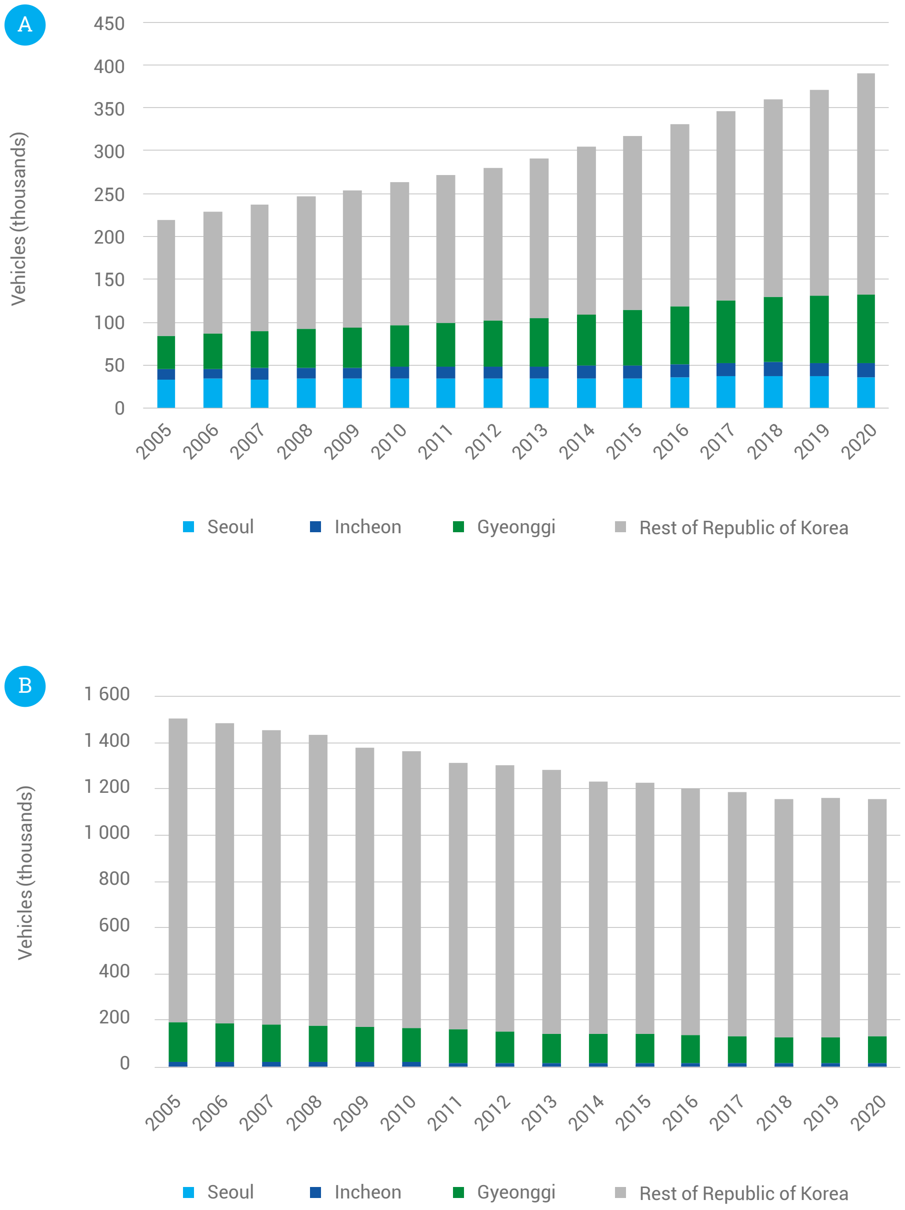
Figure 3.7
Rail use, Republic of Korea, 2005–2020, passenger transport: billion passenger kilometres; freight: million tonne kilometres

Figure 3.8
Vessels in ports disaggregated by a) vessel tonnage and b) region, the Republic of Korea, 2005–2020, thousands



Finally, there is also off-road machinery in the transport sector which, typically, uses diesel fuel and can emit substantial amounts of air pollutants. The number of machines used in the construction sector in the Republic of Korea almost doubled between 2005 and 2020, although the majority of this increase has taken place outside Seoul and Incheon while in Gyeonggi the increase has been in line with the national trend. Forklifts and excavators are the most common type of construction equipment used. Other off-road machinery includes agricultural machinery, which has seen a decreasing trend since 2005, with a 23 per cent decline between 2005 and 2020. Only Gyeonggi has a substantial amount of agricultural machinery, approximately 10 per cent of the national total. Tractors and power cultivators are the main agricultural machines used (Figure 3.9.b).

Figure 3.9
a) Construction and b) agricultural machinery in Seoul, Incheon, Gyeonggi and the rest of the Republic of Korea, 2005–2020, thousands



The Republic of Korea's manufacturing industry primarily uses oil and oil products to generate energy, followed by coal and electricity.

Industry

The sector is a large source of air pollution because of the different types of fuels that are used. A small fraction of the Republic of Korea's industrial GDP is generated within Seoul and Incheon, but almost one-third is contributed by Gyeonggi. Aside from other manufacturing, the largest industries in the Republic of Korea are construction, chemical manufacture, and iron and steel production. Together, Seoul (mainly construction), and Incheon (mainly other manufacturing) account for less than 10 per cent of the Republic of Korea's industrial value-added GDP. In Gyeonggi, more than half of the industrial value-added GDP is contributed by other manufacturing, but iron and steel, and chemical manufacture make significant contributions (Figure 3.10, Table 3.3).

The Republic of Korea's manufacturing industry largely uses oil and oil products for the generation of energy, followed by coal and electricity (Figure 3.11). The consumption of all these fuels has increased since 2005, with a 50 per cent increase in electricity and petroleum consumption, and a 26 per cent increase in coal use. There are three industrial sub-sectors which together are responsible for more than 85 per cent of all energy consumption in the industrial sector, namely oil refining, iron and steel production, and chemical manufacture (Figure 3.12). For oil refining and chemical manufacture, oil products and electricity are the major fuels used. For iron and steel production, however, coal is the major fuel used, contributing more than 75 per cent of energy consumption in iron and steel production (Figure 3.13). Coal use in iron and steel production made 98 per cent of all coal used in the Republic of Korea's industrial sector in 2020. The production of iron and steel using different processes is shown in Figure 3.14. As outlined, more than 21 per cent of iron and steel production in the Republic of Korea occurs within Gyeonggi, as well as 25 per cent of chemical production. No oil refining is carried out within Gyeonggi, but about 8 per cent of it, by value-added GDP, takes place in Incheon (Table 3.3).

Manufacturing industry in Incheon.
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Figure 3.10

Value-added gross domestic product of manufacturing, mining and construction industries disaggregated by major industrial sub-sectors, the Republic of Korea, Seoul, Incheon and Gyeonggi, 2020, KRW trillion

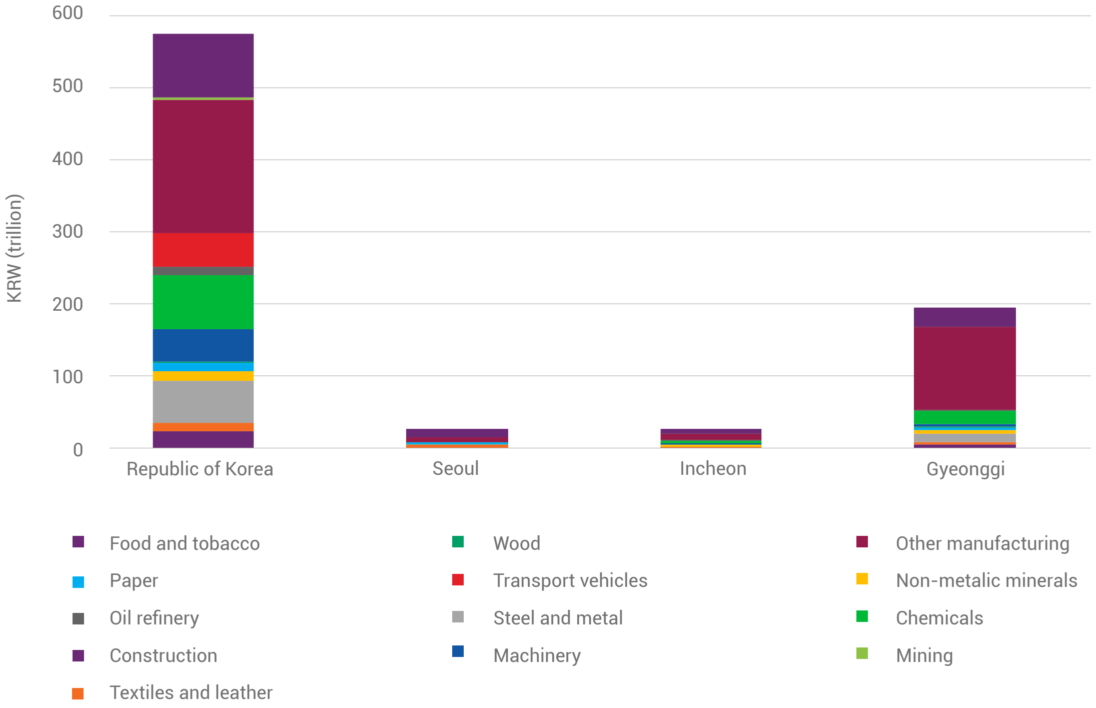


Table 3.3

Value-added gross domestic product of major industrial and services sectors, the Republic of Korea, Seoul, Incheon and Gyeonggi, 2020, KRW trillion

	Republic of Korea	Seoul	Incheon	Gyeonggi
Food and tobacco	23	0	1	6
Textiles and leather	13	5	0	3
Steel and metal	58	1	0	12
Non-metallic minerals	13	0	3	4
Paper	12	2	0	5
Wood	2	0	1	1
Machinery	44	0	1	3
Chemicals	75	1	3	19
Oil refinery	12	-	1	0
Transport vehicles	46	0	1	0
Other manufacturing	186	5	9	116
Mining	2	0	0	0
Construction	88	12	5	26
Services	932	333	42	210
Public administration	113	15	5	20

Figure 3.11
Fuel consumption in manufacturing industry, the Republic of Korea, 2020, million tonnes of oil equivalent

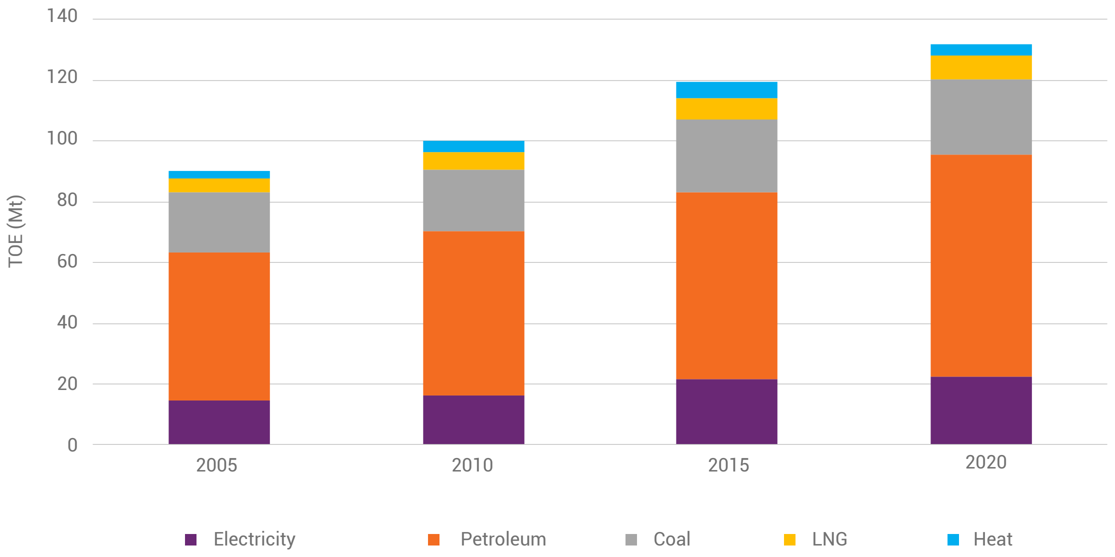


Figure 3.12
Fuel consumption in major manufacturing, construction and mining industries, the Republic of Korea, 2020, million tonnes of oil equivalent

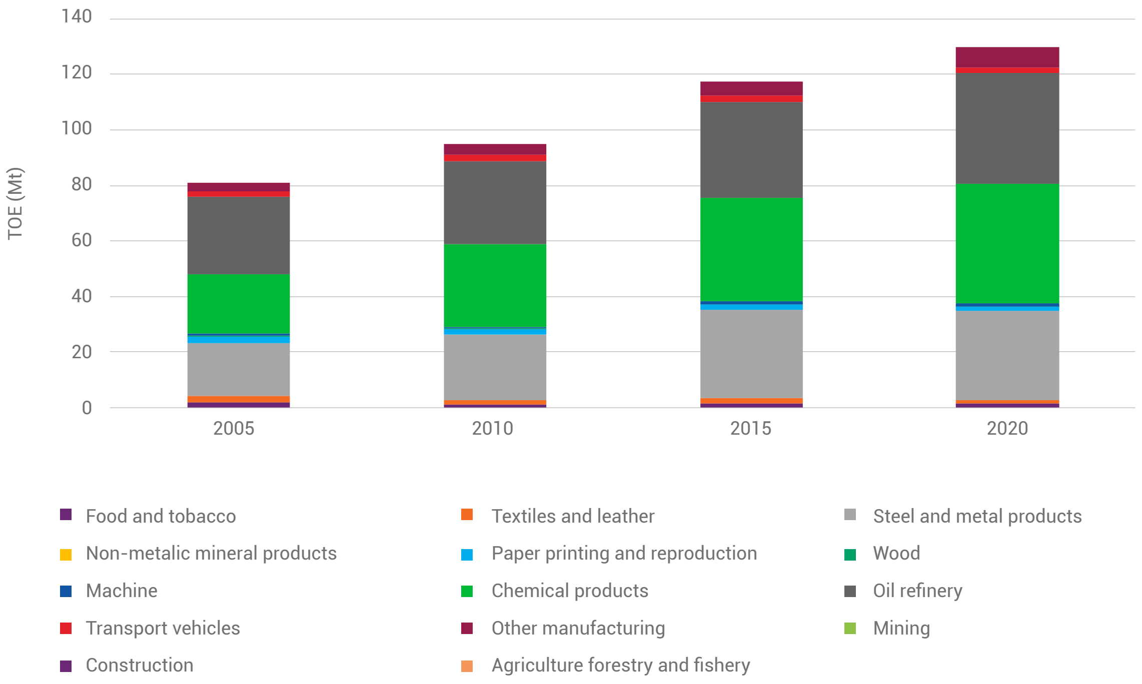


Figure 3.13
Contribution (percentage share) of different fuels to total fuel consumption in the three largest fuel-consuming industries, Republic of Korea, in 2020

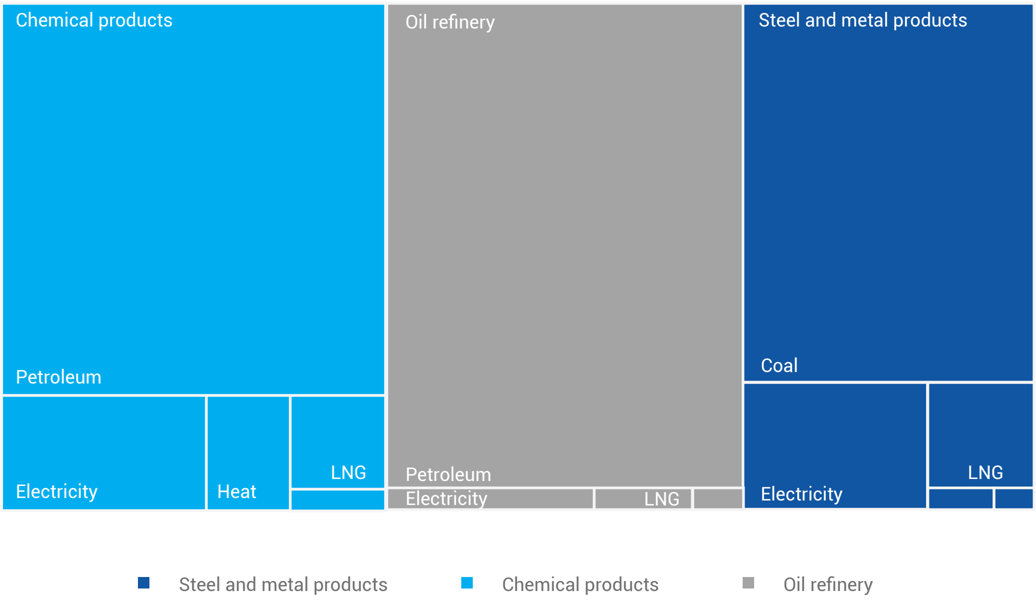
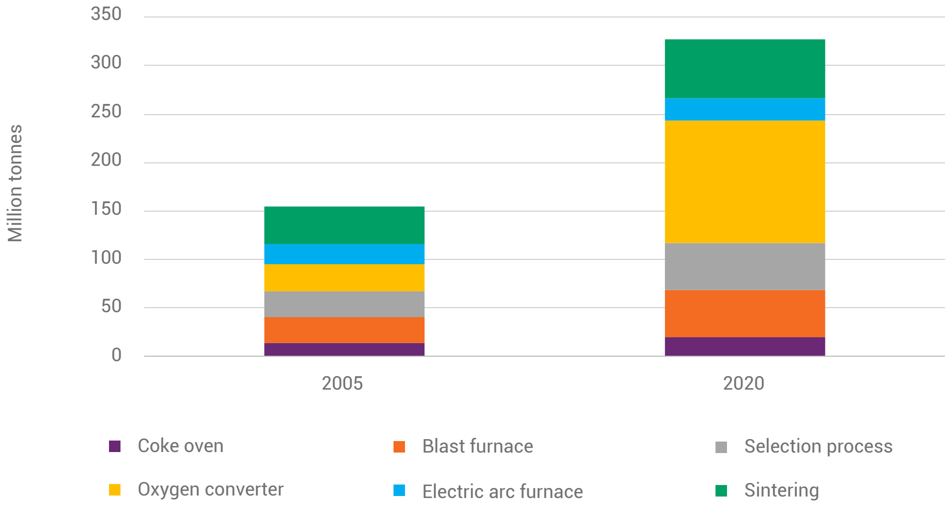


Figure 3.14
Production of iron and steel by different processes, the Republic of Korea, 2005 and 2020, million tonnes



Approximately 16 per cent of electricity in the Republic of Korea was generated at power stations in Seoul, 1 per cent; Incheon, 11 per cent; and Gyeonggi, 4 per cent.

Electricity

In 2020 in the Republic of Korea, the total installed capacity within the electricity network was 123 gigawatts[10] (GW). Of this, less than 1 GW is from power stations located within Seoul, with 14.8 GW and 12.9 GW located in Incheon and Gyeonggi, respectively. The electricity system within the Republic of Korea generated over 550 terawatt[11] hours (TWh) of electricity in 2020, a 151 per cent increase on 2005 levels (Figure 3.15).

Approximately 16 percent of electricity in the Republic of Korea was generated at power stations in SIG, including in Seoul, 1 per cent; Incheon, 11 per cent; and Gyeonggi, 4 per cent.

Electricity generation in the Republic of Korea is dominated by coal, liquified natural gas (LNG) and nuclear power. While there has only been a 10 per cent increase in electricity generated from nuclear power stations between 2005 and 2020, there have been substantial increases in coal generation, more than +40 per cent; and LNG, +92 per cent between 2005 and 2020. In 2020, electricity from renewable sources constituted 16 per cent of total electricity generation but this has increased by more than 20 times since 2005, when renewable sources accounted for only 2 per cent of electricity generation. Despite the increases in electricity generation between 2005 and 2020, since 2010, fuel consumption for electricity generation has fallen – in 2020 it was 4 per cent lower than in 2010. This includes a 20 per cent reduction in LNG fuel consumption between 2010 and 2020, and a 9 per cent reduction in coal consumption, due to efficiency improvements within thermal power stations in the Republic of Korea (Figure 3.16).

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[10] Gigawatt = 10^9 watts

[11] Terawatt = 10^{12} watts

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Figure 3.15
Electricity generation disaggregated by fuel type, the Republic of Korea, 2005–2020, terawatt hours

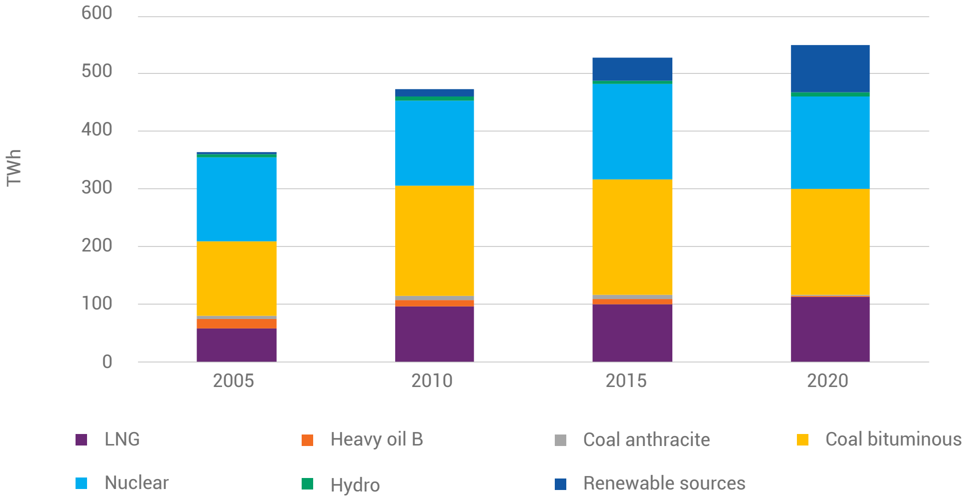
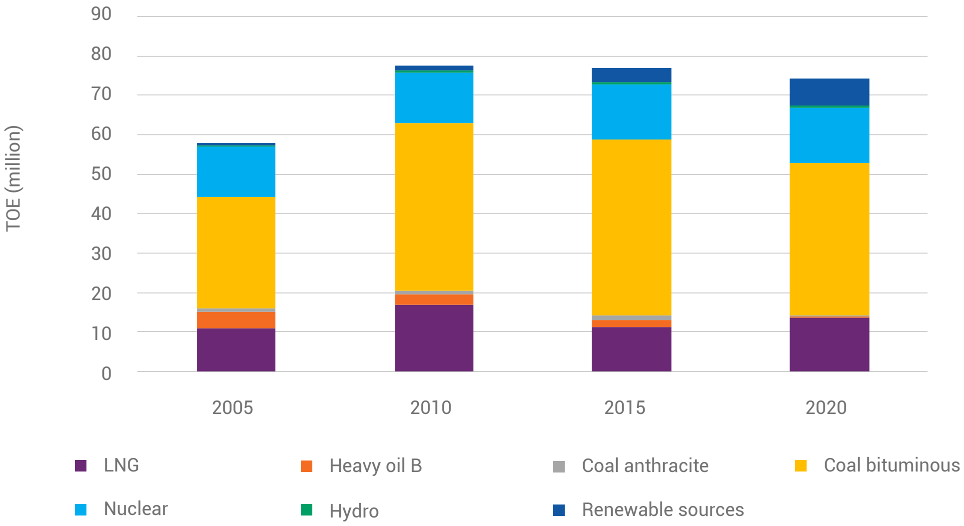


Figure 3.16
Fuel consumption for electricity generation, the Republic of Korea, 2005–2020, million tonnes of oil equivalent



The number of animals in the Republic of Korea increased substantially between 2005 and 2020, but the vast majority are located outside Seoul and Incheon.

Agriculture

In the agriculture sector, air pollutant emissions are produced from both livestock and crop production. Within the livestock sub-sector, NH_3 and NO_x emissions are produced from manure management, storage and application, alongside CH_4 from enteric fermentation in cattle and N_2O, both GHGs. The number of animals in the Republic of Korea increased substantially between 2005 and 2020, but the vast majority are located outside Seoul and Incheon. Gyeonggi, in contrast, in 2020 had 9 per cent of the Republic of Korea's beef cattle, 15 per cent of its pigs, 19 per cent of its poultry and 40 per cent of its dairy cattle (Table 3.4). In both the Republic of Korea and Gyeonggi, the number of beef cattle, poultry and pigs increased by 26–85 per cent between 2005 and 2020, but in both the number of dairy cattle declined by approximately 15 per cent.

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Air pollutant emissions also occur from crop production, through the open burning of agricultural residues and emissions from fertilizer application – both inorganic fertilizers and the application of manure, which emits NH_3 and NO_X. Seoul had only 100 hectares of rice-producing land in 2020 and little other crop production. In Incheon, 65 000 tonnes of rice were produced from 10 000 hectares of land and there is a small amount of other crop production. Gyeonggi accounts for more than 10 per cent of national rice production and a smaller proportion of other crop types (Tables 3.5, 3.6 and 3.7). Rice is the largest crop produced in the Republic of Korea, but its production fell by 25 per cent between 2005 and 2020, and by 28 per cent in Gyeonggi. Between 180 and 220 tonnes of nitrogen (N) fertilizer are applied to fields every year, mainly as urea, mixed fertilizer and ammonium sulphate ($(NH_4)_2SO_4$).

Table 3.4

Number of different types of livestock, the Republic of Korea and Gyeonggi, 2005 and 2020

Region	Livestock	2005 (million)	2020 (million)
Republic of Korea	Beef cattle	1.82	3.37
Gyeonggi	Beef cattle	0.17	0.31
Republic of Korea	Dairy cattle	0.48	0.41
Gyeonggi	Dairy cattle	0.19	0.16
Republic of Korea	Pigs	8.89	11.18
Gyeonggi	Pigs	1.81	1.69
Republic of Korea	Poultry	126.21	179.55
Gyeonggi	Poultry	27.18	34.09

Note: Seoul and Incheon have practically no livestock
Source: Ministry of Agriculture, Food and Rural Affairs, ROK

Table 3.5

Production of rice and other crops, Seoul, Incheon, Gyeonggi and the rest of Republic of Korea, 2005 and 2020

Region	Crop	2005 (thousand tonnes)	2020 (thousand tonnes)
Seoul	Rice	2.9	0.5
Incheon	Rice	107.1	65.2
Gyeonggi	Rice	696.7	503.4
Rest of Republic of Korea	Rice	5 628.2	4 284.1
Seoul	Other	0.2	0.0
Incheon	Other	6.3	4.8
Gyeonggi	Other	42.2	63.5
Rest of Republic of Korea	Other	2 239.1	2 783.8

Source: Ministry of Agriculture, Food and Rural Affairs, ROK

Table 3.6
Crop land, Seoul, Incheon, Gyeonggi and the rest of Republic of Korea, 2005 and 2020

Region	Crop	2005 (thousand hectares)	2020 (thousand hectares)
Seoul	Rice	0.5	0.1
Incheon	Rice	16.2	10.0
Gyeonggi	Rice	108.1	75.3
Rest of Republic of Korea	Rice	855.0	622.8
Seoul	Other	0.1	0.0
Incheon	Other	2.4	1.4
Gyeonggi	Other	30.7	21.5
Rest of Republic of Korea	Other	362.3	274.0

Source: Ministry of Agriculture, Food and Rural Affairs, ROK

Table 3.7
Fertilizer application, Seoul, Incheon, Gyeonggi and the rest of Republic of Korea, 2005 and 2020

Total fertiliser applied	2005 (kg N per hectare)	2020 (kg N per hectare)
Seoul	1 040.8	2 586.8
Incheon	178.2	165.4
Gyeonggi	186.4	162.6
Rest of Republic of Korea	230.0	217.2

Note Seoul fertilizer application rate is uncertain due to the small area cultivated
Source: Ministry of Agriculture, Food and Rural Affairs, ROK

Almost 50 per cent of waste incineration and 40 per cent of composting/ recycling occurring in the Republic of Korea takes place in SIG, mainly Gyeonggi and Seoul.

Waste

In the Republic of Korea, as in other regions, both municipal, and industrial solid waste can be handled through landfilling, incineration, recycling, composting and/or reuse. All these are used in the Republic of Korea, but the majority of solid waste is incinerated. Every year around 5 million tonnes of municipal and industrial waste in the Republic of Korea are incinerated, and a similar amount composted/recycled. Almost 50 per cent of the waste incineration and 40 per cent of the composting/recycling takes place in SIG, mainly Gyeonggi and Seoul (Table 3.8).

The main pollutant produced from processing liquid waste is CH_4. The volume of liquid waste generated is approximately 9 billion cubic metres (m^3) per year. Broadly in line with the proportion of the population in SIG, 46 per cent of the wastewater generated in the Republic of Korea comes from in Seoul, Incheon and Gyeonggi (Table 3.9).

The data presented above highlights that SIG is one of the largest metropolitan regions in the world in terms of population, and as a consequence includes a number of potential sources of air pollution. In addition, as a country that has developed rapidly over the past decades, within the Republic of Korea there are substantial sources of air pollution outside of SIG which can nevertheless impact air quality within it. Major air pollutant emission sources within and outside SIG include the vehicle fleet, household energy consumption, industrial energy consumption and process emissions, electricity generation, agriculture and waste generation.

The aim of the air pollution mitigation assessment is to assess how policies and measures within these sectors, implemented over the next decades, could contribute to continuing the reduction in air pollutant emissions that has been achieved over the past decade. The following sections describe the scope of this assessment, including the pollutants included, the source sectors covered, the methodologies used to estimate past emissions and the assumptions used to create baseline and mitigation scenario projections.

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Table 3.8

Mass of municipal and industrial solid waste that is processed through landfilling, incineration or composting/recycling, Seoul, Incheon, Gyeonggi and the rest of the Republic of Korea, 2005 and 2020

Region	Process	2005 (thousand tonnes)	2020 (thousand tonnes)
Seoul	Landfill	-	-
Incheon	Landfill	1.68	3.65
Gyeonggi	Landfill	0.20	0.11
Rest of Republic of Korea	Landfill	6.78	3.71
Seoul	Incineration	398.64	861.62
Incheon	Incineration	135.11	277.64
Gyeonggi	Incineration	934.02	1 461.99
Rest of Republic of Korea	Incineration	1 365.94	2 659.67
Seoul	Composting/ recycling	914.46	609.72
Incheon	Composting/ recycling	149.81	200.85
Gyeonggi	Composting/ recycling	1 419.32	1 592.02
Rest of Republic of Korea	Composting/ recycling	4 740.59	2 990.42

Table 3.9

Volume of municipal and industrial wastewater generated, Seoul, Incheon, Gyeonggi and the rest of the Republic of Korea, 2005 and 2020

Region	2005 (million m³)	2020 (million m³)
Seoul	1 888	1 822
Incheon	419	463
Gyeonggi	1 769	1 988
Rest of Republic of Korea	6 252	5 001

Gwangmyung Upcycle Art Center.
© Gyeonggi Provincial Government

3.2 Overarching assessment framework

The integrated air pollution and climate change mitigation assessment presented in this chapter estimates air pollutant emissions in four regions, Seoul, Incheon, Gyeonggi and the Republic of Korea. The air pollutant emissions in the rest of Korea, i.e. the Republic of Korea outside SIG, were then estimated by subtracting the SIG emissions from the national total. For the majority of sectors, the emissions represent those emitted within the geographical boundaries of each region, i.e. emitted within SIG. For some sectors, there are also indirect emissions associated with consumption in different regions, including electricity generation, agriculture – food consumption resulting in emissions in other regions where the food is produced, and waste – waste generated in one region being managed in another. For the electricity generation and agricultural sectors, only direct emissions are shown for each region included in the analysis, i.e. only those emissions from power stations and farms within the region. For waste, the emissions assigned to each region are those from the waste generated in each region, regardless of where it is managed.

The aim of this assessment is to evaluate emissions reductions of air pollutants in SIG. To do so, emissions of all air pollutants contributing to the formation of $PM_{2.5}$ and O_3 were estimated from all major source sectors (Section 3.1.2). Particulate matter and O_3 are the two air pollutants that have the largest impact on human health and were therefore chosen as the pollutants on which this assessment would focus (Murray *et al.* 2020). They are formed from primary emissions, $PM_{2.5}$ only, and the secondary formation of $PM_{2.5}$ and O_3 in the atmosphere from the emissions of other gaseous air pollutants. The assessment therefore characterizes the emissions and the contribution of different source sectors of both primary and secondary pollutants (Fuzzi *et al.* 2015).

In addition, the assessment also quantifies emissions of GHGs to assess the synergies between mitigating the contribution to climate change from SIG and reducing air pollution. There is a substantial overlap in the data needed to assess GHG emissions and emissions reductions, and the data needed to quantify air pollutant emissions. Therefore, the development of an integrated air pollutant and climate change mitigation assessment provided the basis for evaluating those policies and measures that would simultaneously improve air quality and mitigate climate change. The full list of pollutants for which emissions were quantified include the following.

Greenhouse Gases

- **Carbon dioxide (CO_2):** a greenhouse gas with an atmospheric lifetime of hundreds of years that makes the largest contribution to global climate change.
- **Methane (CH_4):** a GHG and SLCP with an atmospheric lifetime of approximately 15 years, CH_4 emissions make the second largest contribution to global temperature increases after CO_2. It also contributes to the formation of tropospheric O_3, which has negative effects on respiratory health.

Air Pollutants

- **Particulate matter ($PM_{2.5}$ and PM_{10}):** Particulate matter, with aerodynamic diameters of less than 2.5 µm ($PM_{2.5}$) and 10 µm (PM_{10}) are small solid particles in the atmosphere. They make the largest contribution to air pollution effects on human health through effects on the cardiovascular and respiratory systems. The emissions of $PM_{2.5}$ and PM_{10} calculated here represent their direct emissions to the atmosphere. Other gaseous pollutants, however, such as NO_x, SO_2, NH_3 and VOCs, also contribute to the $PM_{2.5}$ and PM_{10} concentrations to which people are exposed through chemical reactions in the atmosphere that convert gaseous pollutants into solid particles.

- **Nitrogen oxides (NO_x):** an air pollutant which is a precursor to the formation of PM and tropospheric O_3, NO_x is made up of two pollutants, nitrogen oxide (NO) and nitrogen dioxide (NO_2).

- **Sulphur dioxide (SO_2):** an air pollutant which is a precursor to the formation of PM.

- **Ammonia (NH_3):** an air pollutant which is a precursor to the formation of PM.

- **Non-methane volatile organic compounds (NMVOCs):** a collection of a range of different organic molecules emitted from a range of emission sources. They are precursors to the formation of tropospheric O_3 and PM.

- **Carbon monoxide (CO):** a gaseous air pollutant which contributes to the formation of tropospheric O_3.

The emissions of the pollutants listed above were quantified for all relevant major source sectors in SIG and the rest of Republic of Korea. This includes energy generation, industrial processes, agriculture and waste management, as well as their sub-sectors as summarized in Table 3.10. The net CO_2 emissions from the forestry sector are not included in the assessment, as there are no co-emitted air pollutant emissions. Emissions from fugitive/scattering dust are also not included in this analysis because of the substantial uncertainty about their magnitude and the necessary data for their quantification.

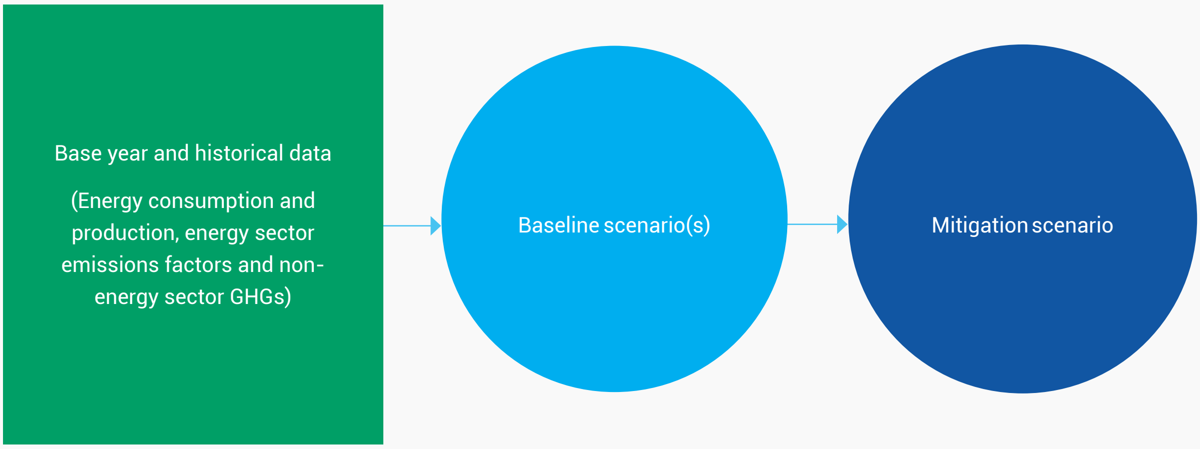
Table 3.10
Source sectors covered in the emissions inventory with the Nomenclature for Reporting (NFR) codes

Source sector	Sub-sectors
1 - Energy	1A1 Energy industries
	1A2 Manufacturing industries and construction
	1A3 Transport
	1A4 Other sectors (commercial/institutional, residential, agriculture, forestry and fishing)
2- Industrial processes	2A Mineral production
	2B Chemical production
	2C Metal production
	2D Solvent use
	2H Other industry
3 - Agriculture	3A Livestock enteric fermentation
	3B Manure management
	3D Agricultural soils
5 - Waste	5A Biological treatment of waste – solid waste disposal on land
	5B1 Biological treatment of waste – composting
	5C Waste incineration
	5D Wastewater handling

Emissions from these sources were estimated for each region for two time periods, past years between 2005 and 2020 to assess the trends in air pollutant emissions in SIG, and for 2021 to 2050 to project emissions into the future with different sets of assumptions. While multiple future scenarios were developed, these were broadly categorized into two groups. First, a baseline scenario was developed that represents a future in which no additional policies and measures were implemented to reduce emissions. The aim of developing a **baseline scenario** was to provide a reference against which emissions reductions from the implementation of policies and measures could be evaluated. Secondly, **mitigation scenarios** were developed which represent the implementation of these policies and measures. The policies and measures identified for evaluation were represented within individual scenarios to evaluate the impact of their implementation individually. Aggregated mitigation scenarios were also developed in which combinations of policies and measures were included to evaluate the impact of implementing a combination of policies and measures. These combined mitigation scenarios account for interactions in the implementation of policies and measures which means that the impact of implementing policies and measures together may not simply be the addition of emissions reductions from their individual implementation. The combined implementation of electromobility, for example, which increases demand for electricity, and the generation of electricity from renewable sources will be different from the implementation of these measures separately.

In total, two aggregate mitigation scenarios were developed. First, a **carbon neutrality (CN) scenario** was modelled which evaluated the impact of policies and measures designed to achieve carbon neutrality, i.e. climate change-focused measures in SIG and the Republic of Korea. The second, the **air pollution (AP) scenario** included additional air pollutant policies and measures to further reduce air pollutants, which are proposed in existing plans and strategies. A table detailing the scenarios is in Section 3.2.3 (Table 3.15). An **overall mitigation scenario**, which implements all policies and measures, i.e. carbon neutrality and additional air pollution measures, was also modelled to show the possible overall reductions in air pollutant emissions possible from the implementation of policies and measures designed to reduce emissions.

Figure 3.17
Stages in conducting an air pollutant emissions mitigation assessment



The integrated assessment of air pollution and climate change was implemented using the Low Emissions Analysis Platform (LEAP)[12] (Heaps 2022). This is a tool that allows emissions to be estimated from all major source sectors. It was used to develop an energy-system model that integrated analyses of energy demand and supply, and the emissions associated with both the final consumption of fuels and their generation.

Non-energy sectors can also be represented using methods and approaches consistent with national and international guidance on emission inventory development – the LEAP modelling framework is shown in Figure 3.18. The platform was specifically designed as a scenario analysis tool. The advantage of the LEAP modelling framework for the assessment of future projections is that the impact of particular changes assumed to occur in the future, such as economic growth or implementation of a particular mitigation measure, across energy demand and supply are modelled, providing a more holistic understanding of the emissions reductions or increases expected from future changes.

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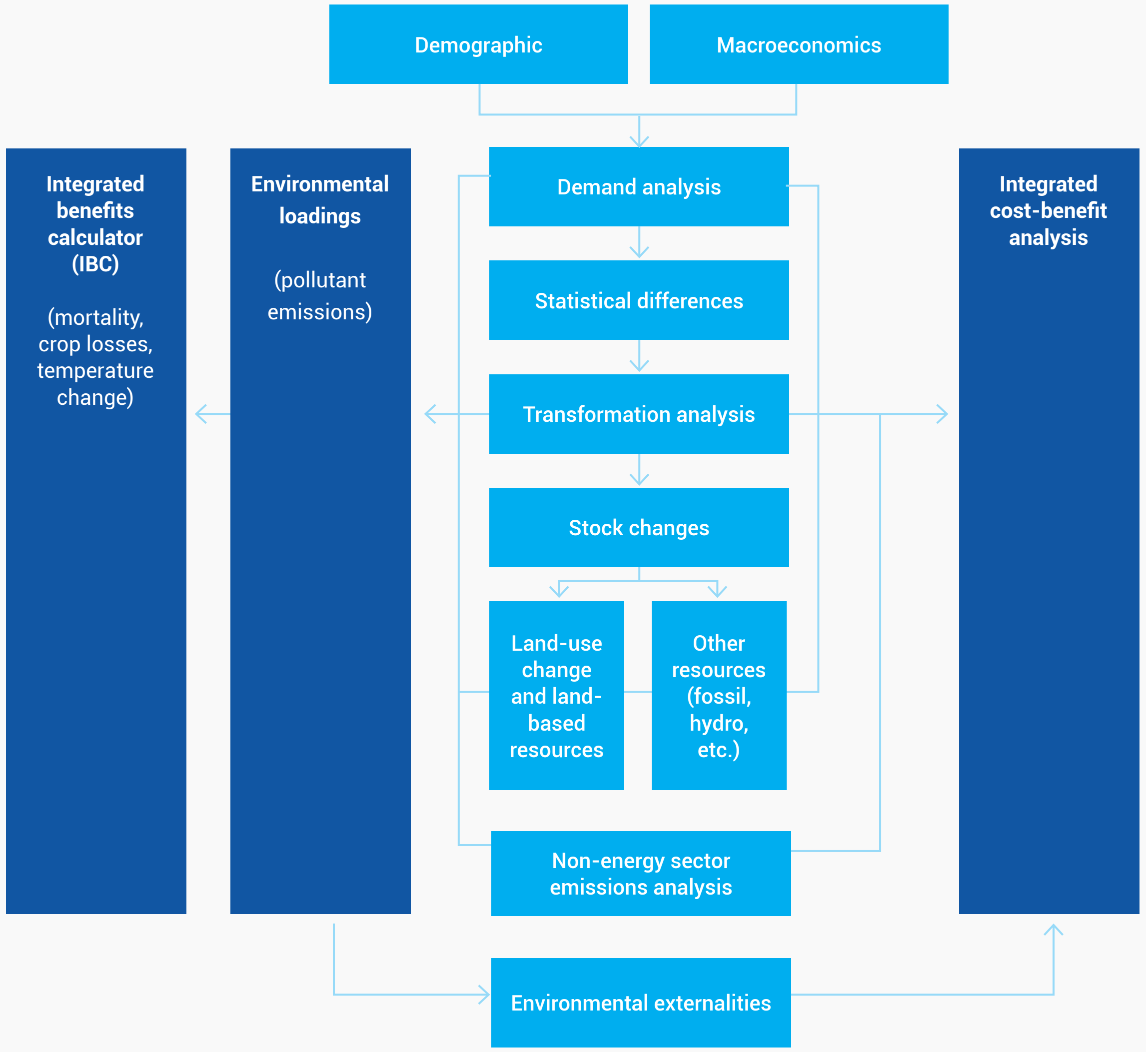
[12] LEAP, Low Emissions Analysis Platform, is a powerful, versatile software system for integrated energy planning and climate change mitigation assessment.
https://www.sei.org/projects-and-tools/tools/leap-long-range-energy-alternatives-planning-system/

Figure 3.18
Representation of the Low Emissions Analysis Platform (LEAP) modelling framework



The specific activity data, emissions factors and methodologies used to quantify emissions in each source sector are defined according to international guidelines on the quantification of greenhouse gas and air pollutant emissions.

3.2.1 Methodologies used to calculate historic emissions

To understand the extent to which mitigation measures could improve air quality and mitigate climate change, it is first necessary to understand the magnitude of emissions of the pollutants and the contribution of major source sectors to emissions of different pollutants to identify those sectors for which mitigation could be targeted to have the largest impact.

To estimate emissions of GHGs, SLCPs and air pollutants from the key sources (Table 3.11) for past years, the key equation used to estimate emissions from all major sources of the pollutants is the multiplication of an *activity variable* (or activity data) multiplied by an *emission factor* (Equation 1). The activity data quantify how big a particular sector or process is in a country, for example, the number of terajoules[13] of fuel consumed in a particular sector, the number of tonnes of production of a particular mineral, chemical or other product. Emissions factors quantify the mass of pollutant emitted per unit of activity, such as the kilograms of BC emitted per terajoule of fuel consumed.

Equation 1
Emissions = Activity x Emission Factor

The specific activity data, emissions factors and methodologies used to quantify emissions in each source sector are defined according to international guidelines on the quantification of GHG and air pollutant emissions. Specifically, the methodologies are consistent with the Intergovernmental Panel on Climate Change (IPCC) 2006 and European Environment Agency/European Monitoring and Evaluation Programme (EMEP/EEA) 2019 emissions inventory guidelines (IPCC 2006; EMEP/EEA 2019). The IPCC 2006 guidelines provide methodologies for the quantification of GHG emissions. They also recommend that for other pollutants, the EMEP/EEA air pollution emissions inventory guidebook is used. The major sources of emissions factors for each pollutant were predominantly from IPCC 2006, and the EMEP/EEA emissions inventory guidebook. In addition, for some sources, emissions factors were taken from the scientific literature.

Note that in the development of the LEAP model, the latest available activity variables and emissions factors were used to characterize the estimates of historic emissions. The updated data used in LEAP means that the emissions results estimated and presented in Chapter 3 differ from those reported in the Clean Air Policy Support System (CAPSS) dataset highlighted in Section 2.5. The differences between the two datasets are small and do not result in significant differences in the magnitude of emissions, or the contribution of major sources to air pollutant emissions in SIG or the rest of Republic of Korea.

In addition, the modelling methods used, while being consistent with international guidelines for estimating air pollutant and GHG emissions, also reflected the need to model the impact of policies and measures on the magnitude of air pollutant emissions. This required that the emissions in sectors were specified with sufficient disaggregation to identify sectors to which policies would be implemented, vehicles, for example, are disaggregated by type. It also requires that sectors are integrated, so that interactions between sectors from the implementation of policies and measures can be reflected, such as how energy efficiency measures implemented in, for example, households, impact electricity generation. Table 3.11 summarizes the key activity data used to model emissions from each sector included; the data itself is shown in the overview of sectors in Section 3.1.1. Table 3.12 shows the disaggregation of activity data and the source of data.

The following section describes the method used to estimate emissions from each sector.

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[13] Terajoule = 10^{12} joules

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Table 3.11

Summary of data sources used to estimate emissions for each source sector in Seoul, Incheon, Gyeonggi and the Republic of Korea

Source sector	Activity data	Source of data
1A1 - Energy industries	• Historic electricity production • Fuel consumption • Power plant capacity, efficiency and availability • Heat generation and fuel consumption	Korea Electric Power Corporation (KEPCO) dataset Korea Energy Agency (KEA) dataset
1A2 - Manufacturing industries and construction	• Fuel consumption in the industrial sector, disaggregated by industrial sub-sector (food and tobacco, textiles and leather, steel and metal, non-metallic minerals, paper and printing, wood, machinery, chemical, oil refining, transport vehicles, other manufacturing, mining and construction), and activity (boiler, oven, motive power, heater and dryer and others)	National GHG Emission Total Information System (NETIS) dataset Korea Power Exchange (KPX) dataset
1A3 - Transportation	**Road** • Vehicle fleet composition (passenger cars, vans, RVs, trucks, taxis, buses, special vehicles) • Per cent of vehicles of different sizes (small, medium, large) • Per cent of vehicles using different fuels (gasoline, diesel, liquified petroleum gas (LPG), electricity, hydrogen), per cent of vehicles meeting different vehicle emission standards (Grades 1-4) • Average distance travelled by vehicle type • Fuel economy by vehicle type, fuel and grade	National Air Emission Inventory and Research Center (NAIRC) dataset Korea Transport Emission Management System (KOTEMS) dataset Vehicle fuel economy and CO2 emissions: data and analysis (KEA dataset)
	Rail • Number of passenger kilometres for trains • Number of passenger kilometres for metro • Number of tonnes kilometres for trains • Fuel (diesel and electricity) consumption per passenger kilometres/tonnes kilometres for trains and metro	Korea National Oil Corporation (KNOC) dataset (PEDSIS) Statistical Yearbook Railroad (Korea Railway Industry Information Center dataset) KEA dataset
	Shipping • Number of vessels of different tonnage (<100 tonnes, 100–500 tonnes, 500–1 000 tonnes, >1 000 tonnes) at Republic of Korea ports • Fuel consumption per vessel	National Logistics Information Center (NLIC) dataset KNOC dataset (PEDSIS)
	Aviation • LTO • Fuel consumption	Korea Airport Corporation (KAC) dataset KNOC dataset (PEDSIS)

Source sector	Activity data	Source of data
1A4 - Other Sectors	**Services** • Gross regional domestic product (GRDP) contribution Fuel consumption	Korea Statistical Information Service (KOSIS) dataset KNOC dataset (PETRONET) Yearbook of Regional Energy Statistics (Korea Energy Economics Institute dataset)
	Public Administration • GRDP contribution • Fuel consumption	KOSIS dataset KNOC dataset (PETRONET) Yearbook of Regional Energy Statistics (Korea Energy Economics Institute dataset)
	Households • Number of households • Fuel consumption	KOSIS dataset KNOC dataset (PETRONET) Yearbook of Regional Energy Statistics (Korea Energy Economics Institute dataset)
	Agriculture, Forestry and Fishing • GRDP contribution • Fuel consumption	KPX dataset Yearbook of Regional Energy Statistics (Korea Energy Economics Institute dataset)
2A - Mineral industry	Production of minerals	NAIR – CAPSS
2B - Chemical industry	Production of chemicals	NAIR – CAPSS
2C - Metal industry	Iron and steel production by process type (coke oven, blast furnace, selection process, oxygen converter, electric furnace and sintering)	NAIR – CAPSS
2D - Non-energy products from fuels and solvent use	Mass of solvent used	NAIR – CAPSS
2H- Other industry	Production of wood and pulp Production of food and beverage	NAIR – CAPSS
3A - Livestock enteric fermentation	Number of animals	KOSIS
3B - Manure management	Number of animals Per cent of manure managed in manure management systems	Agriculture, Food and Rural Affairs Statistics Yearbook (Ministry of Agriculture, Food and Rural Affairs)
3D - Agricultural soils	Crop production Area harvested Inorganic fertilizer application rate	Agriculture, Food and Rural Affairs Statistics Yearbook (Ministry of Agriculture, Food and Rural Affairs
5A - Biological treatment of waste – solid waste disposal on land	Mass of waste treated in landfill	Korea Resource Recirculation Information Center dataset
5B1 - Biological treatment of waste – composting	Mass of waste treated in composted	Korea Resource Recirculation Information Center dataset
5C - Waste incineration	Mass of waste incinerated	Korea Resource Recirculation Information Center dataset
5D - Wastewater handling	Volume of wastewater generated	Korea Resource Recirculation Information Center dataset

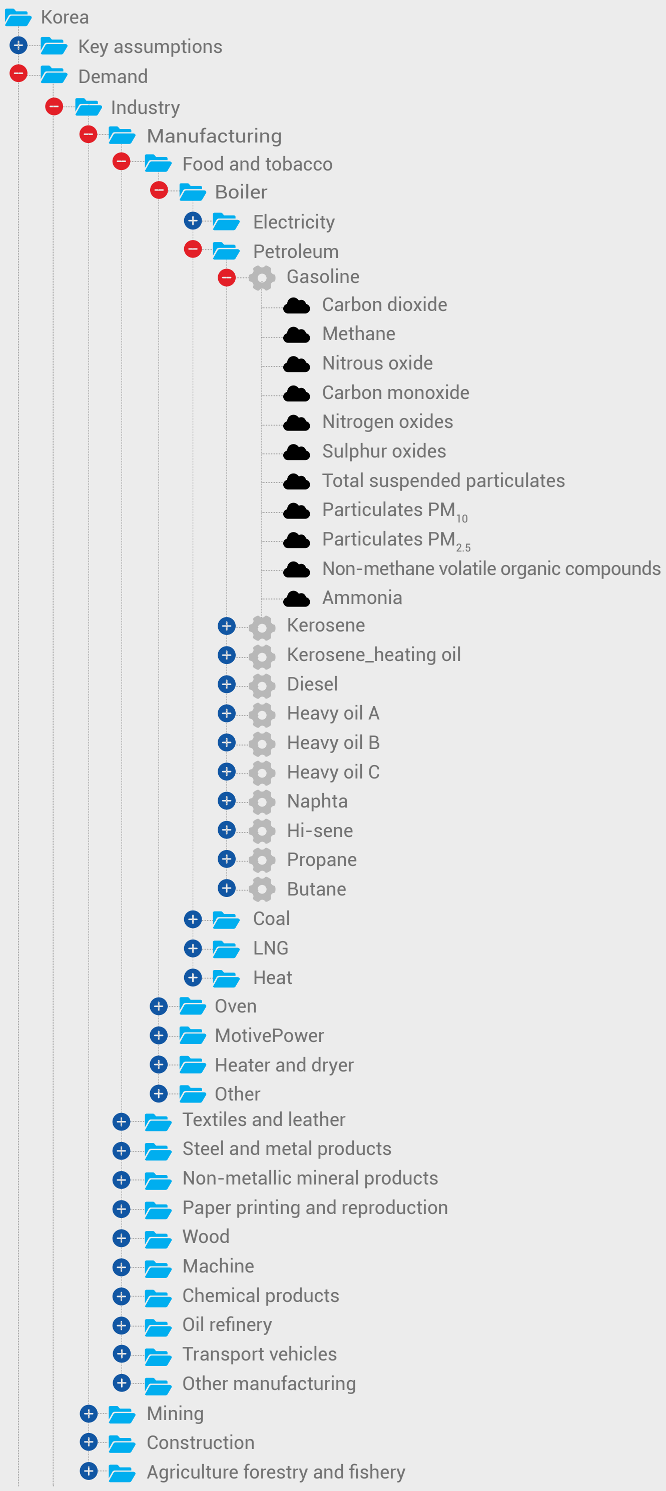
In the industrial sector, fuel consumption was disaggregated by manufacturing, mining, and construction industries, with manufacturing industries further disaggregated by industrial sub-sectors.

Industry

In the energy sector, the activity variable in Equation 1 is the total energy consumption, disaggregated by fuel and often activity, which is then multiplied by fuel, sector, technology, and/or activity-specific emission factors.

In the industrial sector, fuel consumption was disaggregated by manufacturing, mining and construction industries, with manufacturing industries further disaggregated by industrial sub-sectors (Figure 3.19). The fuel consumption for each industrial subsector was further disaggregated by activity, such as boiler, oven, motive power, heater and dryer, and others), and finally by fuel. This allows emissions to be estimated for individual industries and an understanding of the contribution of activities within industries to those emissions.

Figure 3.19
Structure used to model emissions from the industrial sector in the Republic of Korea, Seoul, Incheon and Gyeonggi

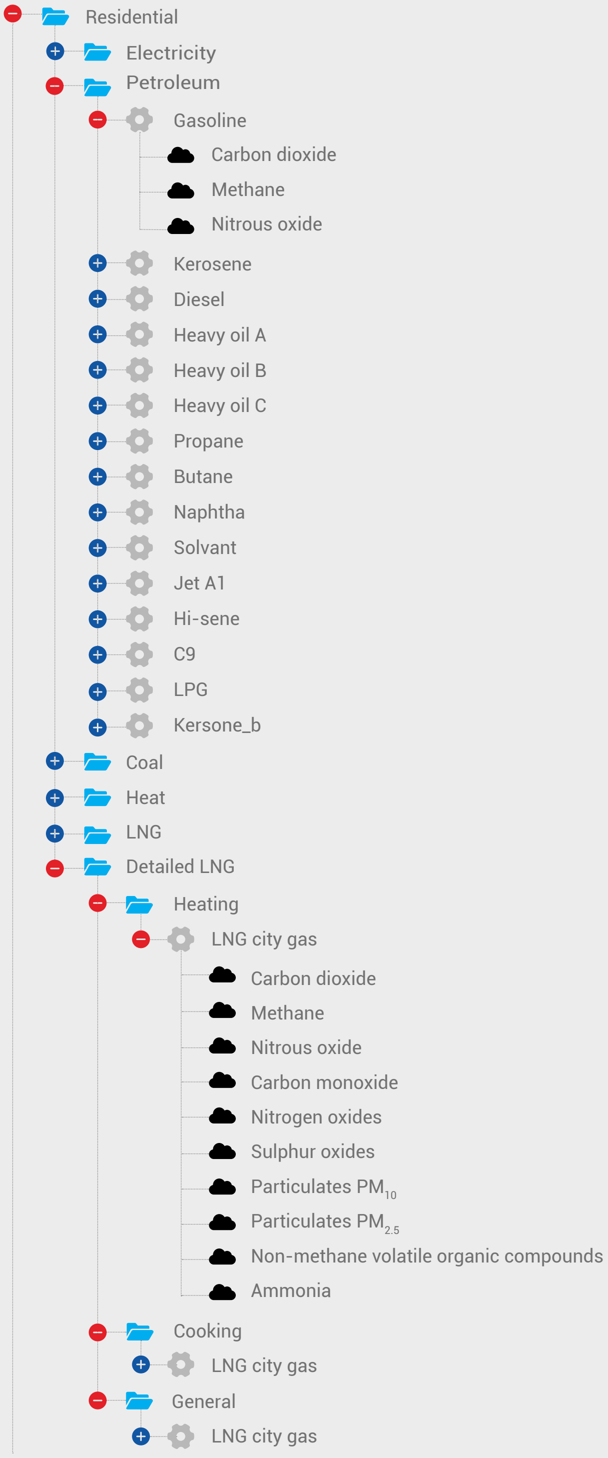


In the residential sector, total fuel consumption is estimated by multiplying the total number of households in Republic of Korea, Seoul, Incheon and Gyeonggi by per household energy consumption for different types of fuel.

Residential

In the residential sector, the total fuel consumption is estimated by multiplying the total number of households in Republic of Korea, Seoul, Incheon and Gyeonggi by per household energy consumption for different types of fuel, shown in Figure 3.20. Liquified natural gas, alongside electricity, is the fuel most commonly used in households and is the only fuel disaggregated by activity (heating, cooking and general, i.e. other uses). The total fuel consumption estimated for households in each region is multiplied by fuel and sector specific emission factors.

Figure 3.20
Structure used to model emissions from the residential sector in the Republic of Korea, Seoul, Incheon and Gyeonggi



- Residential
  - Electricity
  - Petroleum
    - Gasoline
      - Carbon dioxide
      - Methane
      - Nitrous oxide
    - Kerosene
    - Diesel
    - Heavy oil A
    - Heavy oil B
    - Heavy oil C
    - Propane
    - Butane
    - Naphtha
    - Solvant
    - Jet A1
    - Hi-sene
    - C9
    - LPG
    - Kersone_b
  - Coal
  - Heat
  - LNG
  - Detailed LNG
    - Heating
      - LNG city gas
        - Carbon dioxide
        - Methane
        - Nitrous oxide
        - Carbon monoxide
        - Nitrogen oxides
        - Sulphur oxides
        - Particulates PM_{10}
        - Particulates $PM_{2.5}$
        - Non-methane volatile organic compounds
        - Ammonia
    - Cooking
      - LNG city gas
    - General
      - LNG city gas

The total fuel consumption in the road transport sector is estimated separately for different vehicle types, sizes (light, medium and large), fuel types, vehicle emissions standards and model years.

Road transport

In the transport sector, road transport is modelled in substantially greater detail than other transport modes. The total fuel consumption in the road transport sector is estimated separately for different vehicle types, sizes (light, medium and large), fuel types, vehicle emissions standards and model years (Figure 3.21). For each of these vehicle categories, the fuel consumption is estimated by multiplying the number of vehicles in that category by the average annual distance travelled (kilometres per vehicle per year) by a vehicle in that category, and by the fuel economy (litres of fuel consumed per kilometre travelled). This is then multiplied by vehicle category-specific emission factors.

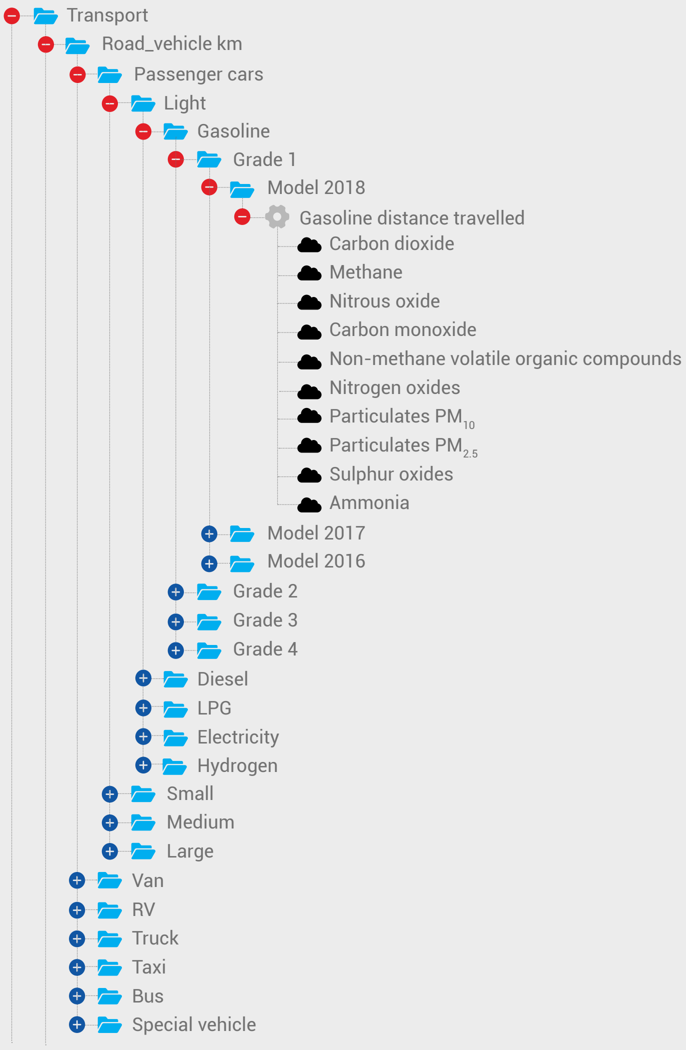


Figure 3.21
Structure used to model emissions from the road transport in the Republic of Korea, Seoul, Incheon and Gyeonggi

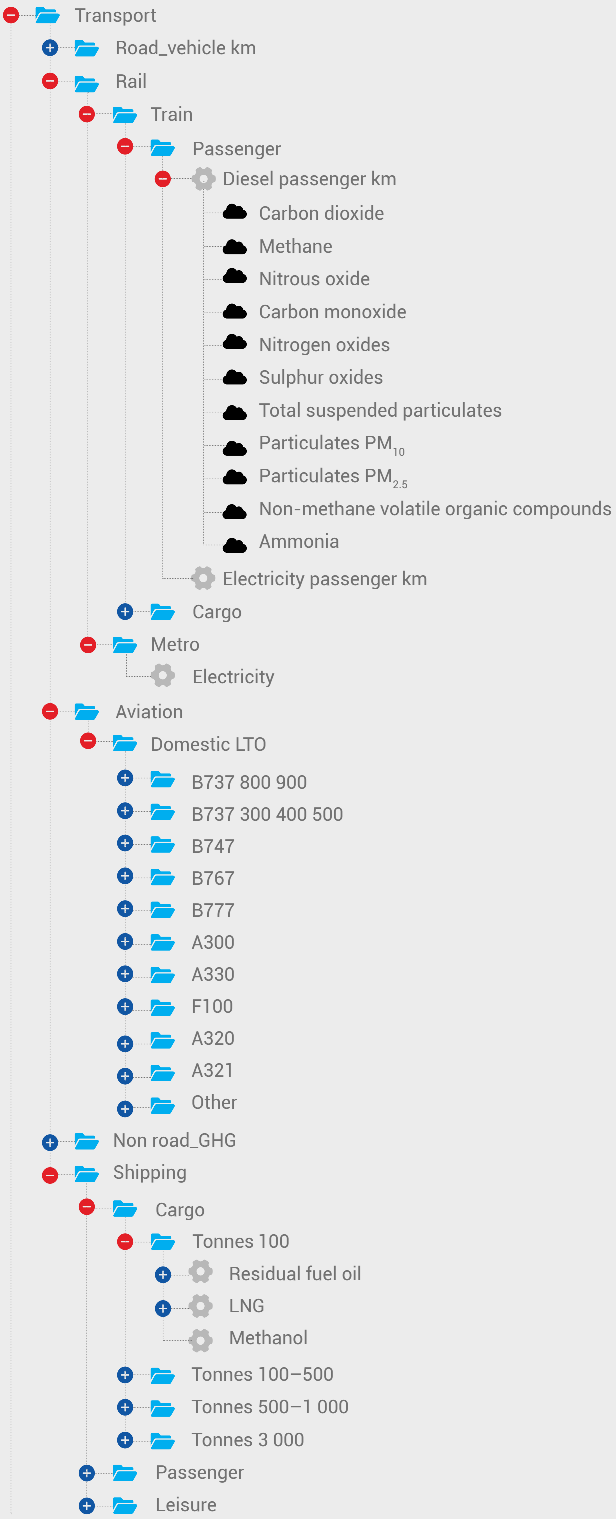
For other transport modes, fuel consumption is calculated by multiplying by a metric of transport activity – the fuel consumption per unit of activity.

Other transport

For other transport modes (aviation, rail and shipping), fuel consumption is calculated by multiplying by a metric of transport activity – fuel consumption per unit of activity. For rail, fuel consumption is estimated for electric and diesel trains for passenger transport, using passenger kilometres on trains and metros as the measure of transport activity. For rail freight, the same approach is followed but using tonnes kilometres as the estimate of transport activity.

For shipping, the number of vessels docking in ports in each region is multiplied by average fuel consumption per vessel.

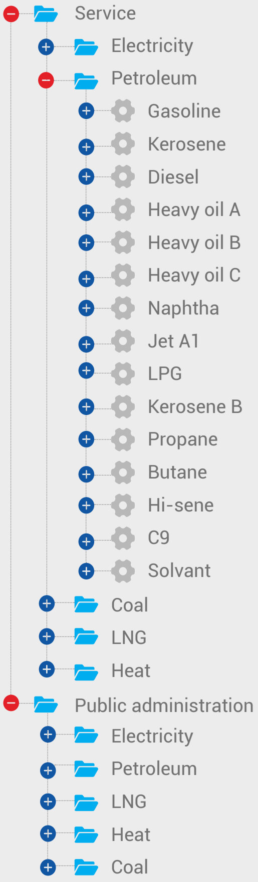
Figure 3.22
Structure used to model emissions from the non-road transport in the Republic of Korea, Seoul, Incheon and Gyeonggi



Services

Fuel consumption in the service and public administration sectors is directly calculated for different fuel types. This fuel consumption is then multiplied by fuel and sector-specific emissions factors.

Figure 3.23
Structure used to model emissions from the services sector in the Republic of Korea, Seoul, Incheon and Gyeonggi

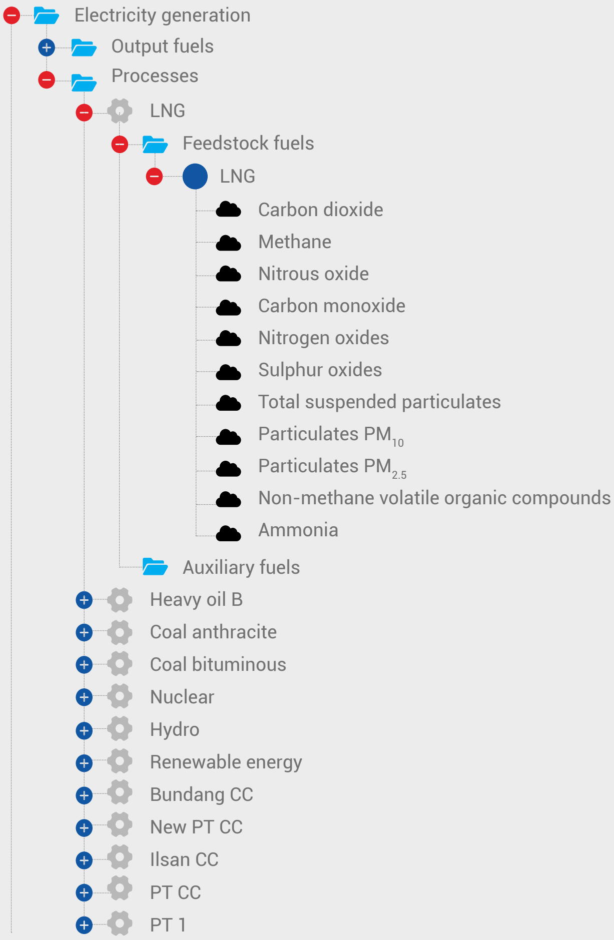


For the Republic of Korea, power stations were specified based on their major fuel types, and for SIG, individual power stations were modelled.

Electricity generation

The previous pages describe the methods used to estimate emissions from energy-demand sectors, i.e. sectors with final energy consumption. Emissions from the energy supply sectors, such as electricity generation, were also modelled by multiplying the total fuel consumed to generate electricity by power plant-specific emission factors. The fuel consumed to generate electricity was estimated first, based on the demand for electricity (the input for each of the sectors as described above). The electricity demand was then adjusted for transmission and distribution losses. For each region, the power stations generating electricity were then included with their key characteristics. For the Republic of Korea, power stations were specified based on their major fuel types and for SIG, individual power stations were modelled (Figure 3.24). The electricity generated from each power station type was determined by its capacity and availability across the year, and a user-assigned merit order dispatch, i.e. no optimization modelling was undertaken. The electricity generated by different types of power stations was then multiplied by an efficiency factor for each station to estimate the fuel consumed to generate that amount of electricity.

Figure 3.24
Structure used to model emissions from electricity generation in the Republic of Korea, Seoul, Incheon and Gyeonggi



In the non-energy sectors, such as agriculture, emissions are estimated using Equation 1, i.e. an activity variable multiplied by an emission factor.

Agriculture

In the non-energy sectors, such as agriculture, emissions are estimated using Equation 1, i.e. an activity variable multiplied by an emission factor. For the livestock sub-sector, emissions were estimated for enteric fermentation and manure management. For both, the activity variable was the number of animals in the categories shown in Figure 3.25. The number of animals was multiplied by animal-specific emissions factors for each category of emission.

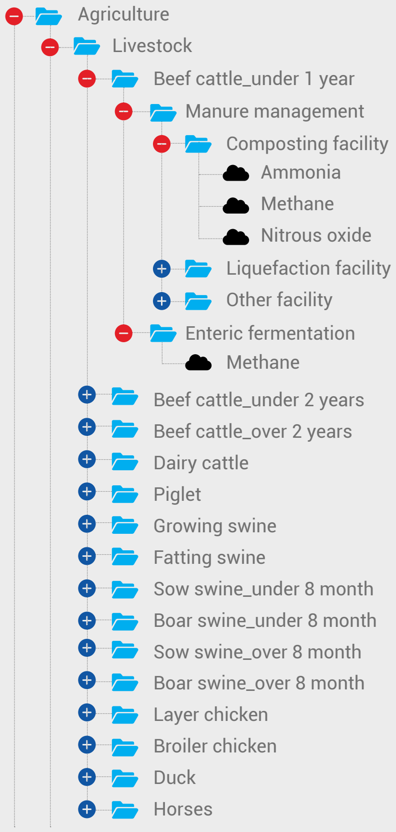


Figure 3.25
Structure used to model emissions from the livestock sector in the Republic of Korea, Seoul, Incheon and Gyeonggi

For crop production, the activity variable was the tonnes of fertilizer applied to fields, which was multiplied by fertilizer- and pollutant-specific emissions factors.

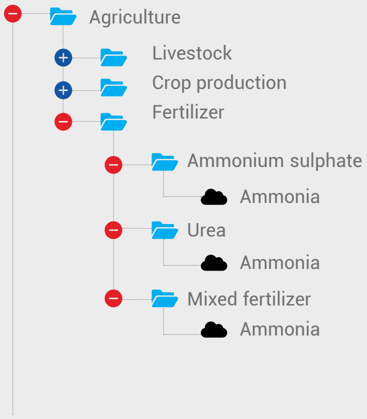


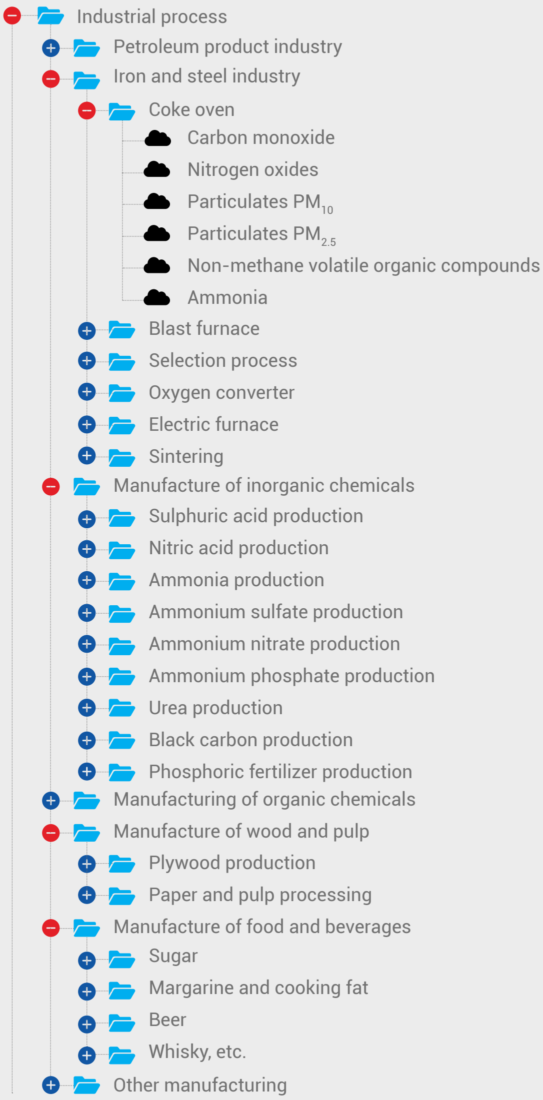
Figure 3.26 Structure used to model emissions from crop production in the Republic of Korea, Seoul, Incheon and Gyeonggi

Within the industrial processes sub-sector, the activity variable for all industries was the annual production of different industrial products.

Industrial processes

Within the industrial processes sub-sector, the activity variable for all industries was the annual production of different industrial products. For the iron and steel sector, the production was disaggregated by major processes, but for all other industries, the total production was multiplied by process-specific emissions factors.

Figure 3.27
Structure used to model emissions from the industrial processes in the Republic of Korea, Seoul, Incheon and Gyeonggi

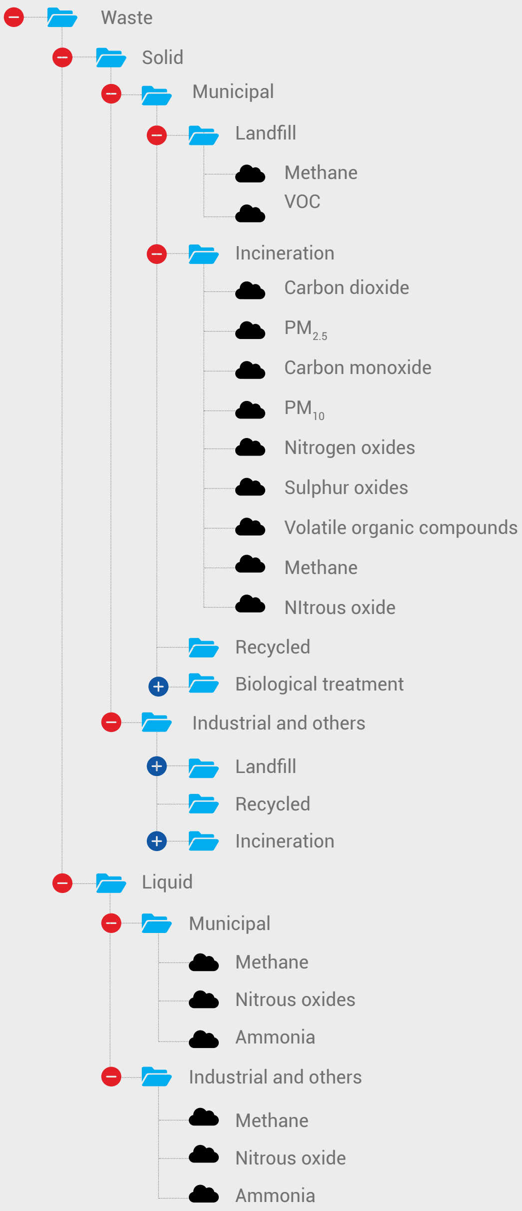


The total mass and volume of waste generated and handled using different management methods were the key activity variables.

Waste

In the waste sector, emissions for solid and liquid waste were estimated for municipal and industrial waste. The total mass (solid) and volume (liquid) of waste generated and handled using different management methods were the key activity variables and were multiplied by pollutant and process-specific emissions factors to estimate emissions.

Figure 3.28
Structure used to model emissions from the waste sector in the Republic of Korea, Seoul, Incheon and Gyeonggi



3.2.2 Estimating future emissions for a baseline scenario

As shown in Chapter 2, emissions of air pollutants have changed in SIG and the Republic of Korea over the past decades as a result of its socio-economic development and as a result of the implementation of policies and measures designed to reduce emissions. Section 3.1 also shows how drivers of these emissions, including energy consumption in households and industry, the vehicle fleet, crop and livestock production and waste generation, have altered to contribute to a changing picture of air pollutant emissions and the contribution of different sources over time.

A baseline scenario, also often referred to as a business-as-usual or reference scenario, was designed to estimate how future emissions *could* change into the future without the implementation of any new air quality or climate change mitigation policies. In doing so, it can act as a reference against which the reduction in emissions from implementing specific new policies and measures can be compared. The baseline scenario, therefore, provides the basis for assessing the effectiveness of different policies and measures, by projecting what emission levels could reach without their implementation.

To develop the baseline scenario, the activity variables used for the development of the historic emissions estimates for the Republic of Korea and SIG were projected into the future, and the calculation of emissions was repeated based on the projected activity variables in future years. In this work, the timespan for future scenarios was 2021–2050. The projection of the activity variables for each source sector (Section 3.2.1) was undertaken by linking the activity variables to specific proxy variables that represent demographic and socioeconomic development in the Republic of Korea and SIG that act as drivers of activity within these sectors.

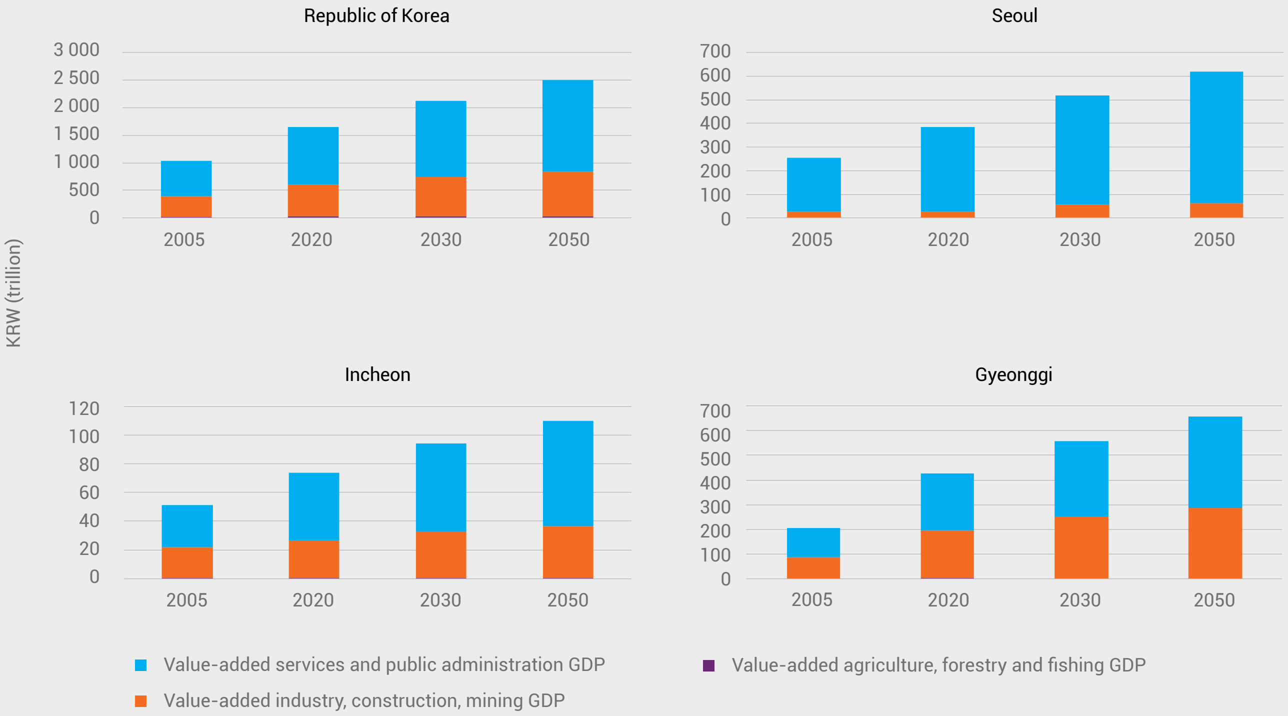
In the baseline scenario, the overarching demographic and macroeconomic assumptions are shown in Table 3.12. Across the Republic of Korea, according to the Korean Statistical Information Service (KOSIS), the population is expected to decline between 2020, 2030 and 2050 with the population 9 per cent lower in 2050 compared to 2020 levels. The population is expected to follow this national trend in Seoul and Incheon, but to increase in Gyeonggi. In contrast, the Republic of Korea's GDP is projected to increase substantially over the next decades, increasing by 51 per cent between 2020 and 2050, an average growth rate of 1.7 per cent per year, according to the Bank of Korea. The economies of Seoul, Incheon and Gyeonggi are projected to increase at a higher rate than the rest of the Republic of Korea, with 72, 63 and 66 per cent growth respectively (Table 3.12). The structure of the Republic of Korea's economy is expected to further increase the share of services to GDP, with a 57 per cent increase in the value-added services GDP between 2020 and 2050, compared to a 39 per cent rise in industrial value-added GDP, and a relatively flat agricultural value-added GDP (Figure 3.29), according to the Institute of Industrial Economics and Trade.

Cheonggye-cheon autonomous driving bus.
© Seoul Metropolitan Government

Table 3.12
Projections of demographic and macroeconomic variables used in the development of the baseline scenario

		2020	2030	2050
Population (million people)	Republic of Korea	51.83	51.20	47.36
	Seoul	9.60	8.95	7.92
	Incheon	2.95	2.96	2.81
	Gyeonggi	13.45	14.42	14.35
GDP (KRW trillion)	Republic of Korea	1 838.90	2 373.80	2 781.80
	Seoul	377.10	543.10	650.50
	Incheon	77.90	109.60	127.00
	Gyeonggi	434.40	614.40	722.60

Figure 3.29
Changes in gross domestic product disaggregated by macroeconomic sector, the Republic of Korea, Seoul, Incheon and Gyeonggi, 2005–2050, KRW trillion



The economic growth expected over the next decades is expected to result in multiple changes within the major air pollution emissions source sectors that are reflected in the baseline scenario. The size of the Republic of Korea's vehicle fleet is expected to increase by 30 per cent between 2020 and 2050, but the growth varies considerably between regions due to differing trends in population and income in each. There is a limited increase in the number of vehicles in Seoul, with only a 1 per cent increase. In contrast, the number of vehicles is expected to increase in Incheon, +56 per cent, and Gyeonggi, +19 per cent (Figure 3.30). Vehicle ownership is expected to continue to increase substantially, with a 54 per cent increase in the number of passenger cars per person, from 261 passenger cars per 1 000 people in 2020 to 403 in 2050 (Figure 3.30).

At the same time, the baseline scenario also reflects that the vehicle fleet is likely to be made up of lower air pollutant emitting vehicles in the future, as older vehicles are retired and replaced by new ones meeting more stringent standards. Figure 3.31 shows an example of the distribution of passenger cars in terms of the vehicle emissions standards they meet, with all vehicles in the Republic of Korea, including SIG, meeting Grade 1 standards by 2030.

Figure 3.30
Baseline projections of the vehicle flee disaggregated by a) region and b) vehicle type, the Republic of Korea, 2005–2050, thousands

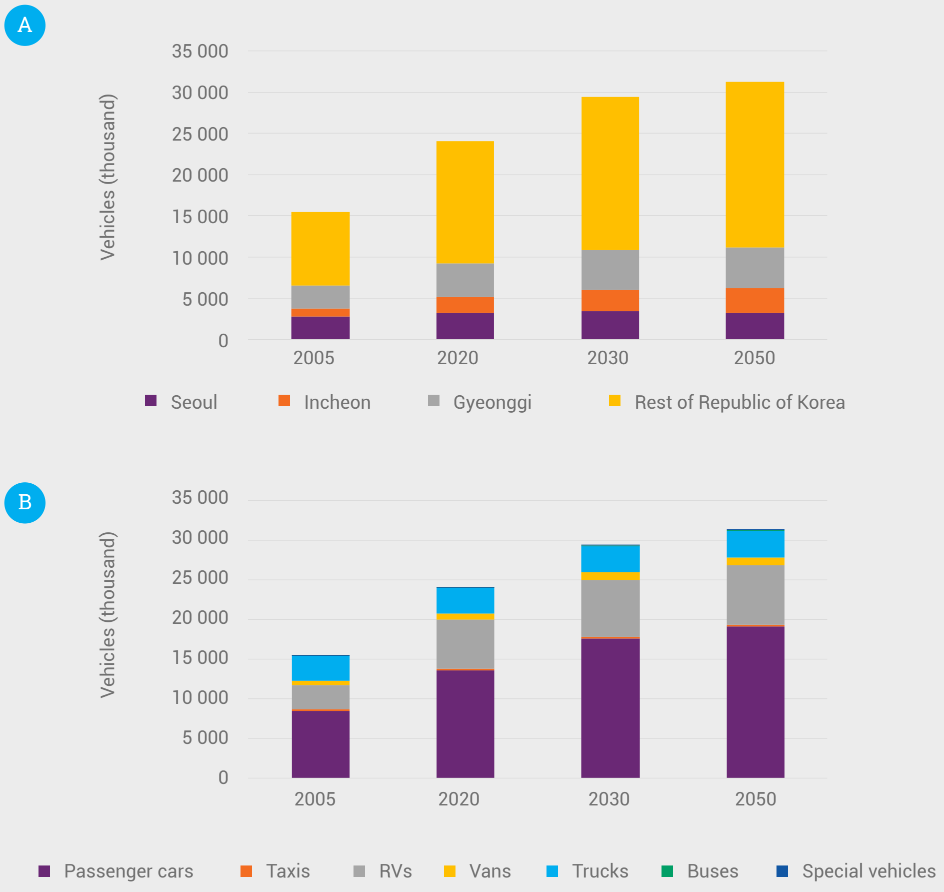
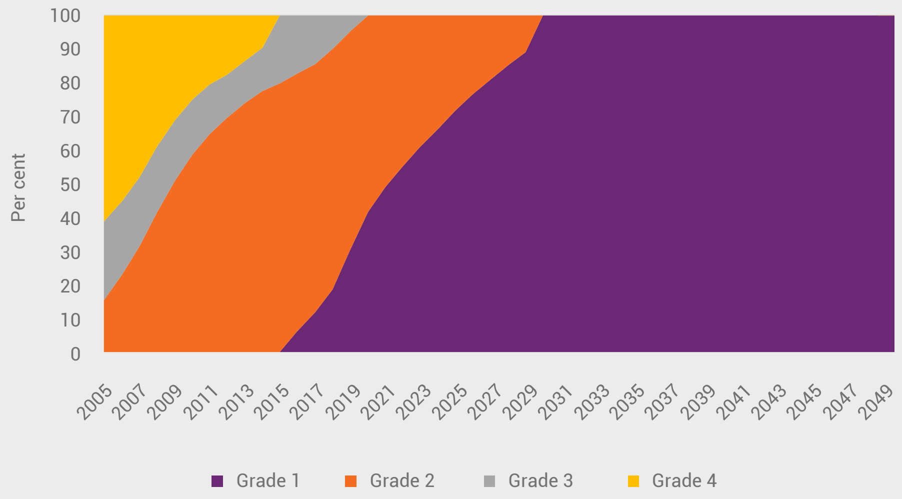


Figure 3.31
Baseline projections of medium-sized passenger cars meeting different vehicle emission standards 2005–2050, per cent

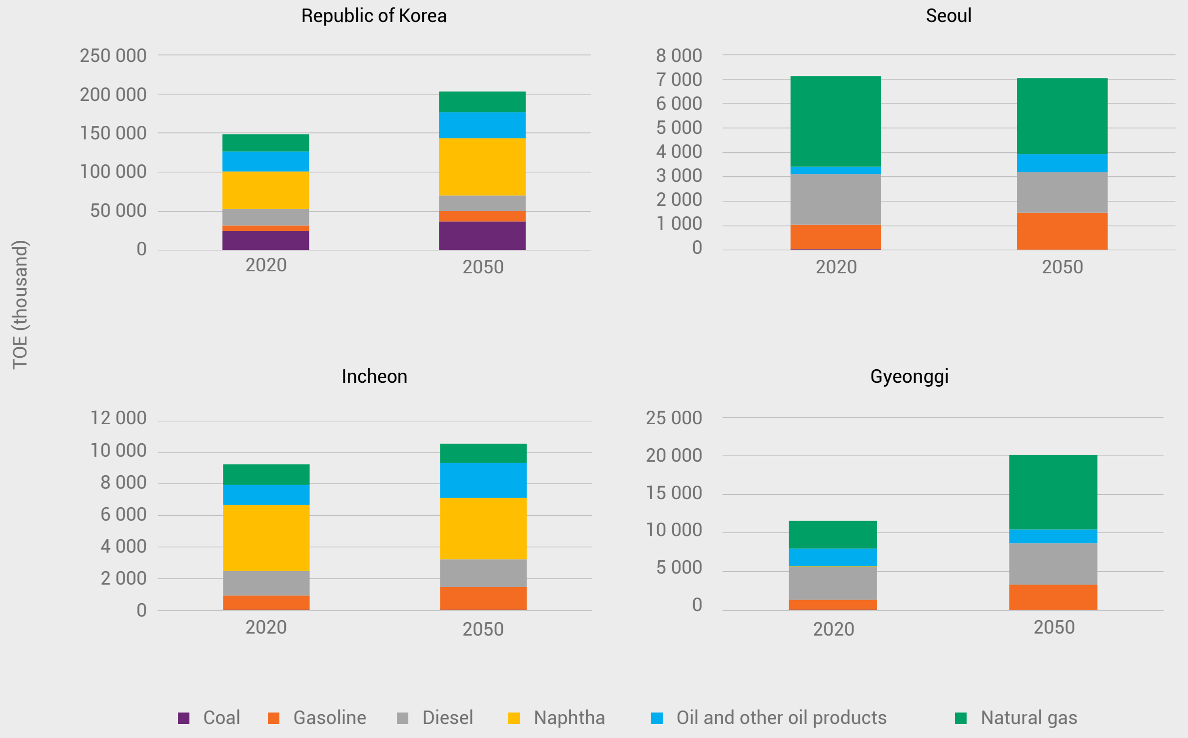


As outlined, in the baseline scenario the Republic of Korea's industrial value-added GDP is expected to continue to grow, albeit at a lower rate compared to the services sector. The three main energy consuming industrial sectors (Section 3.1) are expected to grow between 2020 and 2050. Iron and steel value-added GDP is expected to grow by 19 per cent between 2020 and 2050, chemical production by 39 per cent, while the value-added GDP for oil refining is expected to decrease slightly after 2030. As a consequence, fuel consumption in the industrial sector is expected to increase over the next decades. The baseline shows a 25 per cent overall increase in fuel consumption from industry in the Republic of Korea, including coal and oil products. In Gyeonggi, the growth in industrial fuel consumption is driven by a large increase in natural gas consumption.

Table 3.13
Baseline projections of industrial and services value-added gross domestic product disaggregated by major industry, the Republic of Korea, 2005–2050, KRW trillion

Republic of Korea	2005	2020	2030	2050
Food and tobacco	16.4	23.2	25.8	28.1
Textiles and leather	14.3	12.7	15.3	17.7
Steel and metal	54.4	58.3	64.6	69.1
Non-metallic minerals	9.5	12.9	15.9	17.9
Paper	8.8	11.5	11.4	9.9
Wood	1.7	2.4	2.3	2.0
Machinery	22.7	44.3	58.2	65.7
Chemicals	52.3	75.2	92.5	104.7
Oil refinery	12.6	12.3	13.0	12.1
Transport vehicles	37.7	45.9	53.2	59.8
Other manufacturing	57.3	185.9	259.6	308.3
Mining	3.0	2.1	2.1	2.2
Construction	79.0	89.2	96.1	104.6
Services	570.1	946.0	1 181.5	1 511.3
Public administration	71.1	108.2	133.2	144.2

Figure 3.32
Baseline projections of final energy consumption disaggregated by fuel types, the Republic of Korea, 2020 and 2050, thousand tonnes of oil equivalent



In the baseline scenario, electricity generation responds to the rising demand for electricity. The generation of electricity reflects planned power station construction and the retirement of old power stations at the end of their lives.

For the non-energy sectors, such as the agricultural and the waste sectors, the baseline scenario projects activity in these sectors, for example, the number of livestock and the volume of waste generation, based on projected population trends.

The baseline scenario reflects the likely progression of air pollutant emissions without the implementation of new policies and measures. The continuing impact of existing policies and measures is , however, reflected in the baseline scenario. Therefore, the baseline scenario includes policies and measures, such as vehicle emissions and energy efficiency standards, that have been agreed and whose continuing implementation will impact future air pollutant emissions. These policies and measures are shown in Table 3.14.

Table 3.14
Policies and measures included within baseline scenario

Name of policy/measure	Sector	Description	Plan or policy	Source
Energy efficiency in industry	Industry	Historical trends	*Status quo* (current policy)	
Energy efficiency in buildings	Residential/ services/public administration	Historical trends	*Status quo* (current policy)	
Vehicle emissions standards	Road transport	Euro 6	*Status quo* (current policy)	
Energy efficiency	Railroad	Historical trends	*Status quo* (current policy)	
Tier 4 emissions standards	Off road machinery	Switching to Tier 4 level emissions standard machinery	2nd Basic Plan for Air Quality Management in SMR (2015-2024)	Ministry of Environment (2021)
Electromobility	Road transport	Historical trends	*Status quo* (current policy)	
Waste reduction	Waste	Historical trends (recycle, etc.)	*Status quo* (current policy)	

3.2.3 Estimating emission reduction potential from the implementation of policies and measures

In addition to the baseline scenario, two other scenarios, the carbon neutrality (CN) scenario and an air pollution mitigation (AP) scenario were modelled to reflect the implementation of different, specific policies and measures designed to reduce emissions and thereby contribute to climate change and air pollution.

The individual mitigation measures were grouped into two categories, so that the effect of implementing a group of mitigation measures could be assessed, accounting for interactions between different mitigation action. Each scenario, therefore, includes policies and measures, identified from a review of current plans, strategies and policies, to understand the air pollutant, SLCP and GHG emissions reductions that could be achieved from their implementation. The policies and measures modelled in each scenario are described in Table 3.15.

The individual mitigation measures were grouped into two categories, so that the effect of implementing a group of mitigation measures could be assessed, accounting for interactions between different mitigation action.

Table 3.15

Policies and measures included in the carbon neutrality and air pollution mitigation scenarios

Scenario	Name of policy/ measure	Sector	Description	Plan or policy	Source
CN	Transformation sector energy transition	Energy supply (electricity, heat)	Fuel substitution for electricity generation (from fossil fuels to approximately 72 per cent from renewable sources by 2050) Fuel substitution for heat generation (from fossil fuels to approximately 50 per cent from renewable sources by 2050)	2050 CN (Carbon Neutrality) plan	2050 CNC (Carbon Neutrality and Green Growth Commission) (2021)
CN	Industrial sector energy efficiency improvement	Industry (manufacturing, mining, construction and agriculture)	Energy efficiency improvement, fuel substitution (from fossil fuels to electrification, renewable sources) for all industries	2050 CN plan	2050 CNC (2021)
CN	Zero emission vehicle deployment	Road transport	Full zero-emissions vehicle deployment by 2050 for road vehicle fleet (including electric vehicles and hydrogen fuel cell vehicles)	2050 CN plan, Urban access regulation (Seoul)	2050 CNC (2021)
CN	Fuel economy improvement	Road transport	A fall in the amount of fuel used per kilometre travelled, Increase share of small cars	2050 CN plan	2050 CNC (2021)
CN	Transport demand management	Road transport	Switching from passenger cars to public transport (reduction in passenger car kilometres)	2050 CN plan	2050 CNC (2021)
CN	Other transport measures	Transport (railroad, shipping and aviation)	Energy efficiency improvement, fuel substitution (from fossil fuels to electrification, and use of energy from renewable sources)	2050 CN plan	2050 CNC (2021)
CN	Zero energy buildings	Residential, service, public administration	Improved energy efficiency	Zero energy buildings programme, building emissions cap programme (Seoul)	Ministry of Land, Infrastructure and Transport (2019), Hwang *et al.* (2021)
CN	Fuel substitution	Industrial processes and product use (iron and steel)	Fuel substitution (from fossil fuels to electrification, and use of energy from renewable sources)	2050 CN plan	2050 CNC (2021)
CN	Direct landfill ban	Waste (landfill)	Reduction of landfilling of waste	Municipal waste landfill ban programme	Waste Control Act (2021)
CN	Rice cultivation	Agriculture – crop production	Modification of flooding pattern	CN plan for agriculture	2050 CNC (Ministry of Agriculture, Food and Rural Affairs, 2021)
CN	Livestock management	Agriculture – livestock	Livestock nutrition management	CN plan for agriculture	2050 CNC (Ministry of Agriculture, Food and Rural Affairs, 2021)
AP	Industrial facility emissions cap and trade programme	Energy supply, industry, incineration	Increasing emissions control rates	2nd Basic Plan for Air Quality Management in SMR (2015-2024)	Ministry of the Environment (2021)

Scenario	Name of policy/ measure	Sector	Description	Plan or policy	Source
AP	Transport demand management	Transport – road vehicles	Low emission zone in atmospheric control area in SMR	2nd Basic Plan for Air Quality Management in SMR (2015-2024)	Ministry of Environment (2021)
AP	Non-road Tier 4 emissions standard	Non-road – construction and agricultural machinery	Switching to Tier 4 emissions standard machinery	2nd Basic Plan for Air Quality Management in SMR (2015-2024)	Ministry of Environment (2021)
AP	Improvement of fuel	Industry, transport and others	Decreasing the sulphur content	2nd Basic Plan for Air Quality Management in SMR (2015-2024)	Ministry of Environment (2021)

Seoul Bike Ttareungi (public bike-sharing system).
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Yangjae Green Car Station (a hydrogen and electric vehicle convergence charging station through solar power generation).
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3.3 Air pollution mitigation assessment results

As stated in Section 3.1, this report aims to evaluate historical trends in air pollutant emissions across SIG and assess how these emissions could be further reduced from the implementation of policies and measures in the future. Section 3.2 describes how emissions from all major source sectors in 2005–2020 were estimated and then projected to 2050 for a baseline scenario. Finally, the assessment quantifies the impact of implementing policies and measures that could affect emissions in the future, including achieving carbon neutrality. There are **five key messages** resulting from the assessment, based on the preliminary results. These are described below.

There have been many other studies that have estimated air pollutant emissions in SIG and the Republic of Korea, and the official CAPSS inventory provides regularly updated official air pollutant emissions estimates. In this report, updated data have been used to characterize historical emissions and to create projections for the future. Compared to the 2019 CAPSS air pollutant emissions inventory, this report's estimates are slightly lower (Table 3.16). Despite these differences, the major source sectors are common across the two inventories and the differences are not expected to lead to substantial variations in the conclusions and key messages of this report.


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Key Result #1

Air pollutant emissions fell in Seoul, Incheon and Gyeonggi between 2005 and 2020

As outlined in Chapter 2, previous research has shown that concentrations of $PM_{2.5}$, NO_x and other pollutants have fallen in SIG over the last decades. While some of this has been achieved through reductions in emissions outside of the Republic of Korea, previous research indicates that policies and measures implemented in SIG and the rest of the Republic of Korea have also reduced air pollutant emissions in the Republic of Korea. This assessment also shows that there has been significant progress in reducing air pollutant emissions across SIG and the whole country (Table 3.16).

Primary $PM_{2.5}$ emissions fell by 19 per cent between 2005 and 2020 across the whole of the Republic of Korea, but by larger amounts in Seoul and Gyeonggi, by 75 and 53 per cent respectively. Other pollutants have also decreased substantially. In Gyeonggi, the largest reductions have been in PM_{10}, and SO_2 emissions, -55 and -65 per cent respectively, between 2005 and 2020. In Seoul, NO_X emissions fell by 46 per cent. The reason for these reductions, as outlined in previous research, is the implementation of policies and measures in key source sectors. For SIG, emissions reductions from the transport sector have had the largest impact, with the greatest falls in Seoul because the transport sector makes the largest contribution to $PM_{2.5}$ emissions in Seoul, whereas in Incheon and Gyeonggi other sources also make a substantial contribution.

Table 3.16

Emissions of air pollutants and greenhouse gases in the Republic of Korea, Seoul, Incheon and Gyeonggi, 2005 and 2020, thousand tonnes

	Republic of Korea			Seoul			Incheon			Gyeonggi		
	2005	2020	Change %	2005	2020	Change %	2005	2020	Change %	2005	2020	Change %
CO_2	579 413	725 999	25.3	26 383	22 603	-14.3	69 577	74 132	6.5	52 660	58 096	10.3
CO	674	499	-25.9	78	26	-66.2	38	32	-16.2	114	74	-35.0
CH_4	1 110	1 004	-9.6	151	121	-19.9	29	28	-3.1	153	152	-0.9
NMVOC	893	979	9.6	82	66	-19.3	48	50	3.5	151	167	10.6
NO_x	977	876	-10.3	114	62	-45.7	74	63	-14.2	178	148	-16.9
PM_{10}	144	131	-9.6	5	1	-76.4	3	2	-41.8	9	4	-54.5
SO_2	402	284	-29.4	15	2	-88.9	38	32	-14.6	64	22	-65.1
NH_3	252	275	9.2	2	0	-79.2	5	3	-45.8	39	38	-2.2
$PM_{2.5}$	81.1	65.5	-19.3	4	1	-75.0	4	3	-23.1	8	4	-52.7

In this report, updated data are used to characterize historical emissions and to create projections for the future. Compared to the 2019 CAPSS, this report's air pollutant emissions estimates are slightly lower.

The reduction in air pollutant emissions is consistent with the decreasing trend calculated in the official national air pollutant emission inventory (CAPSS) (Section 2). However, the absolute magnitude of emissions in the LEAP analysis and CAPSS inventory is different for SIG. Tables 3.17 and 3.18 show the total and sectoral emissions, respectively estimated in this analysis for 2019 and in the CAPSS dataset. Due to differences in the data used to estimate emissions and the more disaggregated methods used within the LEAP analysis to facilitate the assessment of policies and measures, there are differences in the total magnitude of emissions of different air pollutants. The emissions estimate in this assessment is generally lower than those from CAPSS. For $PM_{2.5}$ and PM_{10} emissions, the non-inclusion of fugitive dust emissions in the LEAP dataset explains most of the difference, but there are also variations in the estimates of emissions from other sources.

Table 3.17

Comparison of air pollutant emissions estimated by the LEAP analysis with CAPSS air pollutant emission estimates for 2019, the Republic of Korea, thousand tonnes

Pollutant	SIG LEAP	CAPSS	Difference %
CO	506	758	-33.3
NMVOC	982	1 020	-3.8
NO_X	919	1 087	-15.4
PM_{10}	138	208	-33.8
SO_2	299	273	9.6
NH_3	274	316	-13.4
$PM_{2.5}$	69.1	87.6	-21.2

Table 3.18

Comparison of air pollutant emissions estimated by the LEAP analysis with CAPSS air pollutant emission estimates for 2019 disaggregated by major source sector, the Republic of Korea, tonnes

Emissions source category	CO		NO_x		SO_x		PM_{10}		$PM_{2.5}$		VOCs		NH_3	
	CAPSS	SIG LEAP	CAPSS	SIG LEAP	CAPSS	SIG LEAP	CAPSS	SIG LEAP	CAPSS	SIG LEAP	CAPSS	SIG LEAP	CAPSS	SIG LEAP
Other surface-pollutant source	10 552		271		-		599		539		1 281		12 962	
Agriculture	-	-	-	-	-	-	-	-	-	-	-	-	252 444	244 139
Road transport	180 489	97 022	371 851	384 668	308	595	6 719	7 338	6 182	6 782	36 663	21 272	2 615	1 081
Non-road transport	187 565	142 945	311 748	196 238	37 555	32 846	17 265	9 030	15 989	8 350	63 951	56 398	122	119
Fugitive dust	-		-		-		105 037		17 272		-		-	
Non-industry	47 629	17 728	85 814	63 667	15 869	3 181	1 177	873	857	712	2 828	2 906	1 350	828
Biomass burning	218 642	146 828	8 407	5 358	75	-	13 806	8 640	11 482	7 194	83 521	60 292	15	5
Industrial process	26 766	26 766	51 705	62 967	105 699	121 028	6 699	8 573	5 139	6 353	186 292	254 870	44 630	26 211
Energy production	64 327	46 575	75 513	138 685	45 297	86 810	3 365	5 422	2 813	5 078	8 434	6 219	1 422	1 021
Energy transport and storage	-		-		-		-		-		29 062		-	
Solvent use	-	-	-	-	-	-	-	-	-	-	545 244	545 057	-	-
Manufacturing industry	19 737	24 429	169 221	47 460	65 730	52 191	52 932	97 293	27 118	34 301	3 404	1 938	717	360
Waste disposal	2 140	3 227	12 332	19 925	2 326	2 460	267	344	228	309	59 537	32 749	22	0
Total	757 848	505 520	1 086 862	918 969	272 859	299 111	207 866	137 513	87 618	69 080	1 020 216	981 701	316 299	273 763

Note: Totals may not sum due to rounding

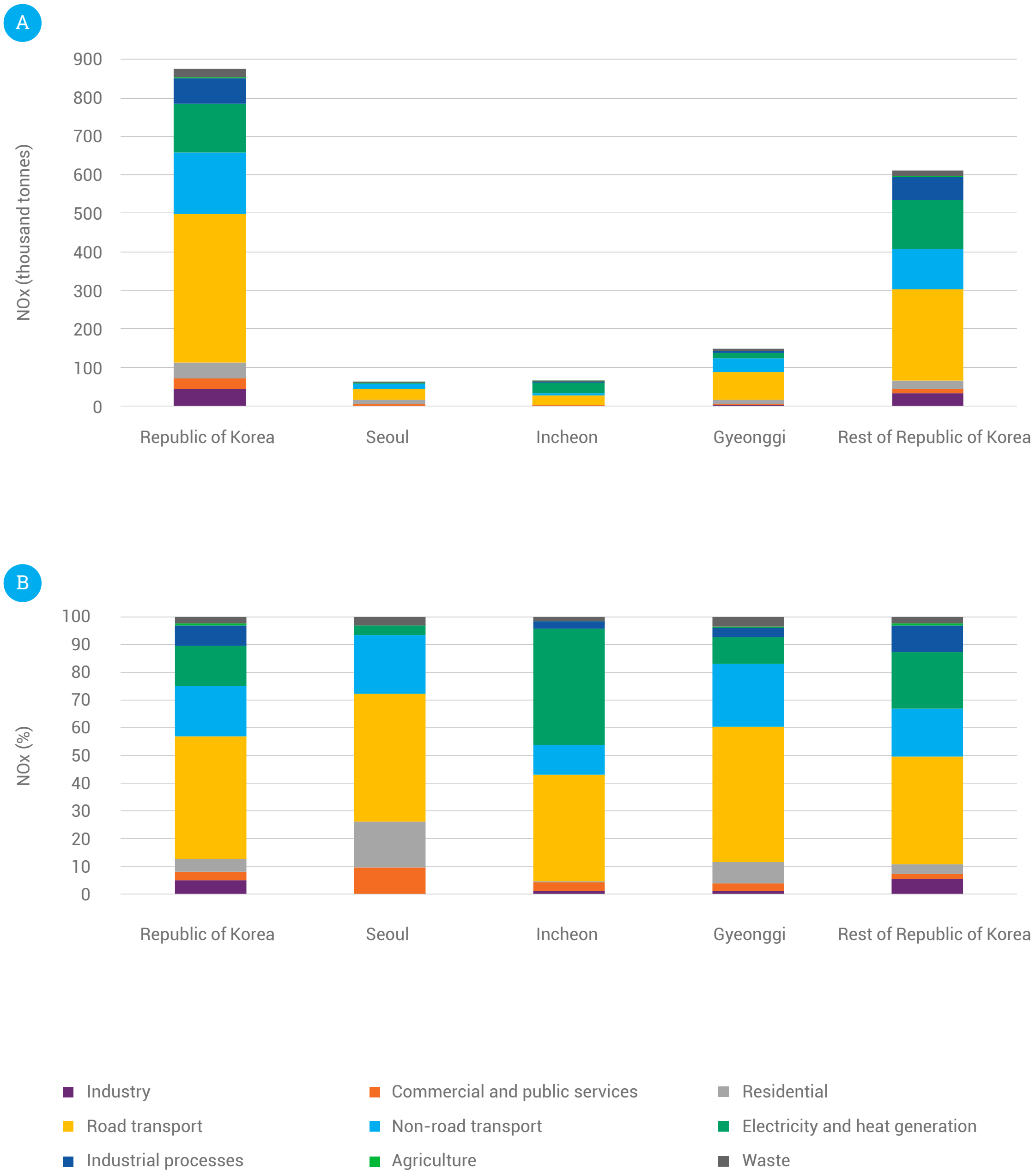
The fall in air pollutant emissions across the Republic of Korea has reduced $PM_{2.5}$ and other air pollutant concentrations in SIG. Nonetheless, concentrations of air pollutants in SIG continue to exceed national and international air quality standards/guidelines. Figure 3.33 shows the current contribution of different sources to total $PM_{2.5}$ concentrations in Seoul, Incheon, Gyeonggi and the Republic of Korea. Across the Republic, the industrial sector contributed just under half of total national $PM_{2.5}$ emissions in 2020. Almost all of these emissions are, however, emitted outside SIG. Transport is the second largest contributor to total national $PM_{2.5}$ emissions, and is the largest single source in Seoul and Gyeonggi producing around 40 and 30 per cent of total $PM_{2.5}$ emissions respectively in 2020. In Seoul and Gyeonggi, non-road transport contributes the majority of the remaining fraction of primary $PM_{2.5}$ emissions, with a minor, but significant, contribution from agriculture in Gyeonggi. In Incheon, transport is a lesser source, producing less than 20 per cent of total $PM_{2.5}$ emissions, but electricity generation makes the largest contribution, more than 60 per cent of primary $PM_{2.5}$ emissions.

For other toxic air pollutants, such as NO_X, there is greater consistency between regions in the contribution of different sources to total emissions in each region (Figure 3.34). The transport sector is the largest source in the Republic of Korea, Seoul, Incheon and Gyeonggi, contributing between 40 and more than 70 per cent in the different regions. Non-road transport and electricity generation make up the largest fraction of remaining NO_X emissions. Within these sectors, however, there are also differences resulting from region-specific factors. In Incheon, for example, there is a larger contribution from non-road transport due to its port, international airport and power plants located within the city.

Figure 3.33
a) Total emissions of primary fine particulate matter and b) contribution broken down by major source sector, the Republic of Korea, Seoul, Incheon Gyeonggi and the rest of the Republic of Korea, 2020, a) thousand tonnes and b) per cent

Figure 3.34

a) Total emissions of nitrogen oxides and b) contribution by major source sector, the Republic of Korea, Seoul, Incheon Gyeonggi and the rest of the Republic, 2020, a) thousand tonnes and b) per cent



Key Result #2:

Reduction in air pollutants has not been achieved alongside reductions in greenhouse gases

While between 2005 and 2020 there have been substantial reductions in health-damaging air pollutants in SIG, the emissions of GHG, particularly CO_2, have not fallen substantially across the different regions included in this analysis. Over this period, primary $PM_{2.5}$ emissions have fallen by 19 per cent in the Republic of Korea but CO_2 emissions have increased by 25 per cent (Figure 3.35). In recent years, however, CO_2 emissions have fallen from their peak in 2018, with 2020 CO_2 emissions 7 per cent lower than in 2018. Between 2005 and 2020, CO_2 emissions increased in Incheon by 7 per cent and in Gyeonggi by 10 per cent in contrast to the trend in the majority of air pollutants. In Seoul, CO_2 emissions have decreased by 14 per cent, but this reduction is far smaller than the reductions in the majority of air pollutants, which have reduced by as much as 89 per cent.

Figure 3.35
a) carbon dioxide emissions and b) primary fine particulate matter emissions by major source sector, the Republic of Korea, 2005–2020, a) million tonnes and b) thousand tonnes

This highlights that, while the legal framework for air quality management in SIG has successfully reduced air pollutant emissions, not all emissions from key sources have been reduced as a result of the policies and measures that have been implemented.

This pattern of differentiated changes in air pollutant and GHG emissions has been a common feature across SIG. The most common policies and measures implemented has been conventional control measures which reduce post-combustion emissions selectively through fitting of control technologies to outlets. Examples of these measures include particle filters fitted to vehicles or industrial facilities that reduce PM emissions, and are responsible, through the implementation of ever more stringent vehicle emissions standards, for the large reduction in $PM_{2.5}$ emissions in SIG's transport sector. The implementation of these post-combustion controls does not, however, result in any reduction in CO_2 emissions, which are defined by the volume of fuel that is combusted. Hence, air pollutant emissions have decreased in Seoul, Incheon and Gyeonggi, but CO_2 emissions have either increased or, at best, have decreased to a lesser extent.

Despite there being different trends in the direction of air pollutant and GHG emissions in SIG and the Republic of Korea, there is also a substantial overlap in the major sources of CO_2 and different air pollutants (Figure 3.36). In 2020, for example, transport was a major source of CO_2 across all regions and the largest source in Seoul and Gyeonggi which accounted for about 40 per cent of their total CO_2 emissions. In Incheon, electricity generation was the largest source, accounting for almost 60 per cent of its CO_2 emissions, and in the Republic of Korea as a whole, industry was the largest source, responsible for just under 50 per cent of total national CO_2 emissions. This is consistent with the major sources of $PM_{2.5}$ emissions in each of these regions.

Hence, there is now a substantial opportunity to design, evaluate and implement strategies that simultaneously achieve the Republic of Korea's commitment to reduce its contribution to climate change and achieve CN while at the same time further reducing air pollutant emissions. The overlap in sources means that both can be mitigated concurrently by identifying policies and measures that simultaneously reduce air pollutants and CO_2. This could reverse the different directions of trends in CO_2 and air pollutant emissions that has been seen between 2005 and 2020 in SIG and the Republic of Korea.

Cheongna lake park, Incheon.
© Incheon Metropolitan City

Figure 3.36
a) Total carbon dioxide emissions and b) contribution broken down by major source sector, the Republic of Korea Seoul, Incheon, Gyeonggi and the rest of the Republic, 2020, a) million tonnes and b) per cent

Reductions in air pollutant emissions achieved across the Republic of Korea, and in SIG in particular, have resulted from the implementation of specific policies and measures over the past decades.

Key Result #3:

Reductions in air pollutant emissions in Seoul, Incheon and Gyeonggi are likely to continue between 2020 and 2050 with the implementation of current policies and measures, but will not reduce greenhouse gases

Reductions in air pollutant emissions achieved across the Republic of Korea, and in SIG in particular, have resulted from the implementation of specific policies and measures over the past decades. At the same time, economic activities in SIG have increased, placing further demand on resources which could result in higher air pollutant emissions from, for example, a larger vehicle fleet and more fuel consumption by households and industry. The baseline projections of air pollutant emissions in different sectors indicate that the reductions in achieved in some regions cannot be taken for granted and could be reversed without the continued implementation of policies and measures (Table 3.19).

The future baseline projection of emissions in different regions depends on the contribution of major source sectors to different air pollutant emissions. In Seoul, baseline $PM_{2.5}$ emissions in 2030 and 2050 are expected to be substantially lower than in 2020, 36 and 54 per cent lower than 2020 levels in 2030 and 2050 respectively, because of the continued renewal of the vehicle fleet, replacing relatively higher emitting vehicles with newer vehicles fitted with advanced $PM_{2.5}$ control technologies. Other measures assumed to be implemented in the baseline scenario are Tier 4 emissions standards for non-road transport vehicles, which make a substantial contribution to reducing $PM_{2.5}$ and other air pollutant from this sector. For the same reason, $PM_{2.5}$ emissions in Gyeonggi and Incheon are also expected to decrease between 2020 and 2030. **Meanwhile, in the Republic of Korea, $PM_{2.5}$ emissions are projected to increase by 7 per cent between 2020 and 2030, and by 20 per cent between 2020 and 2050**. Outside of SIG, industry makes a substantial contribution to these emissions and increases in industrial output and fuel consumption, alongside increased electricity generation using fossil fuels, drives the increase in $PM_{2.5}$ emissions in the Republic of Korea.

Other pollutants show similar patterns to $PM_{2.5}$ but reflect the specific sources that contribute to their total emissions. For example, NO_X emissions from the transport sector make a greater contribution in all regions compared to $PM_{2.5}$, and therefore show reductions in the baseline in all regions, reflecting the renewal of the vehicle fleet and the smaller contribution to NO_X emissions from sources that are expected to increase – electricity generation and industry.

At the same time, CO_2 emissions are expected to increase across most regions of the Republic of Korea – CO_2 emissions in the baseline are estimated to increase by 10 per cent by 2030 and 24 per cent by 2050, relative to 2020. Increases in CO_2 emissions are expected in Seoul and Gyeonggi, and a small reduction is estimated for Incheon.

Table 3.19

Baseline scenario projections for fine particulate matter, carbon dioxide and nitrogen oxide emissions in the Republic of Korea, Seoul, Incheon and Gyeonggi, 2010-2050, thousand tonnes

Pollutant	Region	2010	2020	2030	2040	2050	Change 2020–2050 (%)
$PM_{2.5}$	Republic of Korea	77.8	65.5	70.3	75.4	78.5	19.8
	Seoul	2.8	1.1	0.7	0.5	0.5	-54.3
	Incheon	4.5	3.2	2.6	2.2	2.2	-31.7
	Gyeonggi	6.6	3.8	2.7	2.1	2.1	-45.2
CO_2	Republic of Korea	662 625	725 999	798 677	865 423	896 781	23.5
	Seoul	22 762	22 603	25 016	24 413	22 706	0.5
	Incheon	81 800	74 132	67 410	65 269	66 272	-10.6
	Gyeonggi	50 677	58 096	78 391	80 721	79 359	36.6
NO_x	Republic of Korea	1 050	876	689	628	616	-29.6
	Seoul	103	62	39	32	29	-52.6
	Incheon	85	63	44	41	41	-35.7
	Gyeonggi	188	148	96	80	77	-48.0

Flying "spoonbill" paper airplanes to commemorate the International Day of Clean Air for Blue Skies at Incheon City Hall.
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Key Message #4:

Implementing carbon neutrality measures can substantially reduce greenhouse gas and air pollutant emissions in Seoul, Incheon and Gyeonggi and across the Republic of Korea between 2020 and 2050

The carbon neutrality (CN) scenario identifies policies and measures which can simultaneously reduce greenhouse gas emissions and air pollutants. As outlined in Key Message #2, the reduction in air pollutant emissions in the past has been achieved through the implementation of policies and measures that selectively control specific pollutants, resulting in decreases in air pollutants but increases in greenhouse gas emissions. The policies and measures in the CN scenario provide the potential of simultaneously reducing CO_2 emissions and air pollutants. Examples of the types of policies and measures in the CN scenario that target both GHGs and air pollutants include switching from fossil fuel to the generation of electricity from renewable sources; replacing internal combustion engines with zero-emissions vehicles – electric vehicles; improving energy efficiency in transport, residential, services, and industry; and fuel substitution to electricity or hydrogen in the industrial, residential and services sectors (Table 3.15).

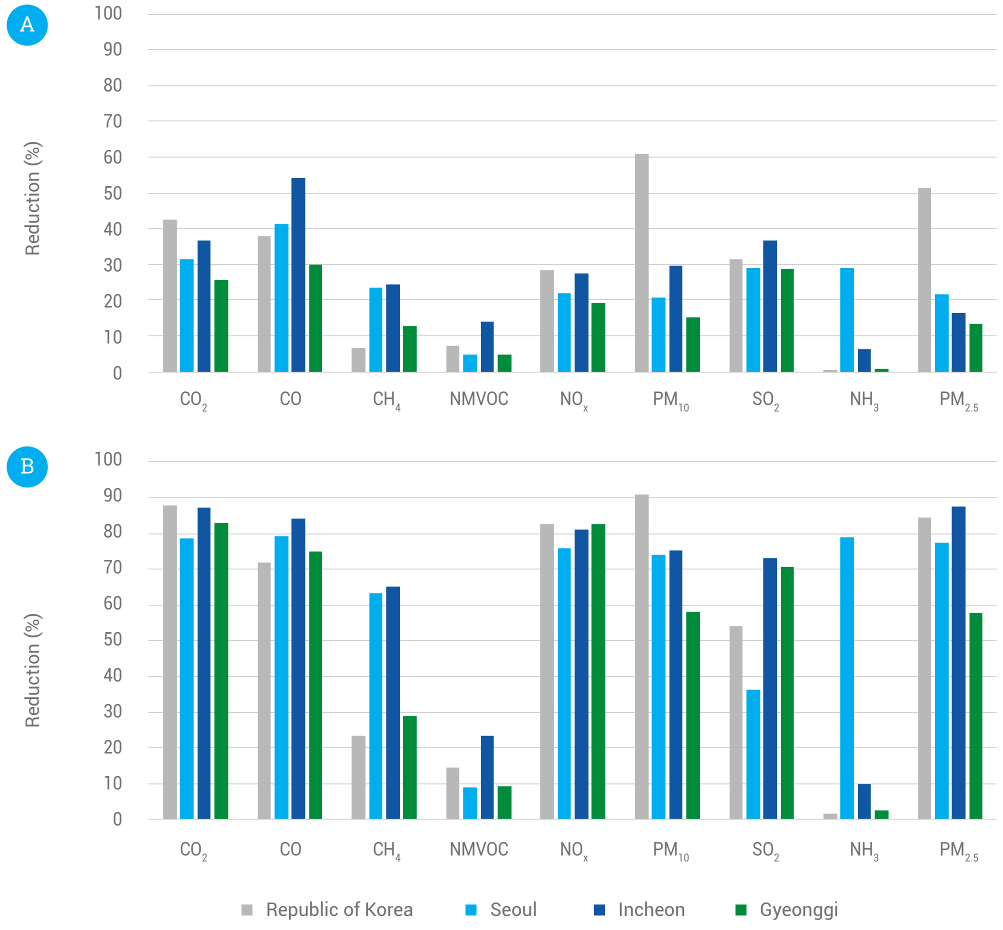
The achievement of the CN scenario through the implementation of these policies and measures listed in Table 3.15 is estimated to achieve substantial benefits for air pollution as well as CO_2 emission reductions in SIG and across the Republic of Korea (Figure 3.37). By 2050, the implementation of the mitigation measures included in the CN scenario reduce national total CO_2 emissions by 88 per cent, with similar emission reductions estimates in SIG for CO_2. At the same time, $PM_{2.5}$ emissions are reduced by 80 per cent in Seoul, 86 per cent in Incheon and 57 per cent in Gyeonggi in 2050 compared to the baseline scenario. Other pollutants with even larger overlaps in major sources with CO_2 fall to an even greater extent. Nitrogen oxide emissions decrease by almost 76 per cent in Seoul, 81 per cent in Incheon and 83 per cent in Gyeonggi (Table 3.20; Figure 3.37).

Hence, this assessment shows that the commitment to achieve CN in the Republic of Korea and in SIG, and the policies and measures that have been identified to achieve it should not be viewed as solely a climate change mitigation target and plan, but also as a public health plan that could substantially reduce the emissions of health-damaging air pollutants in SIG and more broadly across the Republic of Korea. Additionally, the assessment shows that the majority of these air pollutant reductions could be achieved towards the end of the 2020–2050 period, i.e. after 2030. Before then, the air pollutant emission reductions from the implementation of the CN scenario would be relatively modest, for example, a 24 per cent reduction in $PM_{2.5}$ emissions in Seoul in 2030 compared to the baseline. The emphasis on benefits to human health from climate change mitigation plans has been put forward as a motivating factor to increase climate change mitigation ambitions and accelerate the implementation of priority mitigation measures. The assessment shows that the policies and measures selected to achieve CN are the appropriate policies and measures to also achieve benefits for air pollution and human health. Their accelerated implementation could achieve their health benefits even faster than they would be based on the current schedule of implementation.

Table 3.20
Total emissions of fine particulate matter, carbon dioxide and nitrogen oxides under the baseline and mitigation scenarios if all measures are implemented, the Republic of Korea, Seoul, Incheon and Gyeonggi, 2020, 2030 and 2050, thousand tonnes

		2020	2030		2050	
Pollutant	Region		Baseline	All mitigation measures	Baseline	All mitigation measures
$PM_{2.5}$	Republic of Korea	65.5	70.34	34.1	78.45	12.2
	Seoul	1.1	0.66	0.5	0.49	0.1
	Incheon	3.2	2.58	2.2	2.21	0.3
	Gyeonggi	3.8	2.71	2.3	2.09	0.9
CO_2	Republic of Korea	725 999	798 677	458 571	896 781	109 923
	Seoul	22 603	25 016	17 114	22 706	4 841
	Incheon	74 132	67 410	42 700	66 272	8 526
	Gyeonggi	58 096	78 391	58 209	79 359	13 645
NO_X	Republic of Korea	875.9	688.9	493.5	616.3	107.5
	Seoul	61.7	39.2	30.6	29.2	7.0
	Incheon	63.1	44.0	32.0	40.5	7.6
	Gyeonggi	147.6	95.9	77.4	76.8	13.3

Figure 3.37
Reduction in air pollutant and greenhouse gas emissions compared to the baseline scenario, the Republic of Korea, Seoul, Incheon and Gyeonggi and the Republic of Korea, a) 2030 and b) 2050, per cent



The implementation of the mitigation measures included in this assessment that achieve the large emission reductions produce these through the implementation of mitigation action across all major source sectors. Figure 3.38 shows the percentage reduction in emissions in 2050 compared to the baseline for each region for each source sector, and Table 3.21 shows these results for the Republic of Korea. The full deployment of zero-emission vehicles and other measures in the road transport sector lead to reductions of more than 90 per cent in both air pollutants and GHG from this sector across all regions. Similar reductions could be achieved in electricity generation from the deployment of renewable sources. In the residential sector, large reductions could also be achieved through energy efficiency and fuel switching for cooking and heating. The sectors with the smallest reductions in emissions are the agricultural and waste sectors.

Table 3.21
Reductions in emissions compared to the baseline of fine particulate matter, nitrogen oxides and carbon dioxide from each major emitting source sector, the Republic of Korea, 2050, thousand tonnes and per cent

	$PM_{2.5}$		NO_x		CO_2	
Sector	Absolute change (thousand tonnes)	Change %	Absolute change (thousand tonnes)	Change %	Absolute change (thousand tonnes)	Change %
Industry	-49.9	-99	-62	-90	-408	-82
Commercial and public services	-0.1	-40	-9	-41	-6	-50
Residential	-0.3	-80	-33	-80	-20	-80
Road transport	-6.8	-97	-226	-95	-135	-99
Non-road transport	-0.4	-50	-8	-51		
Electricity and heat generation	-4.7	-99	-132	-99	-211	-99
Industrial processes	-4	-54	-22	-31		
Agriculture						
Waste		-81	-17	-81	-7	-82

Figure 3.38
Reductions in emissions compared to the baseline scenario of fine particulate matter, nitrogen oxides and carbon dioxide from each major emitting source sector, the Republic of Korea, Seoul, Incheon and Gyeonggi, 2050, per cent

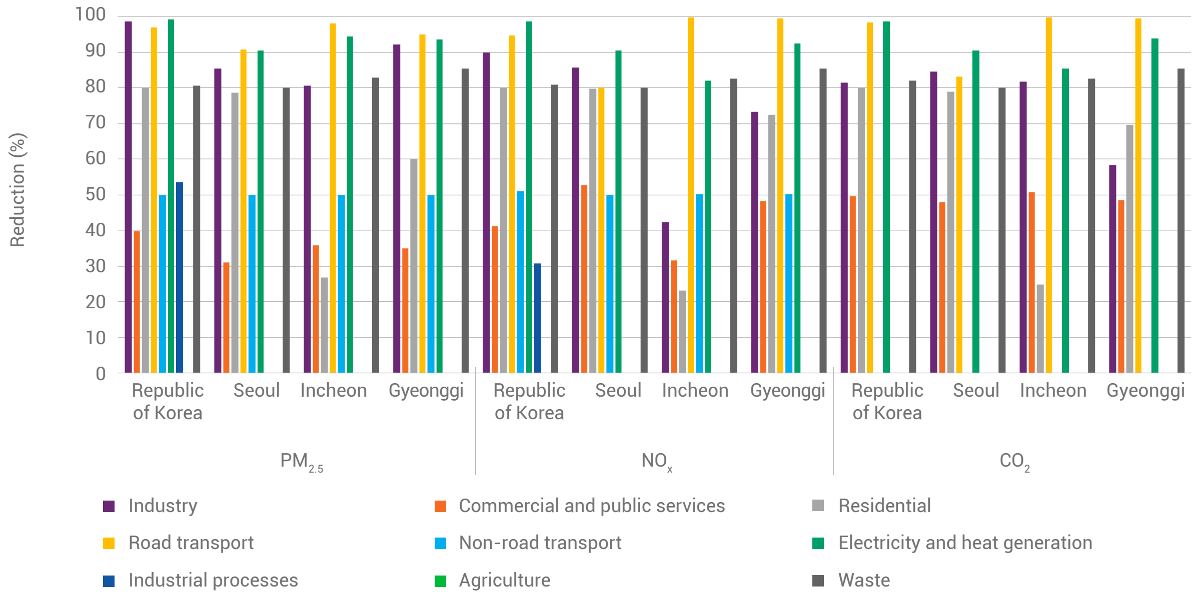


Table 3.22
Reductions in emissions compared to the baseline scenario from the implementation of individual mitigation measures, Republic of Korea, 2050, thousand tonnes

Mitigation Measure	$PM_{2.5}$	NH_3	SO_2	PM_{10}	NO_x	NMVOC	CH_4	CO	CO_2
Baseline	81	382	303	179	616	1.151	863	847	893 059
Zero emission vehicles	3.8	0.4	0.0	1.8	35.7	2.4	2.3	33.0	10.1
Transport demand management	0.5	0.1	0.1	0.2	2.1	0.1	0.6	1.1	1.4
Fuel economy improvements	0.5	0.0	0.1	0.2	1.3	0.1	0.6	0.5	1.5
Non-road transport mitigation	0.5	0.0	0.0	0.2	1.3	0.1	-	0.5	-
Shipping mitigation	8.4	0.0	7.4	3.8	3.4	10.4	0.0	29.7	4.8
Zero energy buildings	1.1	0.2	0.1	0.5	8.3	0.2	0.3	1.4	3.2
Renewable electricity and heat generation	6.0	0.3	23.5	2.8	20.9	0.6	0.3	5.7	22.0
Industrial facility emissions programme	63.8	0.1	32.4	80.5	14.6	0.3	2.8	3.7	45.5
Direct landfill ban	0.5	0.0	0.0	0.2	1.3	0.1	-	0.5	-
Total mitigation	79.5	0.9	48.9	88.1	74.8	13.6	5.8	71.7	86.2

Note: Totals may not sum due to rounding.

Figure 3.39
Reduction in fine particulate matter emissions compared to the baseline scenario after implementation of all measures included in this assessment, the Republic of Korea, Seoul, Incheon and Gyeonggi, 2050, thousand tonnes

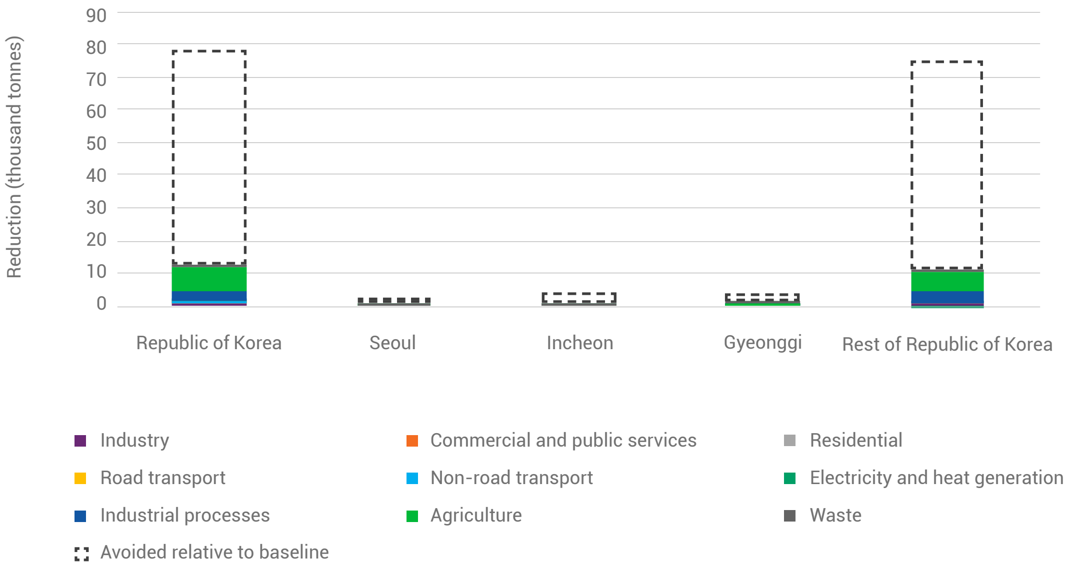


Figure 3.40
Reductions in emissions of nitrogen oxides compared to the baseline scenario after implementation of all measures included in this assessment, the Republic of Korea, Seoul, Incheon and Gyeonggi, 2050, thousand tonnes

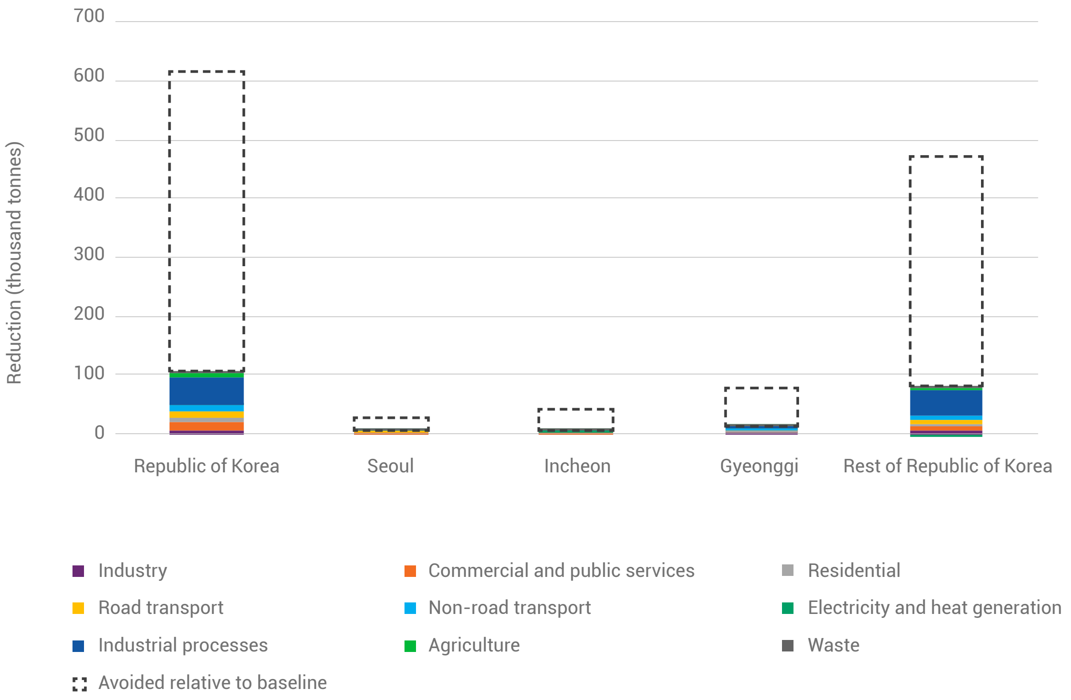
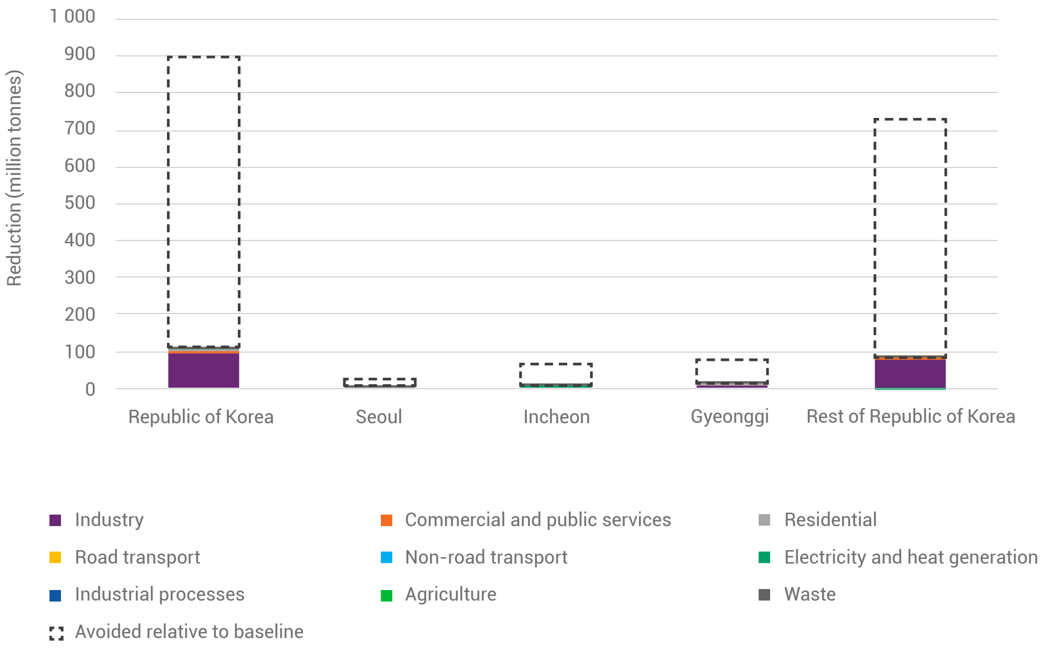


Figure 3.41
Reductions in carbon dioxide emissions compared to the baseline scenario after implementation of all measures included in this assessment, the Republic of Korea, Seoul, Incheon and Gyeonggi, 2050, million tonnes



Key Result #5:

After the implementation of all policies and measures, several sources, for example, non-road transport and agriculture, remain significant emitters of air pollutants

The CN scenario focuses on the major sources of CO_2 emissions. After the implementation of the policies and measures in these key sectors, there remain major sources of air pollutant emissions that are not affected by the policies and measures considered within this assessment. Some of the remaining emissions result from the fact that CN policies and measures do not fully control emissions from major sources of CO_2. Figure 3.41 shows that, even after the implementation of the CN measures, **industry** continues to emit some CO_2 – this assessment does not include forestry and other land use, which may offset some of the residual CO_2 emissions. The lack of total decarbonisation in the industrial sector is in contrast to $PM_{2.5}$, which is almost completely eliminated from industry due to the phase out of coal in steel and metal production, which accounts for more than 90 per cent of industrial $PM_{2.5}$ emissions across the Republic of Korea in 2020. Significant amounts of NO_X will continue to be emitted by industrial sources outside SIG (Figure 3.40), which could be targeted by additional measures to further reduce emissions.

Non-exhaust emissions from transport are another major source of air pollutants. The electrification of the vehicle fleet will not reduce $PM_{2.5}$ emissions from brake and tyre wear, nor from the resuspension of road dust. Identifying additional action to target these sources, such as reducing transport demand, could mitigate these air pollutant emissions.

Finally, one key pollutant that promotes the formation of $PM_{2.5}$ concentrations in SIG has not been targeted either by past mitigation measures or through the CN policies and measures. **Ammonia**, which is predominantly emitted from agriculture through the application of synthetic and organic fertilizers, makes a substantial contribution to the formation of $PM_{2.5}$ in the atmosphere and substantially impacts the magnitude of $PM_{2.5}$ concentrations in SIG. Previous research has emphasized the necessity for NH_3 emission controls to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Ammonia, which is predominantly emitted from agriculture through application of synthetic and organic fertilizers, makes a substantial contribution to the formation of $PM_{2.5}$ in the atmosphere and substantially impacts the magnitude of $PM_{2.5}$ concentrations in SIG.

improve the country's air quality. Across the Republic of Korea, however, the implementation of the measures included in this assessment only reduce total national NH_3 emissions by 1.2 per cent in 2050 compared to the baseline scenario. In Gyeonggi, the only region in SIG with significant agriculture, NH_3 emissions will only be reduced by about 3 per cent (Figure 3.37). Hence there is a substantial need to identify policies and measures which could reduce this pollutant that is not currently being considered within the air quality management frameworks in SIG.

Limitations of analysis

As with all future projections, the air pollutant mitigation assessment conducted in this report represents the possible impact of a set of future scenarios that are inherently uncertain. The baseline scenario emissions, for example, are determined by exogenous population and macroeconomic projections. The drivers of emissions may derive from an optimistic or pessimistic view of economic development in the Republic of Korea. In addition, the policies and measures used in the analysis have targets and timelines, clearly described in Table 3.15, which may not take account of all the barriers to their implementation. There are multiple barriers and challenges associated with implementing mitigation measures, including political, economic, social and cultural ones, as well as other hurdles to the large-scale implementation of a mitigation measure. In the identification and inclusion of the mitigation measures, this analysis has not undertaken a detailed assessment of barriers for each of them and how these could impact their implementation.

In addition, some mitigation measures were not represented in the analysis, but their implementation could nonetheless make a substantial contribution to the achievement of air pollutant emissions reductions in SIG in the future. The Seasonal Management of Particulate Matter in Seoul, Incheon and Gyeonggi, as described in Chapter 2, for example, aims to take pre-emptive and reactive measures to reduce emissions during high PM concentrations episodes in December to March. As these measures are only implemented on a small number of days, the impact of the seasonal management system (SMS) on annual emissions could not be determined by the LEAP. Other measures, including the mitigation of organic solvents or emissions reductions from biomass burning and scattering dust were also not considered in the LEAP analysis. In the future, extensions to this assessment's analysis to evaluate these measures for their air pollution benefits should be conducted.

For the CN scenario and measures, this analysis also focuses on the impact of implementing the national plan for CN in SIG. This creates a harmonized set of projections for each region based on an overarching CN plan. Some regions, such as Seoul, have regional plans, with specific implementation targets and timelines, for mitigating climate change but others do not. To ensure consistency across SIG, only the implementation of the national plan was included in the assessment.

04

Beating air pollution in Seoul, Incheon and Gyeonggi

4.1

Reasons why air pollution has reduced in Seoul, Incheon and Gyeonggi over the past decades

4.2

Recommendations for achieving further air pollution improvements in Seoul, Incheon and Gyeonggi in the next decades

Key Findings

01 Seoul, Incheon and Gyeonggi provide an example to the large number of other cities that are grappling with their own air pollution issues. Over the past decades, Seoul, Incheon and Gyeonggi have managed to reduce their air pollution emissions through a combination of activities, which could be replicated and adapted to other cities.

02 These activities include, i) the development of a robust legal framework for air quality management governing air quality in Seoul, Incheon and Gyeonggi that has been adequately funded for implementation; ii) funding and developing robust and long-term data on air pollution for Seoul, Incheon and Gyeonggi, including emissions inventories and dense monitoring networks; iii) the demonstration of the multiple negative human health impacts from air pollution in Seoul, Incheon and Gyeonggi; iv) the large-scale implementation of key mitigation measures in major source sectors; and v) collaboration between national and sub-national governments in achieving air pollution improvements.

03 Simultaneously, Seoul, Incheon and Gyeonggi face challenges, alongside all major cities, to decarbonise over the next 30 years to mitigate climate change. Doing so has the potential to lead to substantial local benefits, as the mitigation measures identified to achieve decarbonisation also substantially reduce air pollution. The Republic of Korea and Seoul, Incheon and Gyeonggi should work to integrate agendas on air pollution and climate change.

4.1 Reasons why air pollution has reduced over the past decades in Seoul, Incheon and Gyeonggi

This assessment has evaluated the extent to which air pollution in Seoul, Incheon and Gyeonggi (SIG) has improved over the past 15 years and how air pollution there could change in the future. Seoul, Incheon and Gyeonggi have achieved significant improvements in air quality, including the lowering of fine $PM_{2.5}$ concentrations over the past two decades, resulting from fewer emissions within SIG itself, as well as falls in emissions in the rest of the Republic of Korea and other countries that have reduced the transboundary transport of air pollution. This assessment has identified that the improvement in air pollution in SIG over the past 15 years has been achieved for the reasons outlined below. Countries and cities can learn from what has been implemented in SIG to further their own air quality management.

Han River area, Seoul.
© Unsplash/Geonhui Lee

The legal framework that governs air quality management is effective because it concretely identifies the roles and responsibilities of different organizations at national and sub-national levels, creating clarity as to who is responsible for implementing different components of air quality management.

Reason #1:

A robust legal framework governing air quality management in Seoul, Incheon and Gyeonggi that is adequately funded

As outlined in Chapter 2, there are three main pieces of legislation that govern air quality management in the Republic of Korea and SIG specifically. This legal framework is important and effective because it concretely identifies the roles and responsibilities of different organizations at national and sub-national levels, creating clarity as to who is responsible for implementing different components of air quality management. The installation of the air quality monitoring network, for example, is the responsibility of sub-national institutions, while the development of an emissions inventory is the responsibility of the Ministry of Environment. Thus the legal framework **i) establishes a comprehensive set of tools for tracking air pollution concentrations and emissions in SIG, and ii) clearly sets out who is responsible for each of the tools**.

In addition, the legal framework makes clear the planning process for air quality improvements in SIG. A system is described within which a national plan for improving air quality is developed, followed by the development of regional plans for different provinces and cities. This ensures that clear direction for air quality goals is provided at a national scale, which, nonetheless, allows the specific situation in different regions to be reflected in action taken to achieve these goals. As shown in Chapter 3, the major air pollutant emissions sources in Seoul, Incheon and Gyeonggi differ, meaning that different policies and measures are needed in each region. This system allows Seoul, Incheon and Gyeonggi to develop bespoke plans that reflect their particular situations within the framework of a broader national plan.

Finally, the legal framework also provides specific stipulations related to sectors that are major air pollutant emitters to ensure that these sectors are regulated and their emissions reduced. This includes action to reduce emissions from transport and industry.

In addition to having this legal framework, it has also been adequately funded through substantial investment over the last decades. The USD 8.9 billion invested between 2007 and 2020 has allowed the development of a robust scientific basis for action on air pollution in SIG, and the implementation of priority mitigation measures such as establishing and enforcing vehicle emissions standards.

Many countries lack a legal framework for air quality management while in other countries and cities, existing legal frameworks do not clearly identify how air quality management at national and sub-national scales are integrated and aligned. The legal framework governing air pollution in SIG provides a practical example of how air quality legislation can provide clear roles and responsibilities for different stakeholders.

Many developing countries and cities currently lack fundamental research to allow the identification of the magnitude of air pollution and its impacts, as well as the sources of emissions that contribute to it.

Reason #2:

Robust and long-term data on air pollution are available for Seoul, Incheon and Gyeonggi

A consequence of the legal framework governing air pollution in SIG is that, over the past decades, a substantial volume of data on air pollution that can be used to directly inform responses to reduce air pollutant concentrations has been collected.

This includes data collection that is directly mandated by the legal framework. Air quality monitoring networks in SIG comprise hundreds of monitoring sites that measure multiple atmospheric constituents at hourly time resolution. This wealth of data is publicly available through a data repository[14], allowing these data to be used to inform the public on air pollution levels and for a variety of research studies, including the assessment of trends, source apportionment and health impact assessment. The emissions inventory provides details of decades of annual emissions of multiple air pollutants and the contribution of major sources to these emissions at national, provincial and city scales. This allows the impact of implementing policies and measures on emissions within the geographic region to be assessed and quantified.

In addition to the data that are derived specifically from the provisions within the legislation governing air pollution in SIG, over the past decades a wealth of academic research has been published on the nature of the air pollution problem there. This research, as outlined in Chapter 2, provides a detailed understanding of air pollutant concentrations, exposure and associated health impacts, as well as the emissions, source sectors and geographic regions that are the ultimate source of air pollution in SIG. The impact of this research is that there is additional information on SIG that can inform the development of policies and measures to improve air pollution control and evaluate the impact of air pollution in each city. In addition, the collection of gender-disaggregated environmental data (e.g., individual-level data on exposure to air pollution, noise and other environmental risks) could help better target environmental policies and improve environmental outcomes more effectively.

This wealth of research reflects the substantial capacity within national and subnational government agencies and institutions, as well as academic and other research organizations that have expertise on air pollution in Seoul, Incheon and Gyeonggi. Having experts in SIG allows for robust evaluation of policies and measures, both before, during and after their implementation.

Many developing countries and cities currently lack the fundamental research to allow the identification of the magnitude of air pollution and its impacts, as well as the sources of emissions that contribute to it. In addition to the legal framework, developing a programme of research to understand the nature of air pollution in a country or city is a necessary step to effectively reducing emissions, concentrations and health impacts, in the way that has happened in SIG.

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[14] Republic of Korea's national real-time air quality information public website. https://www.airkorea.or.kr/

Reason #3:

Demonstration of negative human health impacts from air pollution in Seoul, Incheon and Gyeonggi

The impact of air pollution on human health has been determined through multiple studies. Until recently, however, these studies have predominantly been carried out in Europe and North America, but more recently, health studies have been conducted in other regions. Impact assessments have applied the results of epidemiological studies to estimate the health burdens of air pollution globally. While these studies provide a useful indication of the extent to which air pollution impacts populations in different regions, they rely on the application of studies from one location to another when the composition of air pollutants and the underlying health status of the population might be different.

In SIG, a large number of epidemiological studies have been conducted which show the negative health impacts of air pollution directly based on data collected there. These studies provide direct evidence for the impact of air pollution in SIG on both adults and children, on mortality health endpoints and negative morbidity impacts. These studies have been possible because of the availability of detailed data that allow assessment of the relationship between air pollutant concentrations and different health outcomes. These data include detailed information about the concentrations of air pollutants in different locations across SIG thanks to a dense monitoring network. They also include health statistics that can be compared with air pollutant concentrations to determine their relationship with exposure to air pollution. As equivalent data are missing in many developing cities and countries, direct evidence of negative health impacts of air pollution within their communities cannot be calculated. Further efforts to collect gender-disaggregated data could be considered to inform air quality policies.

Urban air quality monitoring signs in the street, Seoul.
© UNEP/Eunyoung Seo

Since 2016, when the public concern about air quality was getting serious, many public-private-industry cooperation efforts were made including the establishment of the Fine Dust Countermeasure Committee.

Reason #4

Implementation of key mitigation measures in major source sectors

While the legal framework, disaggregated data and research provide the basis for assigning responsibilities for air quality planning and identifying policies and measures that could be most effective at reducing air pollution, it is the implementation of key mitigation measures that actually reduces air pollution which has improved air quality in SIG over the past decades.

The legal framework, previous research and the assessment of emissions presented in this report (Chapter 3) show that there are specific policies and measures that have reduced air pollutant emissions in SIG. Emissions in the transport sector have been reduced substantially over the past 15 years, as successive vehicle emission standards have been made more stringent. The implementation of policies and measures in the transport sector has received the most investment, equivalent to 56 per cent of the total investment in air quality management in SIG between 2007 and 2020. This means that, as the vehicle fleet has renewed in SIG, vehicles with lower emissions have replaced relatively higher emitting ones. The emissions inventory for SIG, developed for this and previous reports, shows this reduction in transport emissions, allowing the impact of implementing these policies and measures to be assessed and documented.

In addition, the Basic Plan for the improvement of air quality in SIG includes policies and measures across other sectors, including a cap-and-trade system for large point sources, and implementing a polluter pays principle to control of emissions from large sources. For smaller businesses, direct financial support has been provided for them to reduce their emissions. Further measures have been taken to control emissions from households, agriculture, non-road mobile sources and the waste sector (Chapter 2).

Since 2016, when the public concern about air quality was getting serious, many public-private-industry cooperation efforts were made including the establishment of the Fine Dust Countermeasure Committee. As public awareness grew amongst the civil society and civil society groups, the media also covered the problem seriously. This has been deemed effective in improving air quality by influencing government policies and budgeting processes. It seems that it was relatively easy to build consensus and the public's cooperation because fine dust and yellow dust are seen as being directly related to national health.

The National Council on Climate and Air Quality was established in 2019 under Presidential Decree No. 29713. The Council members were recruited from central and local governments, academia, industry and the private sector. It announced the mid- and long-term national policy proposals for the National Climate Environment Conference in November 2020, set the target for $PM_{2.5}$ concentrations of 15 micrometres per cubic metre ($\mu m/m^3$) by 2030 and defined the sectoral tasks covering transport, power generation, climate and the atmosphere. On 30 April 2021, the council activities came to an end as it was absorbed into the Presidential Commission on Carbon Neutrality and Green Growth. The Fine Dust Special Response Committee was established in 2019 under the Prime Minister's Office with members from academia, industry and the private sector. It was given a mandate to review policies, plans and implementation action related to the Special Act on the Reduction and Management of Fine Dust.

The contribution of multiple geographic sources to air pollution levels is a feature not only of SIG but also many other cities and countries.

Reason #5:

Collaboration between national and sub-national governments in achieving air quality improvements

Chapter 2 demonstrates that emissions from outside SIG determine a substantial fraction of its air pollution. This includes pollutants emitted in the rest of the Republic of Korea – a substantial proportion of $PM_{2.5}$ concentrations in SIG originate elsewhere in the country. Chapter 2 shows that between 2005 and 2020, emissions across the rest of the Republic of Korea also decreased due to such policies and measures as the renewal of the vehicle fleet that were also implemented in SIG. A legal framework on air quality management for the Republic of Korea provides the basis for aligned and country-wide implementation of policies and measures that can improve air quality not just in the location/city/province where the emissions reductions take place but in other locations to which emissions are transported.

In addition to the reductions in emissions in the rest of the Republic of Korea, research shows that emissions across Northeast Asia have diminished and, as a result, the amount of air pollution transported to SIG from Northeast Asia has fallen, particularly in recent years. The reduction in emissions in Northeast Asia and its contribution to improving air quality in SIG underlines the importance of international collaboration in solving air pollution problems.

The contribution of multiple geographic sources to air pollution levels is a feature not only of SIG but also of many other cities and countries. Identifying mechanisms, such as the Republic of Korea's legal framework for air quality management, to reduce air pollutant emissions across a country can bring improvements in air quality compared to the benefits from emissions reductions only within a city. Replicating this internationally within regions could maximize advances in air quality that can be achieved from collective action to reduce air pollutant emissions.

Regional coordination across countries to reduce air pollution has not been a feature of improvements in SIG, but has resulted in regional-scale reductions elsewhere, particularly in Europe as a result of the Convention on Long-Range Transboundary Air Pollution. Replicating regional cooperation in Northeast Asia could accelerate improvements in air quality in SIG and across the region (Section 4.2 Recommendation 4).

Blue Sky Committee meets to discuss ways to improve air quality in Incheon.
© Incheon Metropolitan City

Low-emissions vehicles, which are in operation in Seoul, Incheon and Gyeonggi, do not emit pollutants and are powered by clean fuels, contributing to the improvement of air quality.

Reason #6:

Development of region-specific leading policies for air quality management

In addition to the basic plans that they carry out in common, SIG has developed and implemented various policies suited to its regional characteristics to achieve air quality goals. The common air quality improvement policies are as follows.

- **Fine dust forecast and warning system and emergency mitigation measures:** as the rapid growth in the adoption of automobiles increased, and air pollution and citizens' concern about fine dust also grew, a forecast and warning system for PM was introduced in Seoul in 2005, Gyeonggi in 2007 and Incheon in 2008 to minimize damage to citizens' health. Then, an ultrafine dust warning system was introduced in Seoul in 2013, Incheon in 2014, and Gyeonggi in 2015. In addition, in February 2017, Incheon implemented PM mitigation measures to quickly reduce the concentrations when they occurred; Seoul followed in July 2017 and Gyeonggi in August 2018. With the enactment of the Special Act on the Reduction and Management of Fine Dust in 2018 and its enforcement beginning in 2019, local governments were able to run their emergency mitigation measures based on solid legal ground and implement their comprehensive measures for fine dust control, including automobile operation controls, adjustment of time controls on air pollutants emitting operations, temporary school closure recommendations and other fine dust mitigation projects. When, in 2019, the Framework Act on the Management of Disasters and Safety defined PM as a social disaster, the emergency countermeasures were bolstered by a phased system for issuing disaster crisis warnings at varying levels – interest, caution, alert and serious. Its coverage also expanded across the nation.

- **Seasonal management system:** the seasonal management system is a differentiated preventive mitigation approach to managing PM intensively by running more powerful reduction measures than usual from winter to early spring when concentrations are high. The seasonal PM management system complemented the limitations of the emergency mitigation measures that are only taken after PM concentrations have increased. The seasonal management system comes with additional emissions reduction measures including restrictions on driving Grade 5 vehicles, the alternate no-driving day programme for public agencies, inspection on air pollutant emission businesses, designation of intensive fine dust control zones, and strengthening facility inspections to protect the less privileged, plus the region-specific measures.

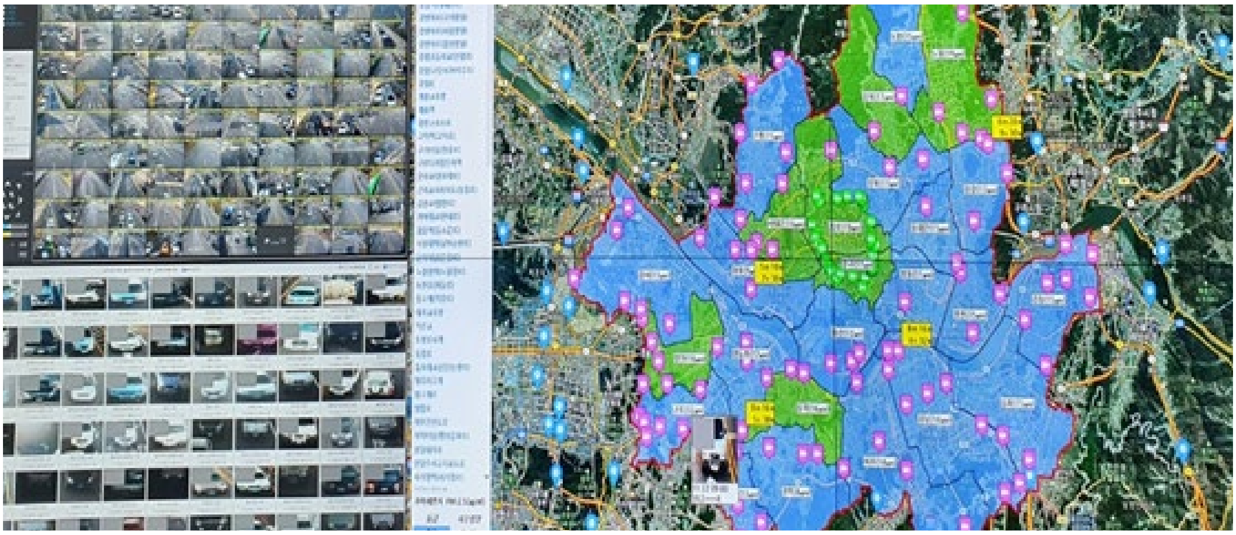
- **Mandatory installation of eco-friendly boilers in households:** Seoul started supplying eco-friendly boilers as part of a special PM management plan to reduce both air pollution and heating costs in 2015, with Incheon and Gyeonggi following suit in 2017. The eco-friendly boilers are equipped with a reduction device for NO_x emissions, which create fine dusts, and are more energy efficient. The installation of such boilers has been mandatory across the three areas since 2020 when the Special Act on the Improvement of Air Quality in Atmospheric Control Areas was enacted. Seoul revised its environmental impact criteria in 2018, making the installation of eco-friendly boilers mandatory in new buildings larger than 100 000 m^3 and also, through the Seoul Metropolitan Government's green building support ordinance, made the installation of eco-label certified eco-friendly boilers in buildings of 500–100 000 m^3 with 30 or more households mandatory. Incheon began a household boiler installation and support project in 2017 and by 2022 had successfully installed around 58 000 units. Gyeonggi also began the installations in 2017 and by 2022 had put around 291 000 units in place.

- **Introduction of eco-friendly buses:** low-emission vehicles, which are in operation in Seoul, Incheon and Gyeonggi, do not emit pollutants and are powered by clean fuels, contributing to the improvement of air quality. The Seoul government introduced low-emission vehicles as part of its preparation for hosting the 2002 World Cup and launched the de-diesel movement, fully converting the city buses to run on compressed natural gas (CNG) in 2014. It also pushed the development of electric bus technology forward through agreements with manufacturers and operators and in December 2010, the city government succeeded in commercializing electric buses, becoming the first city in the world to do so. As of 2022, among the 7 393 city buses, 1 029 are powered by electricity and 44 run on hydrogen. Gyeonggi followed suit in 2016 and by 2022 had 910 electric and 11 hydrogen buses in operation. Incheon began with 15 electric buses in 2019 and had increased the number to 150 by 2020. Its goal, however, is to introduce a fleet of around 2 000 hydrogen-power city buses by 2030.

- **Restrictions on driving pollutant-emitting vehicles:** this is a measure to reduce air pollution from vehicles within the region. High-emission cars are restricted from entering designated zones, and violators are fined. In 2016, the Ministry of the Environment signed agreements with the governments of Seoul, Incheon and Gyeonggi for the development of plans to restrict high-emissions vehicles from entering the air quality management zones and the building of systems to enforce the measure including the installation of surveillance cameras. In 2017, driving was restricted when the fine dust emergency mitigation measures were issued, and in 2018, following the enactment of the Special Act on the Reduction and Management of Fine Dust, restrictions on outdated vehicles and their enforcement were introduced. In addition, following its introduction in 2019, driving restrictions are enforced when the PM seasonal management system is applied.

On top of these common policies, Seoul, Incheon and Gyeonggi have implemented separate region-specific air quality improvement policies.

- **Seoul: Clean Seoul 2010 and Cleaner Seoul 2030** In 2007, the Seoul Metropolitan Government announced Clean Seoul 2010, special measures to improve the city's air quality to that of other developed countries, and implemented relevant policies on a large scale. As a result, the annual average concentration of coarse PM_{10} in Seoul dropped by 22 per cent in 2011 compared to 2006, and concentration of $PM_{2.5}$ fell to their lowest levels in 2020 and 2021 consecutively. The annual average concentration of $PM_{2.5}$ in Seoul in 2021 was, however, 20 µg/m^3, which falls short of the national air quality standard of 15 µg/m^3 and is still higher than those of major cities such as London, Los Angeles and Paris. Therefore, in September 2022, the government announced Cleaner Seoul 2030, a comprehensive set of strengthened air quality improvement measures.



A management screen of the restriction system on driving in old diesel vehicles in Seoul.
© Seoul Metropolitan Government

- **Seoul: restrictions on driving in the green traffic area**
  In March 2017, the Seoul Metropolitan Government designated the 16.7 square kilometre (km^2) area inside Seoul's city walls as the nation's first green traffic area, in which traffic is intensively managed and green modes of transport promoted. Piloting of vehicle restrictions began July 2017 and has been in full operation since December 2017.

- **Incheon: Hydrogen-powered public transport system**
  As part of its speedy transition to a hydrogen-powered transport system, the goal of which is to reduce GHG and $PM_{2.5}$ emissions, the Incheon Metropolitan City supported the supply of 214 hydrogen cars in 2019 and a total of 1 615 vehicles, including hydrogen trucks by the end of 2022. In January 2023, four high-floored hydrogen buses were supplied for the first time in the Republic of Korea. The city plans to have a total of 700 hydrogen buses in operation by 2024. And the first hydrogen filling station was opened in 2019, there will be 14 by the end of 2023, rising to 52 by 2030 as part of Incheon's renewed infrastructure.

- **Incheon: voluntary air pollution emission mitigation activities through public-private partnership**
  Incheon Metropolitan City is promoting the public-private partnership to guide the large polluters, such as the seaport, the airport and power plants – Incheon is home to 9 per cent of the Republic of Korea's power generation facilities and around 40 per cent of power plants supplying the Seoul Metropolitan Region – to voluntarily reduce their emissions. The city formed the Blue-Sky Consultation Group with large power plants and oil refineries in 2010, and the Clean Construction Consultation Group with the airport, the seaport, landfill operators and the Korean Gas Corporation (KOGAS) in 2016 to invest KRW 2.5 trillion in voluntary projects to improve the environment. In accordance with that, the city cut annual emissions of pollutants by 67 per cent in 2022 relative to the 2011 level of 20 748 tonnes. The joint inspection group for the Young Heung thermal power plant, started in 1996, is an example of this private and public cooperation. It is working to evaluate the damage done by the air pollutants generated from the coal thermal power plant and then undertake mitigation projects.

- **Gyeonggi: the Alps project and the air quality management implementation plan**
  Gyeonggi Provincial Government formulated the Alps project in 2016 to reduce high concentrations of $PM_{2.5}$ and protect the health of its citizens. Under the project, the government set the target of reducing the $PM_{2.5}$ emissions by a third by 2020 and implemented various policies including an analysis of PM sources, the establishment of an information service and various mitigation tasks. In April 2020, the government established the Gyeonggi Air Quality Management Implementation Plan 2020–2024, which takes account of regional specificities – Gyeonggi, unlike Seoul and Incheon, is a mixed area with an urban region with high population density and rural areas. In particular, as the most populous province in the Republic of Korea with the most manufacturing businesses and the highest number of vehicles, the government needed to implement tailored measures targeting, for example, traffic, businesses and household pollution sources.

- **Gyeonggi: designation of intensive control zones/roads and the reduction of fugitive dust from paved roads**
  Targeting the areas where annual average concentrations of PM_{10} and $PM_{2.5}$ exceed the national control limits and the public facilities for the vulnerable are concentrated, the Gyeonggi government has undertaken projects to reduce $PM_{2.5}$ emissions, establish an information service and support mitigation facilities. Since March 2020, the government has designated eight areas covering 8.5 km^2 as an intensive management zone. Furthermore, to reduce fugitive dust during the seasonal management period, the government has selected roads for intensive management, conducting road cleaning two to four times a day. In more than 86 zones with 487.6 km of roads in 31 cities and counties, Gyeonggi's government has supported the purchase of fugitive dust cleaning vehicles for paved roads and distributed sprinkler trucks.

4.2 Recommendations for achieving further air pollution improvements in Seoul, Incheon and Gyeonggi in the next decades

Despite the considerable progress that has been made in SIG over the past two decades, air pollution levels still pose a major health challenge and exceed both national standards and international guidelines for the protection of human health. The air pollution emissions reductions achieved in SIG over the past decades, however, are not guaranteed to be sustained without the continued implementation of policies and measures to improve air quality. Chapter 2 shows that, without further action, the baseline scenario projects flat or increasing air pollutant emissions in SIG over the next decades.

Chapter 2 also, however, shows that there is a large opportunity to build on the progress that has already been made and further reduce emissions in SIG either through the implementation of already identified policies and measures in key air pollutant emitting source sectors, or through the identification of new policies and measures in sectors in which the reduction of emissions has not been a priority.

The potential to further reduce air pollution comes from the implementation of a different set of policies and measures that has characterized the improvement in air quality seen over the last 15 years in SIG. In common with many global cities, including in Europe, North America and other Asian countries, the improvement in air quality achieved in the past has resulted from the implementation of technical measures that control the emissions of pollutants post-combustion. In the United Nations Environment Programme's (UNEP) 2019 report *Air Pollution in Asia and the Pacific: Science-Based Solutions*, these types of measures were categorized as "*conventional air pollution control measures*" (Table 3.15) (UNEP 2019b). However, this UNEP report, in identifying the 25 clean air measures for Asia and the Pacific, also included a broader set of measures that, while not traditionally part of air quality management planning, could also be effective in reducing air pollutant emissions, and which are summarized in Table 4.1. The Republic of Korea has already made progress in introducing some of these 'next-stage measures' – for example, in the agricultural sector crop residues are not openly burned in fields as is seen in countries in South and Southeast Asia.

The final set of measures for Asia and the Pacific were concerned with development that achieves air pollutant emission reductions. In many cases, these were those that simultaneously reduce GHG emissions and achieve air pollution benefits. Examples of these measures include electricity generation from renewable sources, energy efficiency and the introduction of electric vehicles. In these cases, controls are not being placed on air pollution after combustion, but technologies and fuels are being shifted to those that do not emit air pollutants. The advantage of these measures is that there is a larger number of broader benefits from their implementation compared to the conventional air pollution controls. The most evident additional benefit from these measures, which reduce air pollutants, is that they reduce emissions of all pollutants to the atmosphere from a particular process or sector. This means that all air pollutants emitted from the source are reduced, as opposed to a subset of air pollutants that may be controlled by conventional measures, such as only PM being reduced by fitting a diesel particle filter to a vehicle.

Table 4.1
Clean air measures identified in 2019 Air Pollution in Asia and the Pacific: Science-Based Solutions report categorized into conventional measures, next-stage measures and development measures with air pollution benefits

Full application of conventional measures to all countries in Asia	
Post-combustion controls	Introduce state-of-the-art end-of-pipe measures to reduce SO_2, NO_X and PM emissions at power stations and in large-scale industry
Industrial process emissions standards	Introduce advanced emissions standards in industries, e.g., iron and steel plants, cement factories, glass production, the chemical industry, etc.
Emissions standards for road vehicles	Strengthen all emissions standards; special focus on the regulation of light- and heavy-duty diesel vehicles
Vehicle inspection and maintenance	Enforce mandatory checks and repairs for vehicles
Dust control	Suppress construction and road dust; increase green areas
Next-stage air quality measures [on dispersed sources]	
Agricultural crop residues	Manage agricultural residues, including strict enforcement of bans on open burning
Residential waste burning	Strictly enforce bans on open burning of household waste
Prevention of forest and peatland fires	Prevent forest and peatland fires through improved forest, land and water management and fire prevention strategies
Livestock manure management	Introduce covered storage and efficient application of manures; encourage anaerobic digestion
Nitrogen fertilizer application	Establish efficient application; for urea also use urease inhibitors and/or substitutes with, for example, ammonium nitrate (NH_4NO_3)
International shipping	Require low-sulphur fuels and control of PM emissions
Solvent use and refineries	Introduce low-solvent paints for industrial and do-it-yourself applications; leak detection; incineration and recovery
Measures contributing to priority goals for development [energy, agriculture, urban planning] with benefits for air quality [including methane-related] + hydrofluorocarbon measures	
Renewables for power generation	Use incentives to foster extended use of wind, solar and hydro power for electricity generation and phase out the least efficient plants
Energy efficiency for households	Use incentives to improve the energy efficiency of household appliances, buildings, lighting, heating and cooling; encourage roof-top solar installations
Energy efficiency standards for industry	Introduce ambitious energy efficiency standards for industry
Electric vehicles	Promote the use of electric vehicles
Improved public transport	Encourage a shift from private passenger vehicles to public transport
Solid waste management	Encourage centralized waste collection with source separation and treatment, including gas utilization
Rice paddies	Encourage intermittent aeration of continuously flooded paddies
Wastewater treatment	Introduce well-managed two-stage treatment with biogas recovery
(HFC) refrigerant replacement	Ensure full compliance with the Kigali Amendment[15]

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[15] Amendment to the Montreal Protocol on Substances that Deplete the Ozone Layer Kigali, 15 October 2016. https://treaties.un.org/Pages/ViewDetails.aspx?src=IND&mtdsg_no=XXVII-2-f&chapter=27&clang=_en

In addition to reducing emissions of multiple air pollutants, the implementation of the next-stage and development measures shown in Table 4.1 also reduces co-emitted GHGs, such as CO_2. This means that these measures can simultaneously reduce a country or city's contribution to climate change, while at the same time improving local and regional air quality. This link resulted in the 2019 UNEP and Climate and Clean Air Coalition (CCAC) report concluding that the implementation of all 25 clean air measures across Asia could bring air pollution concentrations below 10 μg/m^3 for over 1 billion people and simultaneously reduce global temperature increases by 0.3°C (UNEP 2019b).

The assessment presented in this report indicates that the Republic of Korea has a **great opportunity to further reduce air pollutant emissions in SIG through the implementation of the next-stage and development measures** identified within *Air Pollution in Asia and the Pacific: Science-Based Solutions* (UNEP 2019b).

Firstly, the Republic of Korea has committed to CN by 2050 and to achieve this has identified mitigation measures to reduce GHG emissions in SIG. These mitigation measures include the total electrification of the vehicle fleet, transitioning to electricity generation from renewable sources and stringent energy efficiency measures. This assessment shows that across the Republic of Korea, including in SIG, the **achievement of the CN scenario will not only reduce GHG emissions but simultaneously reduce emissions of multiple air pollutants, including $PM_{2.5}$ and NO_X.** This is consistent with previous assessments of the air pollutant benefits of achieving the CN scenarios in the Republic of Korea. One previous study, for example, estimated that across the Republic of Korea, more than 50 000 tonnes of $PM_{2.5}$ emissions, and over 1 million tonnes of NO_X emissions could be avoided by the achievement of CN in the country (Phillips 2022).

Secondly, this assessment highlights that some key sources of air pollutant emissions will remain even after the implementation of mitigation measures aimed at CN and additional air pollution mitigation measures that are being considered in current plans and strategies. After implementation of the CN scenario, for example, substantial emissions of $PM_{2.5}$ from the industrial sector will remain and the non-road transport sector will continue to be a large emitter of $PM_{2.5}$ and NO_X. In the agricultural sector, NH_3 emissions from fertilizer application continue to be emitted after CN is achieved. **The 25 clean air measures in *Air Pollution in Asia and the Pacific: Science-Based Solutions* (UNEP 2019b) provide a selection of policies and measures which could be developed and implemented in SIG to reduce these remaining air pollutant emissions** (CCAC SNAP 2019). These include measures such as the more efficient application of synthetic fertilizers to reduce NH_3 emissions or the substitution of urea with other fertilizers, such as NH_4NO_3. Switching to cleaner fuels in the industrial sector and for non-road transport provide a pathway to reduce remaining air pollutants in these sectors (Table 4.1 and Recommendation 2).

This assessment, therefore, provides an overview of the benefits of reducing emissions that SIG could achieve through the continuation of the implementation of policies and measures that address air pollution, and doing so in a way that integrates with climate change mitigation. These potential benefits will, however, remain theoretical without continued implementation of concrete measures on the ground. Based on the progress made, and the assessment of what is needed to further improve air quality, several recommendations can be put forward that could help to effectively implement and achieve the emissions reductions outlined in this assessment. These recommendations are specific to SIG and based on the assessment of the status of its air pollution. They could, however, equally be applied to other cities and regions which are grappling with how to improve their own air quality and, if applied, also reduce their contribution to climate change at the same time. The recommendations are as follows.

The development and regular updating of an emissions inventory is a key tool to track progress on the implication of policies and measures on emissions.

Recommendation #1

Integration of climate change and air pollution action in Seoul, Incheon and Gyeonggi in the identification and implementation of mitigation measures

As outlined above, the historic improvements in air pollution in SIG have been achieved through the implementation of conventional air pollution measures that primarily target post-combustion emissions through specific control technologies. This has been the method by which countries and cities have improved their air quality in many locations over the past decades. The necessity to reduce GHG emissions to mitigate climate change and achieve international agreements to limit global temperature increases, however, provides an additional consideration and opportunity to further reduce air pollutant emissions. The mitigation measures to achieve CN in the Republic of Korea and SIG have been defined and when their potential is quantified, they are shown to be effective in further reducing air pollutant emissions compared to a baseline projection in which they are not implemented.

To curb all types of emissions, i.e. GHGs, SLCPs and other air pollutants, it is necessary to limit and reduce demand for products, energy sources and services that ultimately cause the emissions, in combination with reducing the emission rate at source through the implementation of technical measures. This combination of emissions reduction strategies is reflected in the policies and measures identified to control emissions in SIG and emissions in the LEAP modelling presented in Chapter 3. The implementation and achievement of the Republic of Korea's CN commitment, through the implementation of such mitigation measures as the electrification of the vehicle fleet and the expansion of the generation of electricity from renewable sources will achieve these reductions, but there are multiple activities that national and local government can undertake to facilitate closer integration of air pollution and climate change planning in SIG.

As outlined in Chapter 2, the development and regular updating of an emissions inventory is a key tool to track progress on the implication of policies and measures on emissions. Currently, however, the emissions inventories for GHGs and air pollutants are developed separately. This creates the potential for inconsistencies based on the data used to quantify air pollutant emissions. It is also inefficient, as there are large overlaps in the data needed to quantify GHG and air pollutant emissions. **It is recommended that the development of air pollutant and GHG emissions inventories be integrated, to ensure that consistent estimates of all pollutants are made and that, as the emissions inventories are updated, they provide a consistent assessment of the changes in emissions as a result of the implementation (or lack thereof) of policies and measures to reduce emissions.**

The legal framework outlined in Chapter 2 also describes the roles and responsibilities of both national and local governments to develop specific plans for improving air quality. The legal framework is specific about the content of these plans and the annual reports to be submitted that assess progress in their implementation. To ensure that climate change mitigation is reflected in air quality plans, it is recommended that the **legislation underpinning air quality management in SIG is updated to mandate that GHG emissions, and progress on the air pollution reductions of achieving carbon neutrality, are reflected in air quality plans and progress reports** at a national and SIG scale. If updates to the legal framework are not possible, then information on climate change and air pollution integration should be included within annual reporting.

Recommendation #2

Identify key mitigation measures for sectors emissions from which are not abated by climate change action

There are several sectors that remain significant sources of emissions in SIG even after the implementation of CN and other air pollution-specific policies and measures. For these sources, it is recommended that policies and measures are identified, integrated within air quality planning, and implemented to ensure that emissions from these sources are also reduced and the reductions in air pollution in SIG are maximized.

The key sources for which additional policies and measures should be identified include the **agricultural sector, specifically synthetic and organic fertilizer application which results in NH_3 emissions** that are not considered within current air pollution mitigation plans. Ammonia is an air pollutant which reacts in the atmosphere to form ammonium nitrate (NH_4NO_3) or ammonium sulphate ($(NH_4)_2SO_4$). Ammonia emissions have been shown to be the controlling factor in determining the extent of secondary inorganic aerosol formation at measurement sites in Seoul (Kim *et al.* 2021; Singh *et al.* 2021). A recent study, for example, showed that a 50 per cent reduction in NH_3 emissions in the Republic of Korea would result in a 9 per cent reduction in annual $PM_{2.5}$ concentrations across the country. Similarly, a 50 per cent reduction in NH_3 emissions in Northeast Asia would also reduce annual average $PM_{2.5}$ concentrations in the Republic of Korea by 9 per cent (Kim *et al.* 2021). Air pollution impacts from a gendered-perspective on the labour market is high among women who are in agricultural production and is associated with health impacts affecting productivity, economy and society.

This emphasizes the crucial role that reductions in NH_3 emission could make to reducing $PM_{2.5}$ concentrations in SIG, as well as the rest of the Republic of Korea. However, this assessment did not identify any concrete policies or measures to reduce them that could be evaluated within the emission mitigation modelling undertaken. Multiple international studies have identified policies and measures for NH_3 abatement in agriculture, including the more efficient application of synthetic fertilizer, with respect to the time of year it is applied, and/or directly injecting fertilizer into the soil. In the livestock sector, improved manure management to reduce N losses can also reduce NH_3 emissions, as well as potentially reducing emissions of such GHGs as N_2O and CH_4, thereby contributing to achieving further simultaneous air pollution and climate change benefits. Understanding the policies and measures that can most effectively be implemented in Gyeonggi, the only region of SIG with significant agricultural activities, and the rest of the Republic of Korea is the necessary first step to mitigating NH_3 emissions as part of air quality management.

Another key source sector that will remain a significant emitter after carbon neutrality is implemented is **non-road transport**. This includes a variety of transport sectors for which alternatives to fossil fuels will be required to achieve substantial reductions in emissions. It includes large machinery used in construction, agriculture and other industries. Switching to electric or hydrogen-powered versions of these vehicles where possible is the most likely solution. The feasibility of these alternatives needs to be assessed in the context of demand for them in the future in SIG. It also includes shipping and aircraft that are particularly significant contributors to emissions in Incheon, which includes a major port and an international airport.

Potential solutions to these non-road emissions include technical changes, such as fuel switches to reduce emissions from those fuels that are most polluting and behavioural changes promoting alternative transport modes/vehicle types for transporting passengers and freight, and changes in demand to reduce the need for ships and aircraft that produce emissions. The most effective and appropriate measures for SIG need to be identified through the air quality planning process, before their impact can be assessed, and their implementation planned and carefully executed.

In addition, to reflect gender considerations in this and other sectors, targeted engagement of women and women-led organizations during relevant events should be undertaken. There is a need for participation, collaboration and dialogue among ministries, government stakeholders and civil society organizations to identify knowledge gaps, mitigation pathways, and raising awareness about air quality in the context of work and to build capacity of policy makers to integrate gender in clean air discussions and implement gender-responsive clean air and climate policies.

Important examples of implementing solutions to reduce air pollution can be found around the world and a number of these have achieved significant progress through regional cooperation.

Finally, in addition to non-road transport emissions, non-exhaust road transport emissions are also likely to be an air pollutant source that will remain significant without further mitigation action. The electrification of the vehicle fleet in Seoul, Incheon and Gyeonggi will eliminate emissions of exhaust air pollutants and GHGs, but brakes and tyre wear, and resuspension of road dust are also sources of PM from road transport. Ensuring that these emissions are cut, by, for example, reducing the number of private passenger cars and modal shifts to public transport, could help to reduce both exhaust and non-exhaust road transport emissions.

Recommendation 3:

International collaboration is required to fully beat air pollution in Seoul, Incheon and Gyeonggi

As outlined above, air pollution in SIG is not caused solely by the emissions from within its geographic boundaries. Emissions from the rest of the Republic of Korea and from other Asian countries make a substantial contribution to its annual average and peak $PM_{2.5}$ concentrations and other air pollutants. To improve air quality in SIG, it is, therefore, necessary to reduce emissions in those geographic regions from which air pollutants are emitted and transported to SIG.

Important examples of implementing solutions to reduce air pollution can be found around the world and a number of these have achieved significant progress through regional cooperation. In Europe and North America, the consensus and willingness to cooperate on air pollution has been strong. National and regional cooperation has significantly contributed to achieving a remarkable reduction in pollutant emissions and concentrations, although problems still remain.

The situation in Northeast Asia is significantly different from that of Europe and North America. Air pollution is now high in Northeast Asia, reminiscent of the highest levels that were seen in Europe and North America in the mid-20th century. While Northeast Asian countries are taking strong action at national scales, there is scope for increased regional cooperation. To solve the severe regional pollution issues, especially those related to impacts on human health, holistic approaches, combining technology, financial and administrative solutions are needed. These can encourage increased national action and promote regional cooperation that could speed up progress.

A 2021 report reviewed cooperation between three Northeast Asian countries, China, Japan and the Republic of Korea, and assesses which aspects of the regional collaboration from Europe and North America could be transferred to this part of Asia. The report reviews the European and North American pollution policy and regional cooperation focusing on the development of intergovernmental agreements such as the Convention on Long-Range Transport of Air Pollution (CLRTAP), but also on the development of European Union (EU) legislation and agreements between the United States of America and Canada. There has been a large degree of political will to collaborate, share data and be transparent in Europe, which has allowed negotiations on emissions reductions over the last 40 years and the EU has been able to harmonize legislation across Europe.

Several regional activities on air pollution in Northeast Asia exist, including the activities of the Acid Deposition Monitoring Network in East Asia (EANET), the Northeast Asian Sub-regional Programme for Environmental Cooperation (NEASPEC), the Asia Pacific Clean Air Partnership (APCAP) and the Climate and Clean Air Coalition (CCAC). Under these cooperation programmes, the focus has been on sharing information and data between countries. This has been ongoing but has not resulted in significant outcomes in terms of emissions reductions. Therefore, the report concludes that the potential impact of enhanced regional cooperation in Northeast Asia in enhancing and accelerating emission reductions is unknown. The report states that most cooperative efforts in Northeast Asia on air pollution do demonstrate the willingness of governments and related organizations to communicate with one another, but they still lack participation by the public.

In considering the environmental cooperation between China, Japan and the Republic of Korea, the report shows that each country faces different issues and obstacles. Each country has concentrated on national action and therefore any collaboration between them has been minimal. Northeast Asia is, however, a very dynamic region and opportunities are arising all the time. Recent changes, such as China committing to decarbonization by 2060, can improve the likelihood of successful, increased cooperation.

Key strategies for regional cooperation between the three countries are considered in the report. One key aspect is developing a strong consensus among the scientific community and the public about air pollution and the potential to improve it. Identifying best practice, by jointly assessing and reviewing activities undertaken in China, Japan and the Republic of Korea, is a crucial component that can lead to progress. A proposal for technological cooperation between the three countries could be a promising strategy if each country were willing to share their experience of using the best available technology. This can enhance connections across the private sector in different countries and boost business opportunities and industrial output.

To solve transboundary air pollution in Northeast Asia, holistic approaches are important so that technical expertise, economic resources and administrative support work in parallel to solve problems. Sharing disaggregated data and information would be a good start, but it is not enough. Developing appropriate strategies, policies and measures is crucial if emissions are to be reduced. The report considers cooperation on key technologies for monitoring, raising awareness and supporting solutions to air pollution through the active participation of the private sector in collaboration with academic institutions. Cooperation can be strengthened by the formation and engagement of gender-balanced networks of scientists, engineers and others to help governments lay out action plans to achieve the common goal of reducing air pollution. The formation of these networks could help increase the participation of the public and private sectors, which in turn would increase the interest of policy makers. Policy-maker engagement can also be enhanced when the public become increasingly aware of air pollution issues. All these aspects have been ingredients in the journey that has achieved reduced air pollution in Europe and North America. The report emphasises that some aspects of the journey in Europe and North America could be relevant to processes in Northeast Asia.

UNEP conducts a peer-review workshop in Seoul to discuss the results of the air quality assessment in Seoul, Incheon and Gyeonggi.
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International cooperation is important for reducing fine dust occurrences. Such technical cooperation and analysis could be used to help other regions find and expand solutions.

Recommendation 4:

Increase cooperation between governments in Seoul, Incheon and Gyeonggi and the national government to improve air quality

Air quality affects local areas but reaches wider ones. That is why international or inter-city cooperation to find solutions is important. The Metropolitan Atmospheric Environment Office of the Ministry of Environment and SIG put together the Metropolitan Atmospheric Environment Management Committee to collaborate by sharing data using integrated environmental management systems and evaluating air quality management performances. Chungbuk and Chungnam areas, which are close to the Seoul Metropolitan Region, also have various emission sources so these areas need to cooperate on data sharing and technical and human support, which require municipal effort as well as the central endeavour.

In 2016 and 2021, the Ministry of Environment conducted a joint onsite observation, KORUS-AQ[16], with the United States National Aeronautics and Space Administration (NASA). The final report, published in 2022, concluded that $PM_{2.5}$ has a high secondary generation rate, influenced by meteorological conditions, and its precursors significantly originated from outside the Republic of Korea. It was also observed that the O_3 concentration was on the rise, which was deemed as an East Asian problem requiring comprehensive cooperation involving all affected countries in the region. That is why international cooperation, such as the Incheon Forestry of Hope in Mongolia, the Republic of Korea and China International Forum, is important for reducing fine dust occurrences. Such technical cooperation and analysis could be used to help other regions find and expand solutions.

As mentioned in Reason #4, various actors, such as citizens, industry and the public sector as well as central and local governments, should participate actively in the cooperation for the longer term. The Incheon city government, for example, formed the Incheon Fine Dust Public-Private Countermeasure Committee with air quality management experts, civil society groups and environmental disease specialists to review the implementation plan and ensure effective air pollution reduction. The Incheon Living Lab is an experiment in citizen participation, through which resident communities, local activists and the public sector, who know their local areas very well, gather to discuss solutions and develop solutions.

In addition, corporate voluntary participation is also encouraged. A voluntary agreement between large companies and ESG management is a case in point. It is the role of central and local governments to incentivize it and provide the necessary information and technical support.

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[16] KORUS-AQ: An International Cooperative Air Quality Field Study in Korea (2016). https://espo.nasa.gov/korus-aq/content/KORUS-AQ

The Framework Act on Carbon Neutrality and Green Growth for Coping with Climate Crisis, which came into force in 2022, aims to create a carbon-neutral society by linking related environmental, energy, land and maritime policies, making a just transition, and fostering green technology in industry.

Recommendation 5:

Assess investment impact of implementing mitigation measures

The Framework Act on Carbon Neutrality and Green Growth for Coping with Climate Crisis, that came into force in 2022, aims to create a CN society by linking related environmental, energy, land and maritime policies, making a just transition, and fostering green technology in industry. Air pollution eduction, gender-responsive policies can create co-benefits such as adjustments in energy consumption and enabling the energy transition.

Envisioning a policy to maximize the cost-benefit could, therefore, be a key to success. Public health and disaster response have been strengthened by the so-called Eight Acts for PM Control. Gearing up for better communication with its people and expanded cooperation, the Republic of Korea should build an end-to-end monitoring system covering planning, implementation, evaluation, feedback and improvement.

The mitigation measures included in this assessment involve taking action across a number of sectors, such as transport, industry, households, agriculture and waste. The implementation of these measures will require that resources are directed toward them. Many of the mitigation measures identified, including energy-efficiency measures and shifting to public transport, have been shown in international studies to be cost-effective and could, over varying timeframes, pay for themselves. The economic impact of the health impacts resulting from exposure to air pollution has also been shown to be substantial, equivalent to 3.7 per cent of the Republic of Korea's GDP in 2015 (Roy and Braathen 2017).

Given the substantial economic impact of air pollution itself, and the opportunity for cost savings from the implementation of mitigation measures, there is a potentially persuasive case for the public and private sector investment to support the implementation of many of the mitigation measures being considered within SIG's climate change plans. There is also need for financial support for gender-responsive clean air initiatives; gender budgeting to ensure equal access to finance and promotion of gender considerations in the environment. This report's final recommendation is, therefore, to ensure that the case for investment is made so that the necessary finance is available to support implementation.

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