# Air Pollutant Emission Inventory Guidebook for the States of the Gulf Cooperation Council, and Introductory Guidance on Air Emissions Dispersion Modelling

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# PREFACE

Air pollution affects the health and well-being of people and the environment and is considered to be the world's single largest environmental health risk. As in other parts of the world, the countries of the Gulf Cooperation Council (GCC) are also facing the challenge of air pollution. Their geographical location also makes GCC countries particularly prone to natural air pollution sources such as sand, dust, and sea salt.

Realizing the challenge, the GCC and the United Nations Environment Programme (UNEP) embarked on an ambitious project under the "Green Gulf Initiative: delivering on the environmental dimensions of the SDGs." One of the aims of the initiative was to develop regional guidance for the collection of air quality data. Consequently, a set of three guidebooks have been produced: **(1)** Air pollutant Emission Inventory Guidebook for the States of the Gulf Cooperation Council, and Introductory Guidance on Air Emissions Dispersion Modelling; **(2)** Air Quality Modelling and Forecasting Guidebook for the States of the Gulf Cooperation Council; and **(3)** Air Quality Monitoring and Data Management Guidebook for the States of the Gulf Cooperation Council.

The current guidebook presents a unified method to compile emission inventories at national level that are suitable for regional comparison. It also provides a state-of-the-art web-based tool that GCC countries can use to facilitate computations and calculations. In addition, introductory guidance for air pollution dispersion modelling provides countries with an overview of the different methods available for dispersion modelling, including their data requirements, application, benefits and limitations.

This guidebook intends to facilitate the compilation of emission inventories of anthropogenic and biogenic emissions for GCC countries and the region. Emission inventories are considered the basis for the design of control strategies to abate air pollution locally and to help assess the contributions of air pollutants transported over long ranges. It is based on updated emission factors published in 2019 under the joint European Monitoring and Evaluation Programme/European Environment Agency (EMEP/EEA) air pollutant emission inventory guidebook.

The guidebook describes the key sources of input data most relevant to the computation of GCC emission inventories, and references the various factors used to create real-time and chemically resolved emissions.

The guidebook is divided into three chapters. **Chapter 1** is an introduction that summarizes the need for emission inventories, basic principles in emission inventory compilation, the pollutants covered, and the source sectors excluded from this guidebook. **Chapter 2** contains succinct descriptions of the main emission sources in the energy, industry, agriculture, and waste sectors. **Chapter 3** serves as an introduction to air pollution dispersion modelling summarizing different forecasting models, assessment methods, and input data requirements.

It should be noted that the guidelines in this guidebook are not legally binding but are intended to assist GCC countries in designing and compiling air pollutant emission inventories. Use of this guidebook will enable the GCC States to develop emission inventories in a harmonized manner and on a regular basis, simplifying the process of decision-making on control and prevention of air pollution in the GCC region.

To achieve the objective of this guidebook, it is recommended to establish a national network, coordinated by the agency responsible for air pollution management, with the participation of national statistical offices and relevant ministries, and further strengthen their capacities for compilation of emission inventories using this guidebook.

# ACKNOWLEDGEMENTS

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# ABBREVIATIONS

| | |
|---|---|
| As | Arsenic |
| BC | Black Carbon |
| Cd | Cadmium |
| $CH_4$ | Methane |
| CHP | Combined Heat and Power |
| CO | Carbon monoxide |
| $CO_2$ | Carbon dioxide |
| Cr | Chromium |
| Cu | Copper |
| EEA | European Environment Agency |
| EMEP | European Monitoring and Evaluation Program |
| GC/MS | Gas Chromatography Mass Spectrometry |
| GCC | Gulf Cooperation Council |
| GFS | National Centers for Environmental Prediction Global Forecast System |
| $H_2S$ | Hydrogen sulfide |
| HCB | Hexachlorobenzene |
| HCl | Hydrogen Chloride |
| HF | Hydrogen Fluoride |
| Hg | Mercury |
| HM | Heavy Metals |
| IFR | Instrument Flight Rules |
| LPG | Liquefied Petroleum Gas |
| LR | Linear Regression |
| LUR | Land Use Regression |
| MSW | Municipal Solid Waste |
| $N_2O$ | Nitrous oxide |
| NCEP | National Centers for Environmental Prediction |

| | |
|---|---|
| NFR | EMEP/EEA air pollutant emission inventory guidebook Nomenclature For Reporting |
| $NH_3$ | Ammonia |
| NMVOC | Non-methane volatile organic compounds |
| NO | Nitrogen oxide |
| $NO_2$ | Nitrogen dioxide |
| $NO_3$ | Nitrate |
| $NO_x$ | Nitrogen oxides |
| $O_3$ | Ozone |
| PAH | Polycyclic Aromatic Hydrocarbons |
| Pb | Lead |
| PCA | Principal Component Analysis |
| PCB | Polychlorinated biphenyls |
| PCDD | Polychlorinated dibenzo-para-dioxins |
| PCDF | Polychlorinated dibenzofurans |
| PM | Particulate matter |
| $PM_{10}$ | Particulate matter having a diameter of 10µm or less |
| $PM_{2.5}$ | Particulate matter having a diameter of 2.5µm or less |
| POP | Persistent Organic Pollutants |
| $SO_x$ | Sulfur oxides |
| SO | Sulfur monoxide |
| $SO_2$ | Sulfur dioxide |
| $SO_3$ | sulfur trioxide |
| VFR | Civil visual flight rule |
| VOC | Volatile organic compounds |
| WHO | World Health Organization |
| WRF | The Weather Research and Forecasting model |
| Zn | Zinc |

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# 1. INTRODUCTION

## 1.1 The need for emission inventories

Atmospheric pollution is of growing concern due to its detrimental effect on human health, agriculture and natural ecosystems. "Ecological footprints," which measure resource consumption, can serve as an indicator of the severity of air pollution in different countries, including the member states of the Gulf Cooperation Council (GCC). Action to limit air pollution is consistent with the Sustainable Development Goals. For example, Sustainable Development Goal 11, among others, aims to reduce the adverse per capita environmental impact of cities, including by paying special attention to air quality.

Good quality emission inventories are the foundation on which optimized emission prevention and control strategies can be developed at different scales. Regional issues such as tropospheric ozone ($O_3$) formation and increasing atmospheric loads of particulate matter (especially $PM_{2.5}$, with a diameter of 2.5 μm or less) also require high quality emission inventories in order to develop regionally coordinated abatement strategies. This is especially true given that the distribution of air pollutants in this region is strongly affected by seasonal sandstorms (Brown et al., 2008; Meo et al., 2013), and compounded by the fact that due to the small land area of GCC Member States such as Qatar, United Arab Emirates and Kuwait, it is difficult to determine unambiguously which pollutants originate from inside a country and which from outside. The recommendations of this guidebook reflect the importance of this aspect.

Therefore, to achieve mutual goals and to protect public health and the environment, additional efforts to assess air quality are needed. Without detailed and reliable emission inventories, there is little opportunity to develop strategic plans to deal regionally, nationally, or locally with air pollution problems and to monitor the effect of such plans. In Europe and North America there is official national reporting of emission inventories for a number of pollutants to the Convention on Long-Range Transboundary Air Pollution. However, in the GCC countries, routine calculation of emission estimates of high quality is either absent or only available for a few countries, and the capacity to undertake the necessary calculations is generally lacking. In the absence of region-specific emission factors, this manual is based on emission factors published in the air pollutant emission inventory guidebook prepared by the European Environment Agency (EEA) and European Monitoring and Evaluation Program (EMEP) (European Environment Agency, 2019). The EMEP/EEA guidebook compiles 10,727 Tier 1 and Tier 2 emission factors, abatement efficiencies, and fuel consumption figures from 429 distinct references including the United States Environmental Protection Agency, the Intergovernmental Panel on Climate Change, and various peer reviewed publications. The EMEP/EEA guidebook also provides a methodology for compiling inventories and default emission factors. However, countries are encouraged to calculate their own specific emission factors to improve accuracy.

The current guidebook provides technical guidance to prepare national emission inventories tailored to the GCC. It is accompanied by an inventory calculator to perform the emission calculation in a way that enables harmonization and aggregation at the regional level.

## 1.2 Principles of good practice in preparing inventories

### 1.2.1 Basic inventory principles

An emission inventory accounts for emissions of different pollutants from well-defined ground sources. The geographical scope of an inventory can range from the global to an individual plant. This guidebook details the steps to calculate a national inventory for a given year. Once established, inventories for multiple years (time-series) can be compared and used to design effective intervention plans to cut emissions of air pollutants.

The guidebook incorporates appropriate quality assurance and quality control checks to ensure that inventories are transparent, accurate, complete, consistent, and comparable. The principles for quality assurance and quality control to be followed in this guidebook have been developed by EMEP (European Environment Agency, 2019) and include:

**Transparency** Provide sufficient and clear documentation to support the calculation based on the requirements set for the inventory.

**Completeness** Report estimates for all relevant sources in the defined geographic area. If elements are missing, their absence should be clearly documented internally and highlighted in association with any published data.

**Consistency** Adopt the same methodology to estimate the inventories for the different years, gases and sources so that differences in the results between years and sources reflect real differences in emissions.

**Comparability** Compile inventories in a way that they can be compared with those from other countries. This is ensured by adopting a common classification and definition of emissions sources and by presenting the data in standard report templates.

**Accuracy** Reduce biases from the inventory by making educated and well-researched estimates.

**Key category** Certain source categories should be prioritized because they are significantly important for one or more air pollutants in a country's national inventory of air pollutants in terms of the absolute level, trend, or uncertainty of emissions.

Consistency in annual time-series and comparability between years present challenges when new emission factors and methods are introduced or additional information becomes available to improve the estimates. In this case, it is important to recalculate by applying the new method and the new data to all the years used in the time-series. Considering the time and effort required for recalculation, this guidebook is accompanied by a newly developed inventory calculator. This standalone tool enables annual (re)calculation to take account of changes in emission factors so that comparisons between years can be made. The inventory calculator also enables the user to easily conduct splicing techniques including extrapolations, interpolations, overlap considerations and use of surrogate data (i.e. data that are correlated with real emissions).

## 1.2.2 Estimation methods

A top-down approach to estimating emissions relies on using general emission factors combined with high-level (national) activity data. An example is the emission estimate for fuel based on total national fuel consumption and the associated emission factor. Emission estimates can be scaled down to a smaller inventory domain based on surrogate data for geographic, demographic, economic, or other sub-activity. This type of estimate calculation is commonly used when local data is not available and/or the cost of gathering local information is high. While the top-down approach requires minimal resources, the generated values are associated with a high level of uncertainty and a potential loss of accuracy in emission estimation (US EPA O., 2007).

A bottom-up approach to estimating emissions uses source-specific data (for point sources) and category-specific data at the most refined spatial level (for non-point and mobile sources). Emission estimations for individual sources (and source categories) are summed to obtain a domain-level inventory. This approach is typically used when source/category-specific activity or emission data are available. As such, it produces better spatial emission distribution.

Tier 1 methodology relies on the use of a single emission factor for each pollutant species, combined with a national statistic for the activity rate. The general equation is:

$$E_{polluant} = AR \times EF_{polluant}$$

Where $E_{polluant}$ is the emission of the specified pollutant, $AR$ is the activity rate, and $EF_{polluant}$ is the emission factor for this pollutant. This equation is applied at the national level. The Tier 1 emission factors assume an averaged or typical technology and abatement implementation in the country. In cases where specific abatement options need to be taken into account, a Tier 1 method is not applicable and the Tier 2 approach must be used.

To apply the Tier 2 approach, both the activity data and the emission factors need to be stratified according to different production/abatement technologies deployed in the country. The general Tier 2 equation is:

$$E_{polluant} = \sum [AR_{technology} \times EF(_{technology, polluant})\,]$$

Where $E_{polluant}$ is the emission of the specified pollutant, $AR_{technology}$ is the production rate within the source category, using a specific technology, and $EF_{technology, polluant}$ is the emission factor for this technology and this pollutant. It is generally advised to use higher tiered methods for key categories when possible.

## 1.2.3 Data collection

The collection of data is an essential step in preparing for the calculation of an emission inventory. Data on emission sources can be obtained from national statistical offices, concerned ministries and (for the compilation of smaller-scale inventories) targeted surveys. Additional data on technologies and abatement is best collected from data providers. If such data is unavailable, an "expert judgement" approach is implemented by asking several experts, independently, to provide estimates based on a well-documented procedure.

Considering the large number of sources in any given country, priority should be given to key sources that significantly contribute to air pollution emissions in the country. If no emission inventory has been attempted in a given country, this country may resort to the top-down approach or the adoption of key priority sources set by another country that exhibits similar national ground sources.

Where no emission inventory has ever been attempted, countries should start by using a Tier 1 methodology for all pollutant sources and provide a complete inventory. Once a first inventory has been completed, improvements in the key categories should be prioritized.

## 1.2.4   Data structure

A clear and unified data structure ensures better transparency and comparability. A uniform data structure also allows inventories to be more readily updated whenever new data is available. When using emission inventories for air quality models, both standard inputs and outputs can be applied to different regional models of transboundary air pollution.

## 1.3   Pollutants covered in this manual

### 1.3.1   $NO_x$

$NO_x$ refers to two forms of nitrogen oxides that exist in the atmosphere, namely, nitrogen oxide (NO) and nitrogen dioxide ($NO_2$). $NO_x$ are emitted from natural and anthropogenic sources like lightning strikes, agriculture processes and synthetic fertilizers, and thermal processes including the combustion of fossil fuels and biomass. When emitted into the atmosphere, $NO_x$ interacts with sunlight and volatile organic compounds (VOCs) to form tropospheric ozone. $NO_2$ also reacts with free hydroxyl radicals and $O_3$ to form nitric acid which contribute to acid rain. The standard way to measure $NO_2$ in air quality studies has been to use surface-conversion techniques to convert $NO_2$ to NO and to subsequently detect the NO by chemiluminescence. $NO_x$ mainly affects the respiratory system when inhaled by causing inflammation of the airways, headache and nausea; long-term exposure can lead to asthma (Finlayson-Pitts & Pitts, 2000; Seinfeld & Pandis, 2016).

### 1.3.2   $SO_x$

$SO_x$ represent various forms of sulfur oxides in the atmosphere including sulfur dioxide ($SO_2$), sulfur trioxide ($SO_3$), and disulfur monoxide ($S_2O$). $SO_x$ are emitted from a variety of natural and anthropogenic sources like sea spray, combustion of fossil fuel, energy production, industrial processes (including mining, smelting and petroleum refining) (Pan, 2011). $SO_x$ usually exist in gaseous states or as aerosols in the atmosphere and have a short lifespan. $SO_2$ reacts photochemically to form $SO_3$ and sulfuric acid, both of which contribute to acid rain.

$SO_2$ is measured in the atmosphere using an $SO_2$ analyzer which operates based on the absorbance of UV light at one wavelength by $SO_2$ molecules which then decay to a lower energy state by emitting UV light at a longer wavelength. Exposure to $SO_2$ harms the respiratory system and can lead to cancer if large concentrations are inhaled. $SO_x$ in the form of aerosols can enter the lungs and cause cardiovascular problems that can lead to mortality when large concentrations are inhaled (Finlayson-Pitts & Pitts, 2000; Seinfeld & Pandis, 2016).

### 1.3.3   $PM_{2.5}$

$PM_{2.5}$ is particulate matter with a diameter of 2.5 μm or less that is primarily formed from anthropogenic sources including the combustion of fossil fuels and biomass in vehicles, industrial processes and extractive industries. Secondary particles can form through chemical reactions among pollutant gases including $NO_x$ and $SO_x$. These fine particles can remain airborne for weeks because of their small size. One method to determine the concentrations of $PM_{2.5}$ in the atmosphere is a gravimetric analysis where the difference between the mass of filters weighed before and after sample collection represents the PM collected. By accounting for the flow rate and sample duration, the $PM_{2.5}$ concentration can be calculated. Fine particles cause eye, nose, throat and lung irritation, coughing, sneezing, runny nose and shortness of breath as a result of short-term exposure. Long-term exposure can lead to asthma, bronchitis, and cardiovascular problems (Finlayson-Pitts & Pitts, 2000; Seinfeld & Pandis, 2016).

### 1.3.4   $PM_{10}$

$PM_{10}$ is particulate matter with a diameter of 10 μm or less formed from natural and anthropogenic sources like forest fires, sea spray, dust storms and construction and includes the finer $PM_{2.5}$. The coarser particles usually stay in the atmosphere only for hours before being lost through sedimentation. As with $PM_{2.5}$, $PM_{10}$ concentrations in the atmosphere are measured using a gravimetric analysis. Exposure to $PM_{10}$ leads to coughing, shortness of breath, tightness of the chest, and irritation of the eyes that can lead to dysfunction in the respiratory system in the long-term (Finlayson-Pitts & Pitts, 2000; Seinfeld & Pandis, 2016).

### 1.3.5   CO

Carbon monoxide (CO) is one of the most toxic air pollutants. It mainly derives from anthropogenic activities, including the incomplete combustion of fossil fuels (mainly in vehicles and industrial processes) and tobacco smoke. It is also formed by the photolysis of some VOCs (especially ones emitted by plants) in the atmosphere. CO itself has a short lifespan in the atmosphere; however, it reacts with oxygen and sunlight to form carbon dioxide ($CO_2$) and $O_3$, which also contribute to air pollution. CO concentration levels in the atmosphere are detected by measuring the absorption of infrared radiation in a non-dispersive photometer. The major health effects of CO include the binding of CO with hemoglobin in the blood, which affects oxygen supply to the body and can prove fatal (Finlayson-Pitts & Pitts, 2000; Seinfeld & Pandis, 2016).

### 1.3.6   $NH_3$

Ammonia ($NH_3$) is an alkaline gas that is widely found in the atmosphere. A major source of $NH_3$ is agriculture, including livestock farming and the application of fertilizers. Vehicle emissions are also recognized as an important source. $NH_3$ reacts with other pollutants to form ammonium-based $PM_{2.5}$. Gaseous $NH_3$ levels are detected by collecting a sample of ambient air on coated denuders that are eluted and analyzed using ion chromatography. $NH_3$ affects the respiratory system by burning of the nose and respiratory tract and disturbance in the airway and alveoli sacs (ASTDR, 2004; Finlayson-Pitts & Pitts, 2000; Seinfeld & Pandis, 2016).

### 1.3.7   NMVOCs

Non-methane volatile organic compounds (NMVOCs) include organic compounds like benzene, ethanol, formaldehyde, cyclohexane, 1,1,1-trichloroethane, and other compounds that have different chemical compositions but behave similarly in the atmosphere. NMVOCs are emitted from a wide variety of sources including fuel combustion, solvent usage, industrial processes, commercial usage, vehicles, agriculture, landfill and waste. In the atmosphere, NMVOCs play an important role in the formation of tropospheric ozone, and some (like benzene, toluene, ethylbenzene and xylene) react with hydroxyl radical and nitrates to degrade them into organic aerosols in the atmosphere. The concentration of NMVOCs in ambient air can be measured using gas chromatography–mass spectrometry (GC-MS) or gas chromatography with flame ionization detector. Some NMVOCs are hazardous to human health, including benzene and 1,3 butadiene, which are carcinogenic. Some compounds affect the respiratory tract when inhaled (Finlayson-Pitts & Pitts, 2000; Seinfeld & Pandis, 2016).

### 1.3.8  $H_2S$

Hydrogen sulfide ($H_2S$) is a colorless gas that is the product of different processes. The emission of $H_2S$ is due to natural and human sources including geothermal activities, industrial processes, wastewater treatment, oil refining, and burning fuels that contain sulfur. Although the lifespan of $H_2S$ in the atmosphere is short, it reacts with $O_3$ in the presence of light and forms $SO_2$, which can in turn increase pollution levels. $H_2S$ levels are measured using gas chromatography and monitored using real-time instruments. When inhaled into the body, $H_2S$ causes irritation in the respiratory tract and can have serious effects on the nervous system (Finlayson-Pitts & Pitts, 2000; Seinfeld & Pandis, 2016).

### 1.3.9  BC

Black carbon (BC) is a fine particulate pollutant that poses a considerable threat to the environment and human health. BC is emitted from sources such as gas and diesel engines, coal-fired power plants and the burning of municipal waste. In order to monitor the levels of BC in the atmosphere, BC is extracted from air samples and analyzed using thermal-optical analysis. While BC is considered a short-lived air pollutant, it contributes significantly to global warming by absorbing sunlight and interacting with clouds. Black carbon can also cause serious health impacts, including respiratory and cardiovascular illness, cancer, and birth defects (Seinfeld & Pandis, 2016; WHO, 2010b).

### 1.3.10  PAHs

Polycyclic aromatic hydrocarbons (PAHs) are a large group of organic compounds that result from the incomplete combustion of fuels, oil refining and waste incineration. PAHs photodecompose under ultraviolet radiation and react with other pollutants. Monitoring is done by extracting PAHs from air samples and using GC-MS to quantify and identify the types of PAHs present. Humans exposed to PAHs mainly via inhalation face health risks including genotoxicity, immunotoxicity, and carcinogenesis (specifically lung cancer) (Finlayson-Pitts & Pitts, 2000; Seinfeld & Pandis, 2016).

### 1.3.11  Benzo[a]pyrene

Benzo[a]pyrene (B[a]P) is a type of PAH. It is classified as a type A carcinogen by the International Agency for Research on Cancer [1]. B[a]P is formed naturally in forest fires and emitted from anthropogenic sources including the incomplete combustion of fuels including in motor vehicles. When emitted into the atmosphere, B[a]P can adhere to PM. It has a short lifespan in the atmosphere and is transformed under photochemical oxidation (Faust, 1994). B[a]P levels in ambient air are measured by collecting and filtering air samples and applying high performance liquid chromatography or GC/MS. Inhaled B[a]P affects the respiratory system, reproductive system and induces immunotoxicity, and long-term exposure increases the risk of cancer (Finlayson-Pitts & Pitts, 2000; Seinfeld & Pandis, 2016).

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[1] The International Agency for Research on Cancer (IARC) is part of the World Health Organization. IARC coordinates and conducts both epidemiological and laboratory research into the causes of human cancer.

## 1.3.12   POPs

Persistent Organic Pollutants (POPs) are organic chemical substances that possess a particular combination of physical and chemical properties such that, once released into the environment, they remain stable for exceptionally long periods of time and become widely distributed throughout the environment (Finlayson-Pitts & Pitts, 2000).

### 1.3.12.1   PCBs

Polychlorinated biphenyls (PCBs) are one class of POPs. They are formed of aromatic chemicals that consist of the biphenyl structure with two linked benzene rings in which some or all of the hydrogen atoms have been substituted by chlorine atoms. The sources of PCBs are mainly anthropogenic, including the manufacture and use of products containing PCBs (such as cooling oil in power transformers), emissions from polluted reservoirs, thermal processes, waste incineration, and some combustion processes. PCBs exist in particulate and vapor phases and have a long lifespan in the environment as they are slow to degrade. They undergo photolysis in sunlight and react with hydroxyl radicals. PCBs are monitored by extracting them from air samples and using GC-MS to quantify and identify the types of PCBs present. PCBs along with most POPs tend to accumulate in the fat tissues of the body. PCBs can affect the respiratory tract, skin, liver, gastrointestinal system, nervous system, reproductive system, and immune system. Prolonged exposure can lead to cancer (Finlayson-Pitts & Pitts, 2000; Seinfeld & Pandis, 2016).

### 1.3.12.2   PCDDs/PCDFs

Polychlorinated dibenzo-para-dioxins (PCDDs) and polychlorinated dibenzofurans (PCDFs) are another class of POPs consisting of tricyclic aromatic compounds that have the same chemical properties. PCDDs and PCDFs are formed as byproducts of various organic chemical reactions, pulp and paper production, and thermal and combustion processes such as smelting, power generation, vehicles, herbicide manufacturing, waste incineration and sewage treatment. When emitted into the atmosphere, PCDDs and PCDFs exist in their free form or as aerosols, have long tropospheric lifespans and are transported over long distances. Both compounds react with hydroxyl radicals under photolysis which causes them to degrade (Atkinson, 1991). Levels of PCDDs and PCDFs are measured by collecting and filtering air samples and applying high performance liquid chromatography or GC/MS. When inhaled, these compounds increase cancer risk and prolonged exposure leads to the suppression of the immune system (Finlayson-Pitts & Pitts, 2000; Seinfeld & Pandis, 2016).

## 1.3.13   Heavy metals

Heavy metals (HMs) in the atmosphere are usually present in the form of PM. Depending on the size, these particulates can travel far and are persistent before settling to the ground.
For monitoring, particulates in air are usually collected on membrane or cellulose-acetate filters using air samplers. Following extraction and preparation, the metals are analyzed using methods including atomic absorption spectrometry, graphite furnace atomic absorption spectrometry, anodic stripping voltammetry, inductively coupled plasma-atomic emission spectroscopy, and isotope dilution mass spectrometry (Finlayson-Pitts & Pitts, 2000; Seinfeld & Pandis, 2016).

### 1.3.13.1   Pb
Lead (Pb) is a hazardous HM that affects the environment when emitted in large quantities.
The main point sources are lead smelters, refining and manufacturing of Pb-containing compounds, incinerators, coal combustion, and other industrial processes. Fuels that contain Pb additives also contribute to emissions. Lead is usually inhaled into the body in the form of PM. Depending on particle size, this PM reaches the respiratory tract or (for finer particles) the bloodstream.
Pb poisoning affects the kidneys as well as the nervous, reproductive, cardiovascular, hepatic, endocrine and gastrointestinal systems (Finlayson-Pitts & Pitts, 2000; Seinfeld & Pandis, 2016).

### 1.3.13.2   Hg
Mercury (Hg) occurs naturally in the Earth's crust. Natural sources include volcanic eruptions and emissions from the ocean. Anthropogenic sources include artisanal and small-scale gold mining, stationary combustion of coal, non-ferrous metals production, and cement production.
Mercury emissions eventually make their way to water bodies where certain microorganisms transform them into methylmercury, a highly toxic form that builds up in fish, shellfish and animals that eat fish. Most human exposure to mercury is from eating fish and shellfish contaminated with methylmercury. Mercury exposure has adverse effects on the brain, heart, kidneys, lungs, and immune system. High levels of methylmercury in the bloodstream of babies in the womb and young children may harm their developing brains (UNEP, 2019) (Finlayson-Pitts & Pitts, 2000; Seinfeld & Pandis, 2016).

### 1.3.13.3   Cd
Cadmium (Cd) is a HM that is toxic even at low exposure levels and has major effects on human health and the environment. Dominant anthropogenic sources of atmospheric emission are non-ferrous metal production, combustion of coal and oil, and waste incineration. Major natural sources are volcanoes and weathering of rocks. Cadmium is not degradable in nature and atmospheric deposition will increase cadmium content in agricultural topsoil causing increased human intake through foodstuffs. Cadmium accumulates in the human body causing renal tubular damage, disturbances of calcium metabolism, hypercalciuria, and formation of stones in the kidney. High exposure can lead to lung and prostate cancer (Nordic Council of Ministers, 2003) (Finlayson-Pitts & Pitts, 2000; Seinfeld & Pandis, 2016).

### 1.3.13.4   Zn

Although zinc (Zn) is important for the human body, it can be toxic in higher concentrations. Zinc oxide and other compounds are emitted into the atmosphere along with Zn particles during the mining, smelting and refining of metals including Pb and copper as well as Zn. While elemental Zn is not harmful, Zn compounds pose health risks when inhaled. Zinc oxide causes metal-fume fever that brings on flu-like symptoms. Zinc chloride is more toxic than zinc oxide and can cause pneumonitis, while the inhalation of Zn salts causes irritation in the respiratory and gastrointestinal tract (Finlayson-Pitts & Pitts, 2000; Seinfeld & Pandis, 2016).

### 1.3.13.5   Cu

Copper (Cu) is a HM that can damage the environment and human health. Cu is emitted into the atmosphere from anthropogenic point sources like coal combustion, thermal processes, solid fuel combustion, and waste incinerators. Cu is a toxic HM that can cause chronic bronchitis, emphysema, asthma, and an increased risk in mortality when inhaled in large concentrations (Finlayson-Pitts & Pitts, 2000; Seinfeld & Pandis, 2016).

### 1.3.13.6   Cr

Chromium (Cr) is a HM that is found in soil, water, and the atmosphere. Although not many forms of Cr are found in the atmosphere and it is not abundant in its elemental form, Cr **(VI)** and Cr **(III)** are measured to assess Cr levels. Naturally, Cr is found in rocks, animals, plants, soil, and gases. Industrial processes emit Cr **(III)** in the form of aerosols. Ore refining, chemical and refractory processing, cement production, and chromic plating contribute to the emission of Cr into the atmosphere. Cr **(VI)** reacts in air with dust particles or other pollutants to form the unreactive Cr **(III)**. While Cr **(VI)** is more toxic than Cr **(III)**, both represent major health risks when inhaled in large amounts. Both elements affect the respiratory tract by inducing shortness of breath, coughing, and wheezing. Chronic exposure to Cr **(VI)** can lead to bronchitis, decreased pulmonary function, pneumonia, and asthma. It also affects the liver, kidneys and immune system and can lead to cancer when inhaled over a long time (Finlayson-Pitts & Pitts, 2000; Seinfeld & Pandis, 2016).

### 1.3.13.7   As

Arsenic (As) is a HM that is found as an organic and inorganic compound in the atmosphere. The abundance of As is due to natural and anthropogenic sources. Naturally, As is formed from dust storms, geothermal/hydrothermal activity and forest fires, whereas anthropogenic sources include metal mining and smelting, the mining and burning of As-rich coals, and tobacco smoke. As is mainly found attached to oxygen, chlorine, sulfur and $PM_{2.5}$ and is stable in the atmosphere. However, As can also react with humidity to form different compounds with varying health effects. Arsenic bound to particulates enters the respiratory tract and cardiovascular system. Inside the body, it increases the risk of cancer and long-term exposure can damage blood vessels and cause genotoxicity (Finlayson-Pitts & Pitts, 2000; Seinfeld & Pandis, 2016).

### 1.3.14   Greenhouse gases

The EMEP/EEA guidebook lists emission factors for greenhouse gases (GHGs) in certain sectors. These GHGs are methane ($CH_4$), nitrous oxide ($N_2O$), and carbon dioxide ($CO_2$). $CH_4$ is emitted during the production and transport of coal, natural gas, and oil. $CH_4$ emissions also result from livestock and other agricultural practices and by the decay of organic waste in municipal solid waste landfills. $N_2O$ is emitted by certain agricultural and industrial activities, combustion of fossil fuels and solid waste, as well as wastewater treatment. $CO_2$ enters the atmosphere through burning fossil fuels, solid waste and biomass, and also as a result of certain chemical reactions (e.g. in the manufacture of cement).

## 1.4 Natural sources not included in this manual

### 1.4.1 Dust storms

Next to Africa, the Middle East is one of the regions most affected by dust. Seasonal variation of dust activity in the Middle East is complex and differs for different geographical areas. In most parts of the Middle East, dust is active all year long but is suppressed in the winter months. Dust activity increases in March and April, peaks in June and July and weakens in September (Hamidi et al., 2014a; Shao et al., 2010a).

The region (including mainly the Arabian Plateau and the Tigris-Euphrates Basin) is an area of active wind erosion. The Arabian Plateau slopes down in a southwest-northeast direction from the higher altitudes bordering the Red Sea towards flat lands adjacent to the Gulf. The literature identifies two dust areas. One area covers the Tigris-Euphrates River alluvial plain, the flat lands in the east of the Arabian Peninsula along the Gulf, and the Ad Dahna and Rubal Khali deserts. The second dust area is found along the Oman coast, and the number of daily dust-storms in this area is much lower (Engelstaedter et al., 2003; Huang et al., 2006; Li et al., 2013; Maki et al., 2014; Ren et al., 2014; Rosenfeld et al., 2001; Sokolik et al., 1998).

Natural dust contributes significantly to high concentrations of atmospheric $PM_{10}$ in the region, and there is growing interest in understanding the environmental and human health risks associated with windblown dust (WHO,2010a). Notably, the fraction of cardiopulmonary deaths associated with dust exposure increases to 15–50% for countries in the Middle East from the global average of approximately 1.8% (Darmenova et al., 2009). Dust contributes to the alteration of solar radiative budgets, modification of cloud properties, reduction of visibility, and long-range transport of organic chemicals, airborne bacterial species, and trace metals (Crooks et al., 2016; Goudie, 2014).

Dust emission involves several complex and nonlinear processes that are governed by meteorology, land surface and soil texture. Dust flux is closely related to wind speed (friction velocity), surface roughness, soil moisture, vegetation fraction, soil type and texture, and air density. Small errors in modelling these parameters can result in large dust flux uncertainties (Ginoux et al., 2004; Hamidi et al., 2014b; Nickovic et al., 2001; Shao et al., 2010b; Sun et al., 2006; Zender et al., 2003). As a result of this and of the fact that dust storms are transboundary phenomena, it is difficult to estimate the impact of dust storms on national air quality using standard emission inventory methods.

Estimation methods are usually based on numerical simulation. A number of dust models have been developed for regional and global dust predictions (Vickery et al., 2013). These models consist of several dust emission schemes coupled with a geographic information system (GIS) and forced by wind data. Other methods to compile a dust inventory are based on visually interpreted satellite data (such as MODIS and MSG-SEVIRI) (Vickery et al., 2013). Such emission estimations are not included in this manual. Methods described in **Chapter 4** can, however, be useful to take a GCC-specific dust dispersion modelling approach for dust prediction in the region.

### 1.4.2 Forest fires

Forest fires are not a major source of emissions in the GCC. Emission from the burning of vegetation include $SO_2$, $NO_x$, CO, $CH_4$, NMVOCs, $NH_3$ and PM (including BC). Burning takes place during conversion of forests, woodlands, or grasslands to agricultural or other uses, prescribed burns for fire management or forest stand maintenance, and other fires started either accidentally by man or naturally by lightning.

Emissions from forest fires depend on **(1)** the duration and intensity of the fire, **(2)** the total area burnt by the fire, and **(3)** the type and amount of vegetation that is burnt. This latter term is often referred to as fuel load. Of those three terms, the one that is measurable with a fair level of accuracy is the total burnt area.

The major products of biomass burning are $CO_2$ and water vapor. However, a large number of particulates and trace gases are also produced, including the products of incomplete combustion (BC, CO, NMVOC and nitrogen and sulfur species, some of which can indirectly influence the production of tropospheric $O_3$). These arise partly from nitrogen and sulfur contained in the vegetation and organic matter in the surface soils. Additionally, emissions can arise from the re-volatilization of substances which have been deposited.

# O2

## 2.   Emission Sources

### 2.1   Energy

#### 2.1.1   Combustion

This section includes emissions from combustion in energy industries, manufacturing, and transport. Non-combustion industrial process related emissions are tackled in section 2.2. The combustion activities undertaken in manufacturing industries generally provide process heat (directly or indirectly usually via steam, water or oil), electricity, or the fuel may be transformed in the production activity. Combustion activities essentially relate to the use of fuels in conventional boilers, furnaces, gas turbines, engines or other combustion. The emissions of pollutants will depend on the fuel and process activity. Relevant pollutants are generally as described for combustion: $SO_2$, $NO_x$, CO, NMVOCs, PM, BC, HMs, PAH, PCDD/Fs and, for some activities, PCBs and Hexachlorobenzene (HCB). Separate entries for different capacities, technologies, and abatements are listed in the accompanying inventory calculator tool.

Transport sector emissions include emissions from the **(1)** combustion of fuel (exhaust emissions) during transport activities, and from **(2)** non-combustion related emissions including evaporative losses from vehicles (excluding refueling emissions at service stations, which are covered under "Fugitive emissions" in this outline (Section 2.5)), tyre/brake wear and road abrasion. The transport activities covered in this section include shipping and aviation as well as road transport. The latter includes passenger cars and light commercial vehicles (<3.5 t) such as pick-ups and delivery vans, and heavy-duty vehicles (>3.5 t).

#### 2.1.1.1   Energy industries
Energy industries include energy production (i.e. energy transformation) or fossil fuel extraction. All energy industries are potential sources of $SO_2$, $NO_x$, CO, NMVOC, $NH_3$, $PM_{10}$, and $PM_{2.5}$ emissions.

##### 2.1.1.1.1   Public electricity production
In general, this activity addresses emission from larger combustion appliances (>50 MW nominal capacity) that generate electricity or produce heat for sale to the public. Emissions from public electricity combustion plants are considered as point sources. The power stations or utilities may be in public or private ownership. The emissions are released by a controlled combustion process (e.g. in a boiler, furnace, gas turbine or stationary engine) and are mainly characterized by the types of fuels used. They may be further characterized according to the size and type of plants as well as primary or secondary emission reduction measures.

Emissions from auto producers that generate electricity and/or heat, wholly or partly for their own use are not included here. These emissions are accounted for in sections 2.1.1.2 and 2.1.1.6.

Detailed methods and data needed to estimate emissions from public electricity production industries are available in the EMEP/EEA air pollutant emission inventory guidebook (addressing Nomenclature for reporting (NFR) Sector 1.A.1.a).

#### 2.1.1.1.2 Petroleum refining

This activity covers emissions released from production and combustion processes within a refinery. Combustion processes include the heating of crude and petroleum products without contact between flame and products. Combustion fuels include additional fuels such as refinery gas.

Detailed methods and data needed to estimate combustion emissions from petroleum refining are available in the EMEP/EEA air pollutant emission inventory guidebook (NFR Sector 1.A.1.b). Process related emissions are covered in section 2.1.2.

#### 2.1.1.1.3 Manufacture of solid fuels and other energy industries

All emissions from the combustion of fuels used during the manufacture of secondary or tertiary products from solid fuels. Included are emissions from the production of coke (from hard coal in coke ovens and gas works), brown coal briquettes (from brown coal or lignite), patent fuel (from hard coal) and charcoal (from wood). Also included are the combustion emissions from own (on-site) energy use in coal mining and in oil and gas extraction.

Detailed methods and data needed to estimate emissions from the manufacture of solid fuels and other energy industries are available in the EMEP/EEA air pollutant emission inventory guidebook (NFR Sector 1.A.1.c).

#### 2.1.1.2 Manufacturing industries and construction

This includes a variety of activities such as combustion in boilers, gas turbines, stationary engines, plaster furnaces and other furnaces, in the production of cement, lime, asphalt, glass, mineral wool, fine ceramic material and enamel, as well as in other mobile machinery/industry. Only combustion-related emissions are included. Process-related emissions are covered in relevant sections under 2.2.

Relevant activities include:

1. Iron and steel manufacture: Combustion emissions from the manufacture of iron and steel occur via processes including metallurgical coke production, sinter production, pellet production, iron ore processing, iron making, steel making, steel casting and combustion of blast furnace and coke oven gases for other purposes. The main processes may occur at an "integrated" facility that includes blast furnaces and basic oxygen steelmaking furnaces or, in some cases, open hearth furnaces.

2. Non-ferrous metals: The non-ferrous metal process includes primary metal production where combustion is relevant to the primary production of many metals. Use of coke, CO and carbonyl formation are relevant to several production schemes. Combustion activities are also used for melting, casting and heat treatment furnaces. The use of melting furnaces for scrap recovery and subsequent purification is typical of many secondary metal recovery activities.

3. Cement manufacture: Portland cement can be produced either by dry or wet processes (there are also semi-dry and semi-wet processes). Combustion occurs in the kiln and, where relevant, the pre-calciner furnace.

4. Lime manufacture: Lime is heated in a kiln to decarbonize (calcine). Two major types of kilns are in use: vertical and rotary kilns.

5.  Asphalt manufacture: Combustion in a roadstone coating plant is mainly associated with drying of aggregates, generally in a rotary dryer.

6.  Glass manufacture: Combustion occurs in the melting of glass in a furnace and its subsequent processing.

7.  Mineral wool: In the manufacture of mineral wool, glass and stone wool fibers are made from molten glass, and a chemical binder is simultaneously sprayed on the fibers as they are created.

8.  Enamel manufacture: Enamel is prepared by fusing a variety of minerals in a melting furnace and then rapidly quenching the molten material.

9.  Food processing, beverages and tobacco: Many food and beverage processes produce their own steam in one or more industrial boilers which burn fossil fuel and/or biomass.

10. Construction industry and brick manufacture: In brick and tile manufacturing, formed clay is dried and then fired at high temperature in a kiln. Various combustion processes are also undertaken in ceramic manufacture.

11. Manufacture of chemicals and petrochemicals: Combustion in the chemicals sector ranges from conventional fuels in boiler plants and recovery of process by-products using thermal oxidizers to process-specific combustion activities (e.g. catalytic oxidation of $NH_3$ during nitric acid manufacture).

12. Pulp and paper industry: The production of pulp and paper requires considerable amounts of steam and power. Most pulp and paper mills produce their own steam in one or more industrial boilers or combined heat and power units which burn fossil fuels and/or wood residues. Mills that pulp wood with a chemical process (e.g. Kraft, sulfite, soda, semi-chemical) normally combust their spent pulping liquor in a combustion unit, for example a Kraft recovery furnace, to recover pulping chemicals for subsequent reuse. These units are also capable of providing process steam and power for mill operations.

13. Mining (excluding coal mining) and quarrying: Standard techniques assumed for this source include blasting, transportation and crushing of materials. The emissions of pollutants will depend on emissions from the combustion of fuels in the quarry and in the plant (drillers, mobile crushers, mobile screeners, electric generators, etc.) or transport machinery (loaders, dumpers, cranes, etc.).

Detailed methods and data needed to estimate emissions from stationary combustion in manufacturing industries and construction is available in the EMEP/EEA air pollutant emission inventory guidebook (NFR Sector 1.A.2.a through g).

### 2.1.1.3 Road transport

#### 2.1.1.3.1 Exhaust emissions

Exhaust emissions from road transport arise from the combustion of fuels such as petrol, diesel, liquefied petroleum gas (LPG), and natural gas in internal combustion engines.
The air/fuel charge may be ignited by a spark ("spark-ignition" or "positive-ignition" engines), or it may ignite spontaneously when compressed ("compression-ignition" engines).
The most important pollutants emitted by road vehicles include:

1. $O_3$ precursors (CO, $NO_x$, NMVOCs)
2. greenhouse gases ($CO_2$, $CH_4$, $N_2O$)
3. acidifying/alkaline substances ($NH_3$, $SO_2$)
4. PM including BC and OC;
5. carcinogenic and toxic pollutants (PAHs and POPs);
6. HMs

Exhaust emissions from road transport are subdivided among passenger cars, light commercial vehicles, heavy-duty vehicles and buses, and mopeds and motorcycles.

1. Passenger cars are vehicles used for the carriage of passengers and comprising not more than eight seats in addition to the driver's seat.

2. Light commercial vehicles are vehicles used for the carriage of goods and having a maximum weight not exceeding 3.5 ton.

3. Heavy-duty vehicles and buses include vehicles used for the carriage of goods and having a maximum weight exceeding 3.5 ton but not exceeding 12 ton, vehicles used for the carriage of goods and having a maximum weight exceeding 12 ton, vehicles used for the carriage of passengers and comprising more than eight seats in addition to the driver's seat, and having a maximum weight not exceeding 5 ton, and vehicles used for the carriage of passengers and comprising more than eight seats in addition to the driver's seat, and having a maximum weight exceeding 5 ton.

4. Mopeds and motorcycles include 2-stroke and 4-stroke motorcycles, mini-cars, and all-terrain vehicles.

Gasoline (and other spark-ignition) engines are used in small vehicles up to 3.5 ton gross vehicle weight, primarily because of their superior power-to-weight ratio and their wider operational range compared with diesel engines, but also for reasons such as lower noise and more refined operation. Diesel (and other compression-ignition) engines dominate in heavy-duty applications because of their greater fuel efficiency and torque compared with petrol engines.

Detailed methods and data needed to estimate exhaust emissions from road transport are available in the EMEP/EEA guidebook (NFR Sector 1.A.3.b.i for passenger cars, 1.A.3.b.ii for light commercial vehicles, 1.A.3.b.iii for heavy-duty vehicles and buses, and 1.A.3.b.iv for mopeds and motor cycles).

### 2.1.1.3.2   Gasoline evaporation

Evaporative emissions refer to the sum of all fuel-related NMVOC emissions not deriving from fuel combustion. In current vehicles, evaporative emissions are controlled by means of an activated carbon canister connected to the fuel tank. The canister adsorbs the fuel vapor escaping from the tank.

Most evaporative emissions of VOCs emanate from the fuel systems (tanks, injection systems and fuel lines) of petrol vehicles. Evaporative emissions from diesel vehicles are considered to be negligible due to the presence of heavier hydrocarbons and the relatively low vapor pressure of diesel fuel and can be neglected in calculations.

The most important sources of evaporative emissions from a vehicle are the following:

1. breathing losses through the tank vent. This is due to evaporation of fuel in the tank as a result of normal diurnal temperature variation;

2. fuel permeation/leakage. Various studies indicate that liquid fuel seepage and permeation through plastic and rubber components of the fuel and vapor control system contribute significantly to the total evaporative emissions.

When modelling evaporative emissions due to breathing losses and fuel permeation, three separate mechanisms are usually considered:

1. diurnal emissions
2. running losses
3. hot-soak emissions

The evaporation of gasoline also takes place during the delivery of fuel to service stations and vehicle refueling. However, these processes are described in Section 2.5.3.

The contribution of evaporative emissions to total NMVOC emissions from road transport has decreased considerably since the introduction of carbon canisters. The observed differences in evaporative emissions in different countries are due to the combined effects of ambient temperatures (minimum and maximum), the volatility of the fuel used, vehicle usage (annual mileage), the technology mix (share of older vehicles without a carbon canister), as well as the share of diesel vehicles in the national car fleet.

Detailed methods and data needed to estimate evaporative emissions from road transport is available under EMEP/EEA air pollutant emission inventory guidebook (NFR Sector 1.A.3.b.iiv.)

### 2.1.1.3.3   Road, tyre and brake wear

Tyre, brake and road surface wear are abrasion processes, not combustion processes and are sources of emissions of PM including BC. The focus is on primary particles – in other words, those particles emitted directly as a result of the wear of surfaces – and not those resulting from the resuspension of previously deposited material.

Airborne particles are produced as a result of the interaction between a vehicle's tyres and the road surface, and also when the brakes are applied to decelerate the vehicle. In both cases, the generation of shear forces by the relative movement of surfaces is the main mechanism for particle production. A secondary mechanism involves the evaporation of material from surfaces at the high temperatures developed during contact.

**PM from tyre wear**
Tyre wear material is emitted across the whole size range for airborne particles. Heavier particles are not airborne and are of limited interest for air pollution, but they contribute the largest fraction by weight of total tyre wear. A study found that roadside tyre debris <100 μm had a mean diameter of 65 m for cars and 80 μm for trucks. Tyre particles contain an estimated 29% elemental carbon and 58% organic material, and Zn is the most abundant metal. The observed mass-weighted size distribution has varied in different studies, and it is not straightforward to draw firm general conclusions.

**PM from brake wear**
As with tyre wear, not all of the worn brake material will be emitted as airborne PM, although proportionally more it seems in the case of brakes, and a significant proportion as $PM_{2.5}$. However, there is still a large amount of variation in the fraction of total wear mass that can be assumed to be airborne. With regard to its chemical composition, brake wear material largely depends on the manufacturer, the application (car, truck, etc.) and the desired properties of the brake pads. Pads are expected to consist mainly of metals bound together with silicon-based materials. It has been shown that iron contributes up to 46%, Cu up to 14%, OC of about 13%, followed by several other metals, including Pb (~4%), Zn (~2%), Calcium and Barium.

**PM from road surface wear**
Emission factors for road surface wear particles are even more difficult to quantify than those for tyre and brake wear, partly because the chemical composition of bitumen is too complex for quantification with chemical mass balance and receptor modelling, and partly because primary wear particles mix with road dust and re-suspended material.

Detailed methods and data needed to estimate road, tyre and brake wear emissions from road transport are available in the EMEP/EEA air pollutant emission inventory guidebook (NFR Sector 1.A.3.b.vi for tyre and brake wear, and NFR Sector 1.A.3.b.vii for road abrasion).

### 2.1.1.4   Water-borne navigation

The emissions produced by navigation are a consequence of combusting fuel in an internal combustion engine. Consequently, the principal pollutants are CO, VOC, $NO_x$ and PM (including BC) which mainly have to do with engine technology, and $CO_2$, $SO_x$, HMs and further PM (mainly sulfate-derived) which depend on fuel speciation.

Navigation includes international maritime navigation, international inland navigation, national navigation (shipping), national fishing, military (shipping), and recreational boats. The criteria for distinguishing between domestic and international navigation depends only on the origin and destination of a ship for each segment of its voyage (departing and arriving in the same country (domestic) or departing from one country and arriving in another (international)).

The international/domestic split should be determined on the basis of port of departure and port of arrival, and not by the flag or nationality of the ship. National navigation covers all water-borne transport from recreational craft to large ocean-going cargo ships that are driven primarily by high, slow and medium-speed diesel engines and occasionally by steam or gas turbines.

It includes hovercraft and hydrofoils. Water-borne navigation causes emissions of $CO_2$, $CH_4$ and $N_2O$, as well as CO, NMVOCs, $SO_2$, PM and $NO_x$. Countries that have domestic navigation have to quantify its emissions within their borders. International navigation, however, is not usually included in national inventories. If relevant for the GGC, international navigation between some member countries might be interesting to include in a regional inventory.

Data on shipping movements is collected on the basis of individual trip segments (from one departure to the next arrival) and do not distinguish between different types of intermediate stops. Basing the distinction on individual segment data is simpler than looking at the complete trip and is likely to reduce uncertainties. It is considered very unlikely that this would make any significant impact on the total emission estimates.

Exhaust emissions from navigation arise from both main propulsion engines and auxiliary engines used to provide power and services within vessels and depend on the type of engine:

1. *Slow speed diesel engines:* these have a maximum operating speed of up to 300 rev/min, although most operate at speeds of 80–140 rev/min.

2. *Medium speed diesel engines:* this term is used to describe marine diesel engines with a maximum operating speed in the range of 300–900 rev/min.

3. *High speed diesel engines:* this describes marine diesel engines with a maximum operating speed greater than 900 rev/min. They are essentially smaller versions of the medium speed diesel engines or larger versions of road truck vehicle engines; they are used on smaller vessels and are often the source of auxiliary power onboard vessels.

4. *Steam turbines:* whilst these replaced reciprocating steam engines in the early twentieth century, they themselves have been replaced by more efficient diesel engines which are cheaper to run. Steam turbine vessels are predominantly fuelled with fuel oil rather than lighter fuels.

5. *Gas turbines:* whilst this type of engine is more widely used in warships, they are currently installed in only a very small proportion of the merchant fleet, often in conjunction with diesel engines.

In addition to the categorization into five types of engines, marine engines can be further stratified according to their principal fuel: bunker fuel oil, marine diesel oil or marine gas oil. Some emissions (e.g. of $SO_x$ and HM) are predominantly fuel-based rather than dependent on engine type. Consequently, knowledge of the fuel used significantly influences emissions estimates in addition to the engine type using it.

Detailed methods and data needed to estimate navigation emissions are available in the EMEP/EEA air pollutant emission inventory guidebook (NFR Sectors 1.A.3.d.i(i), 1.A.3.d.i(ii), 1.A.3.d.ii, 1.A.4.c.ii and 1.A.5.b).

### 2.1.1.5   Aviation

Emissions from aviation include the civil aviation portion of combustion emissions from mobile sources that are related to the movement of people and/or freight by air. The activities comprise international aviation and domestic aviation. International aviation includes international airport traffic (LTO cycles (landing and take-off cycles) ≤ 3000ft (914.4m)), and international cruise traffic (>3000ft (914.4m)). Domestic aviation includes domestic airport traffic (LTO cycles ≤3000ft (914.4m)), and domestic cruise traffic (>3000ft (914.4m)). The distinction between international and domestic air traffic should be determined on the basis of departure and landing locations for each flight stage and not by the nationality of the airline.

Aviation exhaust emissions are categorized as being "international" or "domestic" depending on whether the arrival airport is, or is not, in the same state as the departure airport. The pollutants produced by aviation mainly come from the combustion of jet fuel and aviation gasoline (the latter is used as fuel only by small aircraft and helicopters equipped with piston engines).
The main emission species produced are: $CO_2$, $NO_x$, $H_2O$ vapor, $CH_4$, CO, $SO_x$, NMVOCs and PM. Countries that have domestic aviation have to quantify its emissions within their borders in terms of both airport traffic and cruise traffic. International cruise traffic, however, is not usually included in national inventories. If relevant for the GCC, international cruise traffic between some member countries might be interesting to include in a regional inventory.

The main types of aircraft engines are reciprocating (piston) engines and gas turbine engines. A reciprocating (piston) engine uses piston and crank mechanisms to extract the energy from fuel burnt in a combustion chamber. This drives the propellers to give the aircraft momentum. A gas turbine engine compresses air before burning fuel in a combustion chamber, thereby heating it. The major part of the energy produced is used for propelling the aircraft, while a minor portion is used to drive a turbine, which drives the compressor. There are three main types of gas turbine engine: jet engines, which include turbojet and turbofan engines; turboprop engines; and turboshaft engines. A typical aircraft flight includes several phases of flight: Taxi-out, take-off, climb-out, climb, cruise, descent, final approach, landing, and taxi-in. "Flight movement" starts when an aircraft begins taxiing out and finishes when the aircraft comes to a stop after taxiing in.

Exhaust emissions from aviation arise from the combustion of jet fuel and aviation gasoline. They arise during all activities related to flight movements and can be grouped into groups of activities: pre-departure activities; departure activities; CCD (climb, cruise, descent) activities; emergency activities; arrival activities; post-arrival activities; and maintenance activities. Of these activities, the three main ones for which global fuel usage and emissions inventories are possible are departure activities, CCD activities, and arrival activities. For all types of engines and categories of flight movement, activity rates for emission calculations are LTO cycles.

There are four categories of flight movements that should be included in aviation inventory activities in a country:

**Category 1** – Civil instrument flight rules (IFR) flights. This is the category from which most emissions originate. Flight movement data are often recorded for this category of aircraft, and methods for estimating the amount of fuel burnt and emissions generated by this category are quite mature. Aircraft in category 1 can be classified according to the type of engine they are equipped with: turbojet, turboprop or piston.

**Category 2** – Civil visual flight rules (VFR) flights. This category, also called general aviation, concerns small aircraft used for leisure, agriculture, taxi flights, etc. Aircraft used for civil VFR flights are generally equipped with turboprop or piston engines.

**Category 3** – Civil helicopters. This category concerns all types of rotorcraft. Helicopters are often operated under VFR and rarely under IFR. Therefore, it might be difficult to collect precise information on helicopter movements in a country. At present, most helicopters use turboshaft engines to power their rotors, but some small helicopters still use piston engines.

**Category 4** – Operational military flights. There may be some difficulties in estimating these activities because of scarce and often confidential military data. Some movements of military aircraft, such as non-operational activities, might be included in **category 1**.

Detailed methods and data needed to estimate aviation emissions are available in the EMEP/EEA air pollutant emission inventory guidebook (NFR Sector 1.A.3.a).

### 2.1.1.6   Other sectors

#### 2.1.1.6.1   Mobile sources
This section covers a mixture of equipment distributed across a wide range of industry sectors, typically land-based, and is commonly referred to collectively as non-road mobile machinery (NRMM).

For all these types of equipment, exhaust emissions from NRMM arise from the combustion of diesel, gasoline and LPG to power the equipment. For many countries, the contribution of NRMM to total national emissions will be small i.e. the individual sources are not key sources. However, the contributions from some sectors to some nations' inventories may be moderately important. The more important pollutant species include: $SO_2$, $NO_x$, $CO_2$, PM, CO and NMVOCs, with the relative importance of the species depending on the type of engine (diesel compression ignition or petrol spark ignition), and the type of equipment. The methodology used for estimating emissions of $CO_2$ and $SO_2$ are predominantly fuel-based, and therefore independent of engine technology/type of equipment.

Engines used in these mobile sources comprise:

1. diesel engines, ranging from large diesel engines >200kW (installed in cranes, graders/scrapers, bulldozers, etc.) to small diesel engines, around 5kW, fitted to household and gardening equipment (e.g. lawn and garden tractors, leaf blowers, etc).

2. petrol-fueled engines, virtually all of smaller power, typically less than 10kW, and principally used in household and gardening equipment, with a small number used in industry (e.g. to power fork-lift trucks or small electrical generator sets). Two-stroke petrol engines are generally smaller than four-stroke engines. The equipment used in each application is described in more detail.

3. LPG engines: used in two- and four-stroke petrol engines as an alternative fuel i.e. there are no significant differences in engine technology or design. The most common reason for using LPG rather than petrol is one of cost, but air quality issues can also be an important consideration.

In addition to the division by fuel, an important classification is the division of the engines into variable and constant speed engines. However, it can be challenging to obtain information that allows the machinery fleet to be classified in this way:

1. Constant speed engines are principally those used in generator sets, where they produce electric power at a constant frequency by running the generator at a constant shaft speed. They are potentially important, for example accounting for 25% of the NRMM diesel (gas oil) consumption in the UK.

2. Variable speed engines are used in most types of equipment, including agricultural tractors, excavators, etc, where engine speed varies according to the task being undertaken.

The distinction between these two engine types is important because the emission standards that machinery is required to comply with differs between constant speed and variable speed machinery. In order to identify the vehicles and machinery dealt with, it is helpful to know the types of vehicles and machinery used in addition to engine types used by the machinery.

In agriculture and forestry:

1. Two-wheel tractors: very small single-axle/two-wheel tractors with few kW power output (about 5 to 15 kW) and equipped with two-stroke or four-stroke petrol or diesel engines.

2. Agricultural tractors: two-axle/four-wheel tractors (there are also some articulated wheel and crawler-type tractors which fall under this category) are nearly all exclusively diesel- engine powered with power output of 20-250 kW. The main power range used for agricultural purposes is 100-130kW, and where a second tractor is used to accompany this, it is typically smaller, having a power output of 20-60kW. In forestry, the same tractors are used as in agriculture, having a power range of about 60-120kW. In general, over the last 30 years there has been a clear trend towards the use of higher power outputs and towards four-wheel-drive tractors. Larger four- and six-cylinder diesel engines are equipped with turbo chargers. However, for selected agricultural activities, small tractors are still used (e.g. for vineyards), with typical power outputs of 30-50kW.

3. Harvesters/combiners: used mainly for harvesting grain (chaff, beet, etc.), and are all diesel engines equipped. Older machinery has a power output between 50 and 150kW, but more modern units are typically larger, with power output up to 500 kW.

4. Sprayers, manure distributors, mowers, balers and tillers: they mainly use diesel engines, but two- and four-stroke gasoline engines are also used in these machines. The power output is in the range of 5-50kW.

5. Professional chainsaws/clearing saws: all are two-stroke petrol-engine driven with a power output of about 2-6 kW.

6. Forest tractors/harvesters/skidders: vehicles (e.g. wheel forwarder, crawler forwarder, grapple skidder, cable skidder, etc.) used for general transport and harvesting work in forests. They are all diesel-engine equipment with a power output of about 25-75kW.

7. Tree processors, haulers, fellers, forestry cultivators, shredders and log cultivators: they are mainly diesel-engine equipment; some use two-stroke engines.


Household and gardening:

1. Trimmers/strimmers/edgers/brush cutters: mainly equipped with two-stroke petrol engines with power output of about 0.25-1.4 kW.

2. Lawn mowers: either two-stroke or four-stroke petrol-engine powered, having a power output of 0.5-5kW. Ride-on mowers in the domestic sector are mainly one-or two-cylinder diesel engines and four-stroke petrol engines. Mowers for professional use are typically diesel or four-stroke petrol-engine powered. Ride-on mowers have a power output of about 5-15kW, with displacements between 100-250ccm.

3. Hobby chain saws: do-it-yourself motor saws are mainly equipped with two-stroke petrol engines (care must be taken not to include those with electric motors). Small (hobby) motor saws have a power output of about 1-2kW (professionally used motor saws of about 2-6kW).

4. Snowmobiles/skidoos: generally equipped with two- and four-stroke gasoline engines with a power output of 10-50kW. There has been a trend towards more powerful machines across the last two decades.

5. Lawn and garden tractors, wood splitters, snow blowers, tillers, and similar gardening machinery is included under this category.

6. Non-road vehicles like all-terrain vehicles such as quads, off-road motorcycles, golf carts, etc.

Emissions originate from the combustion of fuel in diesel compression ignition or petrol spark ignition engines to power the machinery considered. $NO_x$, PM, CO, NMVOCs, $SO_2$ and $CO_2$ are all important species emitted from the fuel combustion, the latter two typically being estimated directly from the fuel use.

The emission characteristics of diesel and petrol engines are different. When compared to petrol engines (fuel rich), diesel engines (fuel lean) produce more PM and $NO_x$, and less CO and NMVOCs. The emissions also differ between two-stroke and four-stroke gasoline engines, and the age of the equipment.

All source sectors considered in this chapter can make significant contributions to total emissions of $NO_x$, $PM_{10}$ or NMVOC. Contributions from a single source sector range from 0.1-11% of total emissions but are typically less than 5% of the total. The following sectors/sub-sectors seem of greatest importance for the different pollutants:

1. for $NO_x$: agriculture and construction (part of "industry")
2. for PM: agriculture and construction (part of "industry")
3. for NMVOC: lawn and garden (part of "household and gardening")
4. for CO: light commercial (part of "industry") and lawn and garden (part of "household and gardening")

When comparing emissions of $PM_{10}$ to those of the more physiologically toxic $PM_{2.5}$, whilst the general patterns of importance remain, the significance of $PM_{2.5}$ from off-road machinery to total emissions is higher than for $PM_{10}$. This is because internal combustion engines produce PM with a much smaller mean size than, for example, many industrial processes.

Detailed methods and data needed to estimate NRMM emissions are available in the EMEP/EEA air pollutant emission inventory guidebook (NFR Sectors 1.A.2.gvii, 1.A.4.a.ii, 1.A.4.b ii, 1.A.4.c ii, 1.A.4.c iii, and 1.A.5.b).

### 2.1.1.6.2 Stationary sources

Small combustion installations included in stationary sources are mainly intended for heating and provision of hot water in residential and commercial/institutional sectors. Secondary activities extend to the use of appliances within residential and commercial sectors for cooking.
In the agricultural sector the heat generated by combustion installations is also used for drying crops and heating greenhouses.

Relevant pollutants are $SO_2$, $NO_x$, CO, NMVOCs, PM, BC, HMs, PAHs, PCDD/Fs and HCB. For solid fuels, generally the emissions due to incomplete combustion are many times greater in small appliances than in bigger plants. This is particularly valid for manually fed appliances and poorly controlled automatic installations. For both gaseous and liquid fuels, the emissions of pollutants are not significantly higher in comparison to industrial scale boilers due to the quality of fuels and design of burners and boilers, except for gaseous and liquid fueled fireplaces and stoves because of their simple combustion process.

Residential heating:

Small combustion appliances are used to provide thermal energy for heating and cooking in residential buildings. A wide variety of fuels are used and several combustion technologies are applied. In the residential activity, smaller combustion appliances, especially older single household installations are of very simple design, while some modern installations of all capacities are significantly improved. Emissions strongly depend on the fuel, combustion technologies as well as on operational practices and maintenance. For the combustion of liquid and gaseous fuels, the technologies used are similar to those for the production of thermal energy in larger combustion activities, with the exception of the simple design of smaller appliances like fireplaces and stoves. The technologies for solid fuel and biomass utilization vary widely due to different fuel properties and technical possibilities. Small combustion installations employ mainly fixed-bed combustion technology (i.e. grate-firing combustion of solid fuels). Solid fuels include mineral and biomass solid fuels, with fuel size varying from a few to 300 mm. It can be helpful to consider residential combustion equipment in terms of appliances (manufactured products) and more basic equipment such as "traditional" solid fuel fireplaces.

1. Basic equipment like traditional solid fuel fireplaces, chimeneas, barbecues: such equipment is distinguished by being "open" and consequently have no or very limited air controls. In addition, due to relatively low replacement rates (of buildings and equipment), solid fuel open fireplaces can be a significant part of residential heating stock. Although there may be oil and gas fired devices for which a "basic equipment" label might be applicable, it is considered more appropriate to treat these as appliances. Open fireplaces have significant emissions of PM, CO, NMVOC and PAH resulting from the incomplete combustion of fuels. Fuels for solid fuel open fireplaces include wood (logs), coal, anthracite and manufactured solid fuels. Chimeneas and barbecues (outdoor appliances) burn wood and charcoal solid fuels. They are little different from an open fire in operation.

2. Appliances: these include room heaters (stoves, inset appliances and slow heat release stoves), cookers, central heating boilers and water heaters with a wide range of performance and emission characteristics depending on fuel, age, technology and mode of use. At one extreme, older stoves and open inset appliances may have very limited controls and provide only modest improvements in efficiency and emission performance compared to basic equipment. However, modern wood log stoves and automatic appliances provide better management of the combustion process with improvement in emissions and efficiency. Similarly, modern gas and oil-fired appliances offer improved combustion management and associated emission benefits.

Nonresidential heating:

This subsection covers a broad range of combustion technologies and abatement technologies (in particular for solid fuels) with wide ranges in associated emission. It includes boilers with indicative nominal capacity up to 50MWth used for heating in multi-dwelling residential buildings, office, school, hospital and apartment blocks and are commonly found small sources in commercial and institutional sector as well as in agriculture; nonresidential cooking using solid fuel or gas-fired units in hotels, commercial restaurants and non-commercial sectors (for example schools and hospitals); Indoor and outdoor heating; "Micro" Gas turbines providing small scale generation (typically 15-500 kWe) and gas turbine technology in the <1MWth size range;

Reciprocating engines such as island generators (away from a supply grid), small combined heat and power units, or for cogeneration and standby or emergency uses. Detailed methods and data needed to estimate small combustion emissions is available under EMEP/EEA air pollutant emission inventory guidebook NFR Sectors 1.A.4.a.i, 1.A.4.b.i, 1.A.4.c.i, and 1.A.5.a.

## 2.1.2    Fugitive emissions from fuels

Fugitive emissions from fuels covers all non-combustion activities related to the extraction, processing, storage, distribution and use of fossil fuels. During all the stages from the extraction of fossil fuels to their final use, the escape or release of gaseous fuels or volatile components of liquid fuels may occur. Fugitive emissions from refining, transport and distribution of oil products are a major component of national $CH_4$ and NMVOC emissions in many countries. This sub-sector includes fugitive emissions of $CH_4$, $CO_2$ and NMVOC from crude oil exploration, production and transport, oil refining, the distribution and handling of gasoline (including emissions from service stations) and the production and distribution of natural gas (including venting). It also includes $CH_4$ emissions from underground and surface coal mining, during both mining and post-mining activities. In addition to NMVOC, $CH_4$ and $CO_2$, this subsector also includes fugitive emissions $SO_2$, $NO_x$ and CO from oil refining, emissions of BC and OC from flaring during oil and gas extraction, and emissions of $SO_2$, $NO_x$, CO, $NH_3$, $PM_{10}$, $PM_{2.5}$, BC and OC from the production of coke.

### 2.1.2.1    Exploration, production and transport of liquid and gaseous fossil fuels

This section includes fugitive emissions from the exploration, production and transport of liquid and gaseous fossil fuels. It includes the emissions from onshore as well as offshore activities. The contribution of these activities to the total national emissions varies considerably, but in countries where oil is extracted, they are invariably an important contributor to the national total of NMVOC, as well as for methane ($CH_4$). While in the Middle East, the highest contribution of both oil and natural gas production to the total emissions of NMVOC is found, equal to 53%. Oil and natural gas are produced by the same geological process: anaerobic decay of organic matter deep under the Earth's surface. As a consequence, oil and natural gas are often found together.

In common usage, deposits rich in oil are known as oil fields, and deposits rich in natural gas are called natural gas fields. Oil and gas are found both onshore and offshore and can be used in a variety of processes, including heating of buildings, and in processes such as feedstock in chemical processes. Natural gas is increasingly being used as a fuel for power generation.

Gas is received in the gas terminal facility by pipelines and conditioned for export to the national or international distribution network. This conditioning includes separation, $CO_2$ and $H_2S$ removal, $H_2S$ incineration, pressure relief and blowdown systems. While the transfer of oil occurs from storage tanks or directly from the well into a ship or another container specifically for transport away from the production site. This activity also includes losses during transport. Also, during the oil loading, combustion emissions occur from the oil pump, particularly when pumps are fueled by oil (as in the case of ships pumping oil at maritime terminals). Oil and gas is commonly transported from oil and gas facilities to terminals by pipelines.

These may cross national boundaries. Regarding drilling of wells, it involves the use of specially formulated drilling mud which may contain organic solvents. When the drilling breaks through small oil/gas reservoirs, this may result in the release of emissions.

The emissions from combined oil and gas facilities may be categorized as direct venting of gas into the atmosphere, fugitive losses and evaporation from contaminated wastewater. Venting, which is a direct release of gas from the various processes, is usually related to pressure relief and blowdown systems to ensure safe operations. The operations which result in direct venting also include stripping gas from glycol regeneration, water treatment, relieved gas in seal oil systems, equipment depressurization and other activities leading to venting. Venting emissions may be reduced by flaring (incinerating) the gas. This is desired from an environmental point of view as $CH_4$ is a more potent greenhouse gas per molecule than $CO_2$. Installation of recovery systems for atmospheric vents is also a possibility. The recovered gas may be exported, used on platforms or re-injected. Nitrogen may be used as purge gas instead of hydrocarbons.

Crude oil stabilization involves the removal of the most volatile components of the crude oil. Stabilization of crude oil occurs either on offshore platforms, or less usually, at terminals. Although the process has the potential to cause emissions of VOC, sources claim that emissions are in fact small since the volatiles are generally either used as fuel or are sent to flare rather than being vented directly to the atmosphere. Fugitive emissions arise from several sources, in particular gas leakage through compressor seals, valves and flanges. These emissions may be reduced by implementing procedures for detecting leaks from the process systems, minimizing leaks and spills through equipment changes, procedure changes, improved monitoring, housekeeping, and maintenance practices. For the waste water, it is separated from the oil/gas mixture and first cleaned before disposal. The cleaned water inevitably contains some organic compounds which may evaporate later. The organic compounds removed during cleaning may also evaporate.

1. In facilities producing gas only, which are designed to sell the gas produced; there is less direct venting and flaring of gas. These facilities also produce less waste water.

2. In facilities producing oil only, all gas produced will be flared, vented, used as fuels or re-injected into the reservoirs. Generally, at oil-only facilities the crude oil/gas mixture reaching the surface will contain less gas than the mixture at combined or gas facilities. In general, the $CH_4$ content of vented gas is less than that found in gas-producing facilities.

For crude oil transportation, it is transported from production operations to a refinery by tankers, barges, rail tank cars, tank trucks, and pipelines. When oil is loaded, hydrocarbon vapor will be displaced by oil and new vapor will be formed, both leading to emissions. The mass emitted will depend on:

1. the movement of the vessel—the greater the movement, the greater the emissions;
2. the vapor pressure of the crude;
3. temperature of the crude—temperature should be as low as possible;
4. loading rate into each tank—the greater the loading rate, the lower the emissions;
5. method of loading—splash, submerged, or bottom loading;
6. geometry of the tanks—the higher the surface area to volume, the higher the emissions;
7. tank atmosphere;
8. crude oil washing procedures.

Although unloading in itself is a minor source compared to loading, procedures for unloading may influence the emissions while loading. Recovery systems will be available in the near future that will reduce the NMVOC emissions from offshore loading by about 70%. Technologies to reduce emissions from onshore loading are available. The efficiency is about 85% ($CH_4$ emissions will not be reduced considerably).

Ballasting of marine vessels is another potential source of emissions. Ballasting losses are a major source of emissions from unloading at marine terminals. Ballasting does not occur with all vessels as many (and the new vessels) have segregated tanks where ballasting is not necessary and is even not in use in some countries (e.g. Norway).

Ballasting is the partial loading of cargo tanks after cargo is unloaded to improve stability of the vessel. Cargo tanks are typically ballasted to about 80% of their capacity, resulting in 15 to 40% of the vessel capacity. Emissions occur when the vapors present are displaced by the ballast water. The ballast water is then pumped out prior to loading, thereby reducing the subsequent loading emissions. Emissions may be reduced by containing the vapors through displacing the ballasting vapors into a cargo tank that is simultaneously being unloaded (US Environmental Protection Agency (US EPA, 1996).

Emissions in pipelines may originate from connection points, valves and damaged sections. They may be controlled by inspection procedures followed by repair and upgrading. And emission sources during drilling are penetration of shallow gas pockets, migration of reservoir fluid through the circulated drilling fluid, gas migration through poor casing and cement work, the use of oil or solvent-based drilling mud, and the wash of oil-contaminated cuttings. The main control options are gas removal during drilling and recovery of hydrocarbons from oil-based mud and cuttings.

For natural gas, typically 85–90% of the emissions consist of $CH_4$. Only small amounts of NMVOC are released; and it is estimated that up to 20 % of the gas escaping from leaky pipelines and mains is oxidized in the soil by micro - organisms. However, since it is not possible to measure how much of the gas gets oxidized in this way, it is recommended that this phenomenon is ignored in the estimation of emissions. End-of-pipe techniques are inapplicable because the emissions cannot be collected together in a pipe or duct; instead they arise from a geographically diverse array of small sources emitting directly to the atmosphere. Consequently, the only way is to reduce emissions is by: the use of better materials for pipes, joints and seals; the quicker detection and rectification of leaks; improved maintenance; measures to collect gas purged during commissioning, decommissioning and other maintenance activities.

Detailed methods and data needed to estimate exploration, production and transport of liquid and gaseous fossil fuels emissions is available under EMEP/EEA air pollutant emission inventory guidebook NFR Sectors 1.B.2.a.i and 1.B.2.b

### 2.1.2.2   Oil refining and storage

This section covers emissions from the petroleum refining industry.

This industry converts crude oil into more than 2500 refined products, including liquid fuels (from motor gasoline to residual oil), by-product fuels and feedstock (such as asphalt, lubricants, gases, coke), and primary petrochemicals (for instance, ethylene, toluene, xylene).

Petroleum refinery activities start with the receipt of crude for storage at the refinery, include all petroleum handling and refining operations, and terminate with storage preparatory to shipping the refined products from the refinery.

Mainly, petroleum refineries are sources of $SO_2$ and NMVOC emissions, and less significant sources of particulates, $NO_x$ and CO. Emissions arise as a result of evaporation from storage tanks and the displacement of vapor during filling.

The petroleum refinery industry employs a wide variety of processes. The types of processes operating at one facility depend on a variety of economic and logistic considerations such as the quality of the crude oil feedstock, the accessibility and cost of crude (and alternative feedstock), the availability and cost of equipment and utilities, and refined product demand.

Four main categories can be distinguished within the processes in a petroleum refinery:

1.  Separation processes: of crude oil into common boiling point fractions using three petroleum separation processes: atmospheric distillation, vacuum distillation, and light ends recovery (gas processing).

2.  Conversion processes: Where there is a high demand for high-octane gasoline, jet fuel and diesel fuel, components such as residual oils, fuel oils, and light ends are converted to gasoline and other light fractions.

3.  Treating processes: Petroleum-treating processes stabilize and upgrade petroleum products by de-salting, hydrodesulfurization, hydro treating, chemical sweetening and acid gas removal, and de-asphalting

4.  Blending: Streams from various units are combined to produce gasoline, kerosene, gas oil and residual oil, and in some cases a few specialty items.

Emissions from petroleum products processing, vacuum distillation, catalytic cracking, thermal cracking, sweetening, blowdown systems, sulfur recovery, asphalt blowing and flaring processes have been identified as being potentially significant sources of $SO_2$ and NMVOC from petroleum products processing, with a relatively smaller contribution of particulate, $NO_x$ and CO.

Storage and handling of petroleum products takes place in fixed roof tanks - used for the storage of products such as kerosene, gasoil and fuel oil, and external floating roof, internal floating roof, and variable vapor space tanks used to store crude oils and volatile products.

For all tanks, the total emission of NMVOC is the result of two types of losses. The first type of loss is the breathing or standing loss, which for fixed roof tanks is the release of vapors in the tank due to changes in meteorological conditions such as temperature and pressure, without any appreciable change in the liquid level of the tank. For floating roof tanks, the standing losses are due to vapor leakage past seals, roof fittings, etc. The majority of emissions from floating roof tanks are due to standing losses.

The second type of loss is the working (including withdrawal) loss. For fixed roof tanks this results from the displacement of vapors during filling and the evaporation of product left on the tank shell during emptying. For floating roof tanks, the working loss is only due to the evaporation of product left on the tank shell when the roof level drops as product is removed from the tank. All intermediates and final products should be stored in the appropriate container: pressure vessels for gases, floating roof tanks for volatile liquids, fixed roof tanks for kerosene, distillate, fuel oil and other non-volatile liquids

Detailed methods and data needed to estimate oil refining and storage emissions is available under EMEP/EEA air pollutant emission inventory guidebook NFR Sector 1.B.2.a.iv.

### 2.1.2.3  Distribution of oil products
This source category covers gasoline and other fuel distribution starting from the refinery dispatch station or the border terminal dispatch station from where it is loaded into rail cars, barges, coastal tankers, pipelines for delivery to marketing terminals or depots or into road tankers (tank trucks) for delivery to service stations or small marketing depots. Also covered are emissions from marketing terminals or depots (or directly from border terminals) automotive fuels, e.g. gasoil and gasoline, into tank trucks for delivery to service stations where they are transferred into underground storage tanks and subsequently dispensed into automobile fuel tanks.

Emissions from this source category have historically contributed significantly to the total anthropogenic NMVOC emissions. Plus due to the volatility of gasoline, the majority of NMVOC emissions in the distribution of oil products occur during its storage and handling.

Detailed methods and data needed to estimate distribution of oil products emissions is available under EMEP/EEA air pollutant emission inventory guidebook NFR Sector 1.B.2.a.v.

### 2.1.2.4  Venting and flaring
Flaring is basically combustion of gas, but without utilization of the energy that is released. Included are flaring during extraction and first treatment of both gaseous and liquid fossil fuels and flaring in oil refineries; in addition to emissions from incineration after a well testing. Flaring emissions from the extraction of gas and oil are an important source of emissions for countries that produce oil and gas. Pollutants emitted are $NO_x$ and NMVOC, but also $SO_x$, CO, HM, PM including BC may be emitted.

In gas and oil extraction gas is flared on oil-and gas- production installations for safety. The main reasons are lack of process or transport capacity for gas, a continuous surplus gas flow, start up, maintenance and emergency (need for pressure relief). The gas is led through a pipeline to a flare tip located high above and away from the platform. Well testing is performed as a part of the exploration activity. After a discovery, the well is tested to check the production capacity and the composition of the reservoir fluid. Due to lack of treatment, storage and transport facilities, the oil or gas extracted may be disposed of by burning.

In oil refining blowdown systems are used to collect and separate both liquid and vapor discharges from various refinery process units and equipment. The gaseous fraction, that may represent a planned or unplanned hydrocarbon discharge, may be either recycled or flared.

Flaring provides a widely used safety mechanism and emission control option for blowdown systems when the heating value of the emission stream cannot be recovered due to uncertain or intermittent releases during process upsets/emergencies. Non-condensed vapors from the blowdown system may be combusted in a flare which is designed to handle large fluctuations of both the flow rate and hydrocarbon content of the discharge. Alternatively, thermal oxidizers are used for destroying gas streams that contain more corrosive halogenated or sulfur-bearing components. There are different types of flares (steam-assisted elevated flare systems, ground-level enclosed flares (oxidizers))

Detailed methods and data needed to estimate venting and flaring emissions is available under EMEP/EEA air pollutant emission inventory guidebook NFR Sector 1.B.2.c.

### 2.1.2.5   Fugitive emissions from coal mining and handling
This section covers emissions from mining and handling of coal. Peat and other solid fuels, and the subsequent treatment of coal, such as fuel conversion, coking, gasification and liquefaction are excluded. Coalfields contain a proportion of highly volatile material which is released during the working, extraction and storage of coal. The volatile material is known as firedamp, made up primarily of $CH_4$, although other compounds are also present in minor amounts. The release of firedamp often results in an emission to air as it is not always economical to contain the gas due to the high dilution that renders it unusable as fuel or for combustion purposes.

The extraction and treatment of coal result mainly in emissions of $CH_4$. However, NMVOC, PM and $CO_2$ are not covered in this manual.

Detailed methods and data needed to estimate fugitive emissions from coal mining and handling is available under EMEP/EEA air pollutant emission
inventory guidebook NFR **Sector 1.B.1.a.**

### 2.1.2.6   Fugitive emissions from solid fuel transformation
Coke is a fuel produced by heating coal to high temperatures. The fuel product (coke) has few impurities and is often used in iron smelting and steel production. Coke production in general can be divided into coal handling and storage, coke oven charging, coal coking, extinction of coke and coke oven- gas purification.

In a coke oven, coke and coke by-products (including coke oven gas) are produced by the pyrolysis (heating in the absence of air) of suitable grades of coal. The process also includes the processing of coke oven gas to remove tar, $NH_3$ (usually recovered as ammonium sulfate), phenol, naphthalene, light oil, and sulfur before being used as a fuel for heating the ovens. For coke production, hard coal first should be crushed, mixed and sieved. The emissions related to coke production can be attributed to four sub-processes:

1. coal handling and storage: emitting coal dust;
2. coke production and extinction: emitting coal and coke dust and coke oven gas;
3. coke oven gas handling and purification: emitting benzene, toluene, xylene, phenol, PAH (polycyclic aromatic hydrocarbons), $H_2S$, hydrogen cyanide (HCN) and $NH_3$;
4. combustion of coke oven gas: emitting hydrocarbons, $SO_2$, $NO_x$, CO, $CO_2$, hydrogen fluoride (HF), and soot.

Coke ovens are a major source of fugitive emissions. The coking process emits $SO_x$, $NO_x$, $CH_4$, $CO_2$, CO, $NH_3$, PM, and HMs. In general, emissions of $N_2O$ are not relevant. Coke ovens are also an important source of PAH emissions.

Besides these compounds, the following by-products are also components of the coke oven gas produced: tar, phenol, benzene, pyridine, $NH_3$, $H_2S$, HCN and carbon bisulfide. The by-product recovery section of a coking plant (e.g. $NH_3$ processing, tar processing) may release significant amounts of NMVOC, $CH_4$, $NH_3$ and PM.

Detailed methods and data needed to estimate fugitive emissions from solid fuel transformation is available under EMEP/EEA air pollutant emission inventory guidebook NFR Sector 1.B.1.b.

## 2.2   Industrial processes and product use

This section refers to air pollutant emissions produced as a by-product of various non-energy-related industrial activities. That is, these emissions are produced from an industrial process itself and are not directly a result of energy consumed during the process. For example, raw materials can be chemically transformed from one state to another.

### 2.2.1   Mineral products

**2.2.1.1   Cement production**
Cement manufacture is a major mineral commodity industry. During the manufacturing process, natural raw materials are finely ground and then transformed into cement clinker in a kiln system at high temperatures. The clinkers are cooled and ground together with additions into a fine powder known as cement. Cement is a hydraulic binder, i.e. it hardens when mixed with water. Cement is used to bind sand and gravel together in concrete. Portland cement is a hydraulic cement which is cement that not only hardens by reacting with water but also forms a water-resistant product.

PM from cement plants mainly originates from pre-and after-treatment. The main emissions from the production of cement are emissions to air from the kiln system. Releases come from the physical and chemical reactions of the raw materials and the fuels. Emissions from the kiln are a combination of combustion and process emissions but the emissions of the main pollutants $NO_x$, $SO_x$, CO, NMVOC, and $NH_3$—as well as HM and POPs are assumed to originate mainly from the combustion of the fuel.

Detailed methods and data needed to estimate emissions from cement production are available in the EMEP/EEA air pollutant emission inventory guidebook (NFR Sector 2.A.1).

**2.2.1.2   Lime production**
Lime (CaO) is the high-temperature product of the calcination of limestone. The production occurs in vertical and rotary kilns fired by coal, oil or natural gas. Two major types of processes can be considered within the lime works operations: quarrying, crushing, and size grading of minerals; and combustion of fuels in lime kilns.

Atmospheric emissions in the lime manufacturing industry include particulate emissions from the mining, handling, crushing, screening and calcining of the limestone and emissions of air pollutants generated during fuel combustion in kilns. These emissions are not very significant on a global or even regional scale. However, lime works can be an important emission source of air pollutants on a local scale. The production of lime causes emissions from both processes and combustion. Pollutants released are $SO_x$, $NO_x$, NMVOC, $CH_4$, CO, $CO_2$, $N_2O$ and PM.

Detailed methods and data needed to estimate emissions from lime production are available in the EMEP/EEA air pollutant emission inventory guidebook (NFR Sector 2.A.2).

### 2.2.1.3 Construction and demolition

The construction of infrastructure and buildings constitutes an important source of fugitive PM emissions. Frequently, elevated ambient $PM_{10}$ concentrations are observed at and around construction works. A significant proportion of construction activities takes place in urban and other densely populated areas. Consequently, a large number of people may be exposed to PM emitted from construction activities. Besides being a source of fugitive PM emission, construction activities may emit other pollutants as well. This mostly concerns combustion products such as $NO_x$, soot and $CO_2$, and fugitive NMVOC emissions resulting from the use of products.

In construction there are many possible activities that result in air emissions.
For instance, the following activities, typical in construction, are relevant sources of fugitive PM:

1.  Land clearing and demolition
2.  Earth-moving and cut-and-fill operations
3.  Equipment movements
4.  Mobile debris-crushing equipment
5.  Vehicular transport (loading, unloading and hauling of materials, track out of dirt on paved roads and subsequent dust resuspension)
6.  Further site-preparation activities
7.  Specific building activities such as concrete, mortar and plaster mixing, drilling, milling, cutting, grinding, sanding, welding and sandblasting
8.  Various finishing activities
9.  Windblown dust from temporary unpaved roads and bare construction sites

Fugitive PM emissions are largely of mineral composition and mechanical origin, with soil dust typically comprising a significant part. The resuspension of soil dust by hauling traffic is an important contributor according to literature, but since resuspension by road transport as a whole may also be estimated elsewhere, there is a danger of double counting of emissions.
For many activities that result in fugitive dust emissions, the dust emission is strongly dependent on the material or soil moisture content because moisture tends to prompt particles to clog together, preventing them from becoming airborne.

Detailed methods and data needed to estimate emissions from construction and demolition are available in the EMEP/EEA air pollutant emission inventory guidebook (NFR Sector 2.A.5.b).

## 2.2.2  Chemical industry

The chemical industry is for most pollutants only a minor source of emissions. Although the products from the chemical industry can be very different, all processes in the chemical industry consist basically of a series of comparable unit operations. They are usually also highly integrated and linked. In chemical engineering and related fields, a unit operation is a basic step in a process. For example, in $NH_3$ production the gasification, reforming and the $NH_3$ synthesis are each unit operations that are connected to create the overall process.

The main air pollutants from chemical processing are $SO_2$, $SO_3$, $H_2S$, carbon disulfide ($CS_2$), $NO_x$, $N_2O$, $NH_3$, HCN, chlorine gas ($Cl_2$), bromine gas ($Br_2$), HF, hydrogen chloride (HCl), hydrogen bromide (HBr), and VOC. Detailed methods and data needed to estimate emissions from the chemical industry are available in the EMEP/EEA air pollutant emission inventory guidebook (NFR Sector 2.B.1 for $NH_3$ production, 2.B.2 for nitric acid production, 2.B.3 for adipic acid production, 2.B.5 for carbide production, 2.B.10.a for other chemical industry, and 2.B.10.b for storage, handling, transport of chemical products).

## 2.2.3  Metals production

The metals sector consists of metal production facilities that smelt, refine, and/or cast ferrous and nonferrous metals, including primary aluminum, ferroalloy, iron and steel, lead, magnesium, and zinc, from ore, pig, or scrap using electrometallurgical and other methods. The sector also includes foundries and any other metal production facilities.

Detailed methods and data needed to estimate emissions from metals production are available in the EMEP/EEA air pollutant emission inventory guidebook (NFR Sector 2.C.1 for iron and steel production, 2.C.2 for ferroalloys production, 2.C.3 for aluminium production, 2.C.4 for magnesium production, 2.C.5 for lead production, 2.C.6 for zinc production, 2.C.7.a for copper production, 2.C.7.b for nickel production, 2.C.7.c for other metal production, and 2.C.7.d for storage, handling and transport of metal products.

## 2.2.4   Solvent and product use

**2.2.4.1   Asphalt roofing production**
The industry manufactures saturated felt, roofing and siding shingles, and roll roofing and sidings. Most of these products are used in roofing and other building applications. This source category covers emissions of NMVOC, CO and particulate material from all related facilities, with the exception of asphalt blowing. Detailed methods and data needed to estimate emissions from asphalt roofing production is available in the EMEP/EEA air pollutant emission inventory guidebook (NFR Sector 2.D.3.c).

**2.2.4.2   Road paving with asphalt**
Asphalt, commonly referred to as bitumen, asphalt cement, asphalt concrete, or road oil is mainly produced in petroleum refineries. In some countries the laid mixed product is also referred to as "asphalt," in others it is known as "macadam." Asphalt surfaces and pavements are composed of compacted aggregate and an asphalt binder. This section covers emissions from asphalt paving operations as well as subsequent releases from the paved surfaces.

Asphalt is a source of VOC. When coal tar is used in the process, PAHs are emitted, though this technique has been largely discontinued.

Detailed methods and data needed to estimate emissions from road paving with asphalt are available in the EMEP/EEA air pollutant emission inventory guidebook (NFR Sector 2.D.3.b).

**2.2.4.3   Other solvent and product use**
In some countries, the use of solvents and other products containing light hydrocarbon compounds can be a major source of emissions to the atmosphere of NMVOCs. The general approach to estimating emissions is to find out the extent of the relevant activity – for example, the tonnage of solvent-based paint used in a particular application – and multiply this by an emission factor (for example, kg of NMVOCs per ton of paint used). Emissions from solvent use may alternatively be estimated using mass balances. This is more accurate, but also more data intensive as it requires information about detailed consumption of pure solvents, solvent containing products and their solvent content.

Detailed methods and data needed to estimate emissions from other solvent and product use are available in the EMEP/EEA air pollutant emission inventory guidebook (NFR Sector 2.D.3.i and 2.G).

### 2.2.5   Other industrial production

**2.2.5.1   Pulp and paper industries**
Pulp and paper production consist of three major processing steps: pulping, bleaching, and paper production. The type of pulping and the amount of bleaching used depends on the nature of the feedstock and the desired qualities of the end product. Below is a discussion of three different chemical pulping processes:

1. Kraft (sulfate) pulping: the most widely used pulping process and typically used to produce strong paper products. It includes wood (or other cellulose- bearing materials) digestion in a water solution of sodium sulfite and sodium hydroxide, pulp washing, bleaching, chemical recovery and by-product recovery.

2. Sulfite pulping (acid sulfite process) involves chemically pulping the wood using $SO_2$ adsorbed in a base solution. Sulfite pulping produces a weaker paper than some other types of pulping, but the pulp is less colored making it more suitable for printing, often with little bleaching.

3. Neutral sulfite semi-chemical pulping (NSSC): one of the chemical pulping processes that can be used; involves partial delignification of wood feedstock using a buffered sodium sulfite solution, with completion of the pulping process by mechanical means. NSSC pulps are used in corrugating media and in certain writing and printing papers.

4. Main emissions from paper and pulp production include dioxins, NMVOC, $SO_x$, particulates, $NO_x$ and CO.

Detailed methods and data needed to estimate emissions from pulp and paper industries are available in the EMEP/EEA air pollutant emission inventory guidebook (NFR Sector 2.H.1).

**2.2.5.2   Food industry**
Emissions from food manufacturing include all processes in the food production chain which occur after the slaughtering of animals and the harvesting of crops. Food manufacturing may involve the heating of fats and oils and foodstuffs containing them, the baking of cereals, flour and beans, fermentation in the making of bread, the cooking of vegetables and meats, and the drying of residues. These processes may occur in sources varying in size from domestic households to manufacturing plants. Food processing may occur in open vessels without forced ventilation, closed vessels with periodic purge ventilation or vessels with continuous controlled discharge to the atmosphere. In the larger plants, the discharges may be extremely odorous and consequently emission may be controlled using end-of-pipe abatement.

Detailed methods and data needed to estimate emissions from food industries are available in the EMEP/EEA air pollutant emission inventory guidebook (NFR Sector 2.H.2).

## 2.3   Agriculture

Several types of agricultural activity emit air pollutants, including: livestock enteric fermentation (a source $CH_4$ emissions), livestock manure management ($NH_3$ and $CH_4$), animal housing ($PM_{10}$ and $PM_{2.5}$), application of nitrogen-containing fertilizers ($NO_x$ and $NH_3$), and savanna burning and burning of agricultural crop residues ($NO_x$, $SO_x$, $NH_3$, CO, $CH_4$, NMVOC and PM).
Most of the emission factors for this source sector are Tier 1 factors.

### 2.3.1   Manure management

There are five main sources of emissions related to livestock husbandry and manure management: livestock feeding (a source of PM); manure generated in livestock housing and on open yard areas ($NH_3$, PM, NMVOCs); manure storage ($NH_3$, NO, NMVOCs); field-applied manure ($NH_3$, NO, NMVOCs); and excreta deposited during grazing ($NH_3$, NO, NMVOCs).

$NH_3$ is emitted if excreta or manure are exposed to the atmosphere, namely in livestock housing, from manure stores, after manure application to fields and from excreta deposited by grazing animals. NO is formed initially through nitrification and subsequently also by denitrification in the surface layers of stored manure or in manure aerated to reduce odour or to promote composting. In addition to manure management, silage stores are a major source of NMVOC emissions. PM emissions originate mainly from feed, which accounts for 80-90% of total PM emissions from the agriculture sector.

Detailed methods and data needed to estimate emissions from manure management are available in the EMEP/EEA air pollutant emission inventory guidebook (NFR Sectors 3.B.1.a, 3.B.1.b, 3.B.2, 3.B.3, 3.B.4.a, 3.B.4.d, 3.B.4.e, 3.B.4.f, 3.B.4.g.i, 3.B.4.g.ii, 3.B.4.g.iii, 3.B.4.g.iv and 3.B.4.h).

### 2.3.2   Crop production and agricultural soils

There are four main sources of emissions from crop production and agricultural soils: mineral N fertilizer, livestock manure, and organic waste application ($NH_3$); soil microbial processes (NO); crop processes ($NH_3$ and NMVOCs); and soil cultivation and crop harvesting (PM).

Detailed methods and data needed to estimate emissions from crop production and agricultural soils are available in the EMEP/EEA air pollutant emission inventory guidebook (NFR Sectors 3.D.a.1, 3.D.a.2.a, 3.D.a.2.b, 3.D.a.2.c, 3.D.a.3, 3.D.a.4, 3.D.b, 3.D.c, 3.D.d and 3.D.e).

## 2.4 Waste

Methods for treating and disposing of wastes include incineration/burning, landfills and aerobic and/or anaerobic treatment of municipal sewage.

### 2.4.1 Waste incineration

Waste incineration is defined as the combustion of solid and liquid waste in controlled incineration facilities. Modern refuse combustors have tall stacks and specially designed combustion chambers, which provide high combustion temperatures, long residence times, and efficient waste agitation while introducing air for more complete combustion. Types of waste incinerated include municipal solid waste (MSW), industrial waste, hazardous waste, clinical waste and sewage sludge. The practice of MSW incineration is currently more common in developed countries, while it is common for both developed and developing countries to incinerate clinical waste.

It is important to note that in cases where energy is recovered from the waste combustion either for heating or electricity generation, it is good practice to report the emissions in the relevant combustion sector described in Section 2.1.1 (NFR section 1.A). If no energy recovery is applied, it is good practice to report the emissions in the waste incineration sector.

#### 2.4.1.1 Municipal waste incineration

Principally, this section includes the emissions from chimneys and ductwork with no heat recovery. The emissions of compounds such as VOCs, $SO_2$, HCl and PM from waste incineration are unlikely to contribute significantly to total emissions. However, waste incinerators have been a major source of emissions of PCDD/Fs, other POPs and some HM such as cadmium (Cd) and mercury (Hg). Pollutants released are $SO_x$, $NO_x$, NMVOCs, CO and $NH_3$. MSW incinerators in many countries now apply extensive abatement techniques and comply with emission limits, and in these cases the contribution of MSW incinerators to total emissions of PCDD/Fs HM has greatly decreased.

Detailed methods and data needed to estimate emissions from municipal waste incineration are available in the EMEP/EEA air pollutant emission inventory guidebook (NFR Sector 5.C.1.a).

#### 2.4.1.2 Industrial waste incineration

The composition of industrial waste varies considerably. Principally, this section covers the emissions from chimneys and ductwork. Industrial waste includes any unwanted hazardous/chemical waste such as acids and alkalis, halogenated and other potentially toxic compounds, fuels, oils and greases, used filter materials, animal and food wastes. Industrial waste sources include chemical plants, refineries, light and heavy manufacturing, etc. Most waste incinerators are small hazardous/chemical waste incinerators constructed on-site, intended for the industries' own use. In general, industrial waste incinerators are unlikely to be a significant source of emissions, because the waste treated often has a high toxicity and efficient abatement is required to meet emission standards.

The relative proportion of emissions contributed by industrial waste incineration is likely to vary between pollutants. Emissions of $CO_2$, VOCs, HCl and PM from industrial waste incinerators are likely to be less significant than from other sources. However, industrial waste incinerators are likely to be more significant emitters of dioxins, Cd and Hg than many other sources. This depends on the type of waste, the combustion efficiency and the degree of abatement. There are many different furnace designs in use at industrial waste incinerators. A range of grate designs and fluidized beds are used, but the exact furnace design depends on the type of waste burned, its composition and the throughput of waste. The principal influences of the incinerator type on the level of atmospheric emissions are the waste burning capacity of the incinerator, the operational techniques and the degree of abatement included in the process design. Small industrial waste incinerators with a restricted waste supply are often operated as batch processes. This increases the frequency of startup and burn-out emissions, which are often significant.

Detailed methods and data needed to estimate emissions from industrial waste incineration are available in the EMEP/EEA air pollutant emission inventory guidebook (NFR Sector 5.C.1.b.i, 5.C.1.b.ii, and 5.C.1.b.iv).

### 2.4.1.3   Clinical waste incineration

Hospital waste may be identified as "specific hospital waste" and "other hospital waste." Specific hospital waste includes human anatomic remains and organ parts, waste contaminated with bacteria, viruses and fungi, and larger quantities of blood. Incineration of hospital wastes has been banned in some European countries. In countries where the process is allowed, for the most part incinerators are currently small facilities located on-site at hospitals. However, there is generally a move towards larger, centralized facilities.

This section includes the volume reduction, by combustion, of hospital wastes. Principally, this section covers the emissions from chimneys and ductwork. In some cases, hospital waste is combusted in municipal waste incinerators, or in "hazardous waste incinerators" along with hazardous/chemical wastes from industrial processes.

The relative proportion of emissions contributed by hospital waste incineration varies between pollutants. The process is likely to be a source of some POPs, such as PCDD/Fs, HCBs, PAHs and some HM such as Cd, Hg, etc. Emissions of compounds such as VOCs, $SO_2$, $NO_x$ and PM from hospital waste incineration are unlikely to contribute significantly to total emissions.

Detailed methods and data needed to estimate emissions from clinical waste incineration are available in the EMEP/EEA air pollutant emission inventory guidebook (NFR Sector 5.C.1.b.iii).

### 2.4.1.4   Open burning of (agricultural) waste

This section covers the volume reduction, by open burning, of small-scale (agricultural) waste. It does not include stubble burning, forest fire, or burning of rubber tyres or waste oil on farms. Examples of agricultural wastes that might be burned are crop residues (e.g. cereal crops, peas, beans, soya, sugar beet, oil seed rape, etc.), wood, pruning, slash, leaves, plastics and other general wastes. Straw and wood are often used as fuel for the open burning of agricultural wastes. Poultry and animal excreta are difficult to burn except under controlled conditions.

One of the main concerns regarding agricultural waste combustion is the emission of smoke/particulates. Toxic organic micropollutants, such as PAHs and dioxins are likely to be present in the emissions. In many cases the combustion will be slow and inefficient, and therefore emissions of CO and VOCs will be more significant than emissions of $NO_x$. The burning of plastics is likely to produce particularly toxic emissions, such as dioxins, other chlorinated organic compounds and cyanides.

The emissions arising from open burning depend on a number of factors.
The most important variables are the type of waste burned and the moisture content of the waste. The ambient temperature and wind conditions, and the density/compactness of the pile of waste also affect the combustion conditions and hence the emissions. The open burning of agricultural waste is carried out on the ground, in air curtain incinerators, in pits in the ground, or in open drums or wire mesh containers/baskets.

Detailed methods and data needed to estimate emissions from open burning of waste are available in the EMEP/EEA air pollutant emission inventory guidebook (NFR Sector 5.C.2).

## 2.4.2   Disposal of wastes in landfills

MSW landfills, or sanitary landfills, are sites where MSW is managed to prevent or minimize health, safety, and environmental impacts. Waste is deposited in different cells and covered daily with soil; many have environmental monitoring systems to track performance, collect leachate, and collect landfill gas. Industrial waste landfills are constructed in a similar way as MSW landfills, but accept waste produced by industrial activity, such as factories, mills, and mines. After being placed in a landfill, organic waste (such as paper, food scraps, and yard trimmings) is initially decomposed by aerobic bacteria. After the oxygen has been depleted, the remaining waste is available for consumption by anaerobic bacteria, which break down organic matter into substances such as cellulose, amino acids, and sugars.

These substances are further broken down through fermentation into gases and short-chain organic compounds that form the substrates for the growth of methanogenic bacteria.
These $CH_4$ producing anaerobic bacteria convert the fermentation products into stabile organic materials and biogas consisting of approximately 50% biogenic $CO_2$ and 50% $CH_4$, by volume.

Landfill biogas also contains trace amounts of NMVOC and VOC that either result from decomposition by-products or volatilization of biodegradable wastes. $CH_4$ and $CO_2$ are the primary constituents of landfill gas generation and emissions. Additionally, emissions of NMVOC and VOC are not estimated because they are considered to be emitted in trace amounts.

$N_2O$ emissions from the disposal and application of sewage sludge on landfills are also not explicitly modeled as part of greenhouse gas emissions from landfills. $N_2O$ emissions from sewage sludge applied to landfills as a daily cover or for disposal are expected to be relatively small. Therefore, only $CH_4$ generation and emissions are estimated for landfills under the waste sector.

$CH_4$ generation and emissions from landfills are a function of several factors, including: **(1)** the total amount of waste-in-place, which is the total waste landfilled annually over the operational lifetime of a landfill; **(2)** the characteristics of the landfill receiving waste (e.g., composition of waste-in-place, size, climate, cover material); **(3)** the amount of $CH_4$ that is recovered and either flared or used for energy purposes; and **(4)** the amount of $CH_4$ oxidized as the landfill gas passes through the cover material into the atmosphere.

Each landfill has unique characteristics, but all managed landfills have similar operating practices, including the application of a daily and intermediate cover material over the waste being disposed of in the landfill to prevent odor and reduce risks to public health. Based on recent literature, the specific type of cover material used can affect the rate of oxidation of landfill gas. The most used cover materials are soil, clay, and sand. Some states also permit the use of green waste, tarps, waste-derived materials, sewage sludge or biosolids, and contaminated soil as a daily cover. $CH_4$ production typically begins one or two years after waste is disposed of in a landfill and will continue for 10 to 60 years or longer as the degradable waste decomposes over time.

Detailed methods and data needed to estimate emissions from disposal of wastes in landfills are available in the EMEP/EEA air pollutant emission inventory guidebook (NFR Sector 5.A).

### 2.4.3   Wastewater handling

In most cases, wastewater handling will be an insignificant source for air pollutants. However, in urban areas, NMVOC emissions from wastewater treatment plants will be of local importance. Activities considered within this sector are biological treatment plants and latrines (storage tanks of human excreta, located under naturally ventilated wooden shelters). Biological treatment plants are only of minor importance for emissions into air, and the most important of these emissions are greenhouse gases ($CO_2$, $CH_4$ and $N_2O$). Air pollutants include NMVOC and $NH_3$; however, their contribution to total emissions is only minor and of local importance. Latrines are generally only a minor source of emissions (mainly $NH_3$) from a free evaporation process. $NH_3$ emission from latrines depends on the quantity and form of nitrogen compounds in human excreta, as well as on weather conditions.

Wastewater treatment processes can produce anthropogenic $CH_4$ and $N_2O$ emissions. Wastewater from domestic and industrial sources is treated to remove soluble organic matter, suspended solids, pathogenic organisms, and chemical contaminants. Treatment may either occur on site, most commonly through septic systems or package plants, or off site at centralized treatment systems. Centralized wastewater treatment systems may include a variety of processes, ranging from lagooning to advanced tertiary treatment technology for removing nutrients.

Soluble organic matter is generally removed using biological processes in which microorganisms consume the organic matter for maintenance and growth. The resulting biomass (sludge) is removed from the effluent prior to discharge to the receiving stream. Microorganisms can biodegrade soluble organic material in wastewater under aerobic or anaerobic conditions, where the latter condition produces $CH_4$.

During collection and treatment, wastewater may be accidentally or deliberately managed under anaerobic conditions. In addition, the sludge may be further biodegraded under aerobic or anaerobic conditions. The generation of $N_2O$ may also result from the treatment of domestic wastewater during both nitrification and denitrification of the N present, usually in the form of urea, $NH_3$, and proteins. These compounds are converted to nitrate ($NO_3$) through the aerobic process of nitrification. Denitrification occurs under anoxic conditions (without free oxygen) and involves the biological conversion of nitrate into $N_2$ gas. $N_2O$ can be an intermediate product of both processes but has typically been associated with denitrification. Recent research suggests that higher emissions of $N_2O$ may in fact originate from nitrification. The principal factor in determining the $CH_4$ generation potential of wastewater is the amount of degradable organic material in the wastewater.

In general, air emissions of POPs as well as NMVOC, CO and $NH_3$ occur from wastewater treatment plants, but are mostly insignificant for national total emissions. However, NMVOC emissions from wastewater treatment plants to air may in some cases be significant in urban areas and may even contribute significantly at a national level. Emissions from biological treatment plants are mainly greenhouse gases: $CO_2$, $CH_4$ and $N_2O$. Small quantities of $NH_3$ and NMVOC are emitted as well. Emissions from latrines are mainly $NH_3$ and also small quantities of $CH_4$.

Detailed methods and data needed to estimate emissions from wastewater handling are available in the EMEP/EEA air pollutant emission inventory guidebook (NFR Sector 5.D).

# O3

## 3. From emissions inventory to air quality assessment and forecasting

Air quality assessment entails inferring the air quality at times and locations where observations are insufficient or lacking. In many cases, the assessment is about predicting the spatial distribution of pollutants averaged over time periods on a monthly, seasonal or an annual basis. In these studies, maps of pollutant concentrations enable the identification of hot zones, and when coupled with population patterns, provide valuable insights about exposure. In addition, some of the modelling tools described below allow for exploring "what-if" scenarios, thus providing an effective framework for mitigation, informing policy makers, and planning.

An especially important form of air quality assessment is air quality forecasting, which entails prediction of future air quality, starting with a set of initial conditions. An accurate and reliable air quality forecast is a key component of air quality management system that **(i)** provides effective health alerts to the vulnerable population, **(ii)** supplements traditional emission control programs, **(iii)** empowers operational planning, and **(iv)** enables more effective emergency response. Example of governments control measures include limiting traffic circulation and temporarily shutting down factories and plants. Improving air quality forecasting also involves prediction over a longer period of time, which allows for better preparation for extreme events.

This chapter is intended to provide a basic understanding of pollution dispersion assessment and forecasting tools to help countries make informed choices as to which air quality assessment tool is most suitable to answer a given question. After introducing the concepts of air quality assessment and forecasting, the importance of air quality measurements is discussed.

This is followed by the presentation of the different types of data, including on emissions, required by air quality modelling tools. Then, different approaches to air quality forecasting are then presented, followed by the showcasing of two methods for assessment and forecasting: land use regression (LUR), and physically-based numerical dispersion. LUR is a widely used statistical method that correlates observations with land use data to infer the spatial distribution of the pollutant concentration. The physically-based numerical dispersion method is the tool of choice for predicting the spatio-temporal concentration distribution when emissions, geometrical, and meteorological data are available.

A more detailed and encompassing exposition of air quality assessment and forecasting approaches and the associated modelling tools is presented in a separate guidebook,[2] where the different methods are compared in terms of their applicability, data requirements, spatio-temporal resolution, and computational cost.

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[2] Air Quality Modelling and Forecasting Guidebook for the States of the Gulf Cooperation Council.

## 3.1   Air quality measurements

Availability of periodic air quality measurements that are adequately spaced is key to improving the accuracy of air quality assessment and forecasts. Air quality measurements refer mainly to ground or near-ground observations of ambient concentrations of pollutants. Air quality measurements also improve the ability of modelling tools to identify pollutant sources (where and when), quantify the contribution of different source types (e.g. traffic, industry), explore what-if scenarios, assess mitigation strategies and plan for the future, and uncover the dominant patterns and the underlying dynamics. Measurements over long periods of time are necessary for climate forecasts such as predictions of the ozone layer thickness and spread, and of temperature and sea level rise.

## 3.2    Data requirements for air quality assessment and forecasting

Air quality assessment involves spatio-temporal modelling of the dispersion of pollutants. These advanced computer models predict the distribution of pollutant concentrations in space and time. The choice of modelling approach and the types of data required are strongly dependent on the desired spatial and temporal resolutions. The data can be arranged in the following categories: **(a)** meteorological, **(b)** emissions, **(c)** geometric (buildings), **(d)** geographic, **(e)** observations (e.g. air quality measurements), and **(f)** land use.

Air quality assessment requires meteorological data. The starting point of any air quality forecasting is a meteorological forecast. The weather forecast predicts the time-dependent thermophysical properties of air that drive and characterize the local transport of pollutants. Thus, the accuracy of the air quality forecast depends, in part, on the reliability of the weather forecast. To produce the most accurate weather forecast possible, the output of several forecasting models is typically combined with local experience and knowledge. The most accurate air quality forecast possible is therefore one that follows a similar approach.

The emission inventory, which is the main subject of this guidebook, is widely used as an input to air quality models. This is especially true for physical models that model the dispersion of the pollutants originating from the emission sources. In these models, the emission inventory is incorporated through specifying the locations of the emission sources and their emission rate as a function of time. Emission sources include residential buildings, industrial buildings, power plants and generators, traffic, agriculture and forest fires. Depending on the scale of the study and the intended spatial resolution, the emission sources can be represented individually (if the study domain is a street canyon) or as area or line sources (if the study domain is a country or larger). Air quality assessment based on statistical modelling tools, such as LUR models, typically employs distances from emission sources or zones of high emissions such as highways or industrial plants.

Air quality assessment and forecasting models also take as input the digitized representation of topography (terrain) in addition to other obstacles such as buildings. The resolution of these representations has to be compatible with the length scale resolved by the model. This length scale is determined, to a large degree, by the domain size.

Air quality ground monitors provide direct measurements of pollutant concentrations at ground level. Ground measurements are commonly taken on a daily or, preferably, on an hourly basis. The spatial distribution of the monitoring stations is key when used by a modelling tool to improve air quality assessment. Pollutants can also be measured using satellites, aircraft and balloons. Other aspects include supporting and training local scientists in data collection, including meta data such as sensor height above the ground, and distance from buildings, roads, and emission sources. To enable regional solutions to be possible, the data has to be shared among the stakeholders.

Some statistical methods such as LUR require land use data. Land use data describe the use of land for various human activities including industrial, agricultural, residential, recreational and other activities.

## 3.3    Modelling tools for air quality assessment and forecasting

Modelling tools may be categorized based on the length and time scales they resolve. An example of the different meteorological forecasting tools used to resolve different length scales is shown in **Figure 1**.
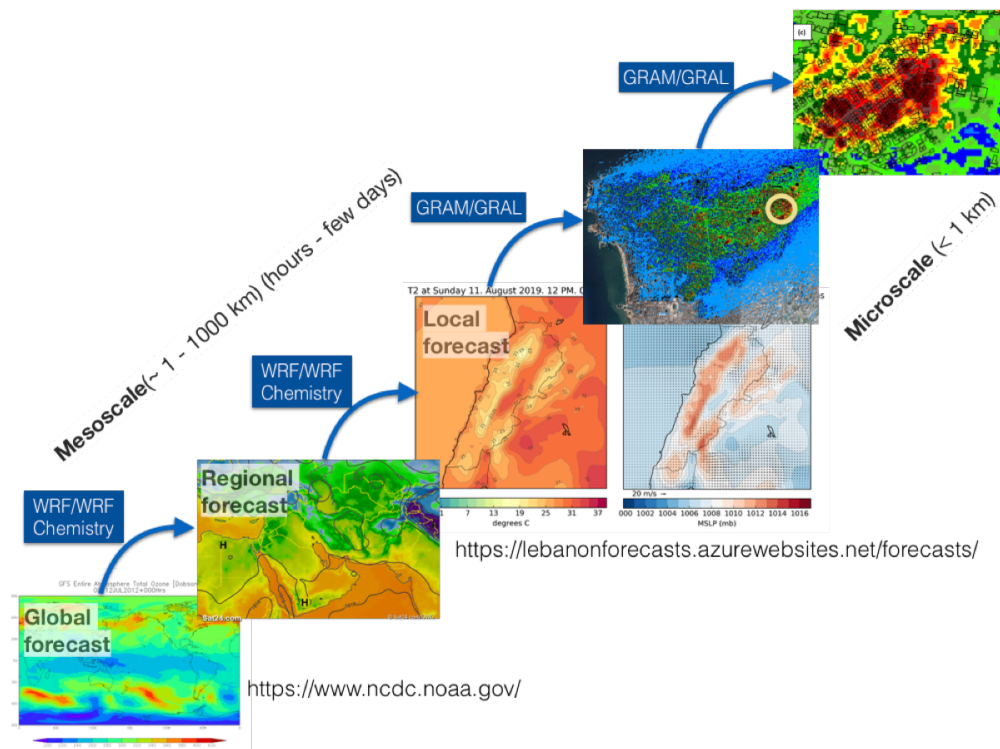


**Figure 1** *Example of different tools used to resolve different length scales.*

A global forecast, such the Global Forecast System (GFS) produced by the National Centers for Environmental Prediction (NCEP), provides weather forecasts for up to 16 days into the future at a resolution of 28-70 km. Regional and local operational forecasting down to the ~ 1 km scale is carried out using tools such as the Weather Research and Forecasting (WRF) model.[3]  These tools incorporate the GFS forecasts and numerically model transport based on the governing physical laws, while allowing assimilation of data from observations.

Different techniques of varying complexity have been used for weather and air quality forecasting. Air quality forecasting methods fall into two broad categories: deterministic and probabilistic. While a deterministic forecast predicts a specific event, such as a storm, that will take place at a specific time and location, a probabilistic forecast yields an ensemble of possible events each with a quantifiable likelihood (or uncertainty). Given the numerous uncertainties and in some cases the limitations in observations, probabilistic methods are increasingly used by researchers to quantify the uncertainties associated with the predictions.

These uncertainties arise from lack of full and accurate knowledge of local weather conditions, measurements (e.g. local pollution emissions and concentrations) and boundary conditions (e.g. long-range transport [4]) in addition to model parameters such as the mixing coefficient. Models for assessing and forecasting air quality can be alternatively divided into three categories: potential forecasting, physically-based numerical methods and statistical methods.

Physically-based refers to methods that numerically solve equations governing the conservation of mass and momentum. Statistical methods, on the other hand, rely on tools such as linear regression (LR), principal component analysis (PCA), statistical trend analysis, neural networks, and more recently artificial neural networks and deep learning. Physically-based numerical models can be deterministic in the sense that they yield a fixed output for a given input, or stochastic in the sense that they yield a probabilistic ensemble of solutions which arise from uncertainty in model parameters.

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[3] https://www.mmm.ucar.edu/weather-research-and-forecasting-model
[4] Concentrations and emissions at distant sources and their transport: advection, mixing, and chemistry.

## 3.4  Forecasting methods

As mentioned earlier, air quality forecasting is a type of assessment that predicts future air quality, starting with a set of initial conditions. Three categories of air quality forecasting approaches are presented briefly below.

### 3.4.1  Potential forecasting

Potential forecasting is a qualitative method that relies on meteorological conditions such as atmospheric dilution and ventilation capacity to issue a warning when these conditions are expected to be similar to those associated with serious pollution (Tong and Wan, 2001).

Increasing the reliability of these forecasts involves collecting data on pollution levels for different meteorological conditions over many years. The potential forecasting method is a good predictor when weather patterns are similar to those of previous years.

If the patterns are different, for example due to global warming, the accuracy of the forecast will suffer. Predicting air quality using this method is based on associating elevated pollution levels with specific meteorological conditions. This requires employing sophisticated weather typing schemes for identifying recurrent weather patterns accompanying high pollution levels. Potential forecasting has the advantage of being relatively simple and cost-effective. Since it does not rely on pollution measurements or emissions, the potential method has the disadvantage of being qualitative and less accurate than the quantitative methods discussed below.

### 3.4.2  Statistical methods

Statistical forecasting methods range from classical statistical methods such as LR to more recent methods of artificial intelligence (AI) and machine learning (Kaya & Gündüz Öğüdücü, 2020). These methods are capable of short and long-short (24 hrs) range prediction and enable the prediction of several pollutants from knowledge of one pollutant.

Statistical methods include linear and nonlinear supervised learning methods and are easily distinguishable from deterministic models by their randomness properties, which arise from treating the modelling and measurement errors respectively as system and observation noise obeying certain probability distributions (Sawaragi et al., 1977). Machine learning approaches from statistical models have proved their superiority to deterministic models in many air pollution studies (Kaya & Gündüz Öğüdücü, 2020). They have also been shown to be superior to traditional statistical methods such as multiple regression, autoregressive models and classification and regression trees (Yi & Prybutok, 1996; Chaloulakou et al., 2003).

The association between pollutant levels and meteorological and aerometric variables can be quantified by analyzing historical data sets using standard statistical analysis packages. Methods such as LR and PCA (Bai et al., 2018) enable estimation of the model parameters. An example of a multivariate analysis, which employs correlation analysis, PCA, and cluster analysis is presented in Núñez-Alonso et al. (2019) to interpret and model air pollution data ($PM_{10}$, $NO_x$, $O_3$) collected from 22 stations in the city of Madrid during 2010-2017. Statistical trend analyses, for instance using the Mann Knedall and Sen's slope estimator approaches, enable the prediction of pollutants (CO, $NO_2$, $SO_2$, $PM_{2.5}$ and $PM_{10}$) in Varanasi, India, when combined with the autoregressive integrated moving average model (ARIMA), as presented in Jaiswal (2018).

A real-time pollution forecast with early warning ability to predict pollutants (CO, NO, $PM_{2.5}$, $NO_2$) in three different locations in Valencia, Spain, is presented in Ochando (2015). The regression models in Ochando (2015) are trained using **(i)** meteorological features (temperature, pressure, relative humidity, wind speed, and rain), **(ii)** calendar features (year, month, day in month, day in week, and hour), **(iii)** traffic intensity features (traffic levels in surrounding stations) and **(iv)** pollution features (pollution levels in target stations 3 and 24 hours earlier). Classification and regression tree (CART) statistical models use meteorological or air quality variables that are strongly correlated with ambient pollution levels to predict future air quality based on the current air quality and the meteorological forecast. An example is presented in Yoo et al. (2018).

An example of a recent air quality forecasting model that employs deep learning in presented in Kaya & Gündüz Öğüdücü (2020). The deep flexible sequential (DFS) learning model employs a dataset that includes hourly pollution and meteorological data from four stations in Istanbul, Turkey between 2014 and 2018, in addition to traffic data. The flexibility in the model makes it applicable to time-series data. This is in contrast to traditional artificial neural network models (ANN) that do not forecast with sequential information (Kaya & Gündüz Öğüdücü, 2020).

### 3.4.3   Physically-based numerical dispersion models

These methods quantify the relationship between pollutant concentrations and emission sources, meteorological processes, and physico-chemical changes. These methods are deterministic when the model parameters are deterministic so that the output is fixed for a given fixed input.

Examples of physically-based numerical dispersion methods are shown in **Figure 1** for different scales. Another commonly used deterministic model that is widely used in Asia is the community multi-scale air quality (CMAQ) modelling system (Bai et al., 2018; Tong & Wan, 2001).

Also of note are recent efforts towards hybrid approaches that combine statistical analysis with physically-based numerical prediction. An example is the method presented in Chen et al. (2015), which was used to forecast the daily $PM_{10}$ concentrations in Beijing, China, from January 1 to December 30, 2013. Air quality data from 12 stations in Beijing for the period 2000-2011 were used in the study.

## 3.5   Assessment methods

To showcase statistical and physically-based numerical methods for air quality assessment and forecasting, we discuss below two of the most widely used air-quality assessment methods in urban environments. The LUR model for spatial assessment and the Lagrangian dispersion computational model for spatio-temporal assessment. Note that the Lagrangian model can be used for air quality forecasting.

### 3.5.1   Land Use Regression models

LUR is a widely used method to estimate individual exposure to ambient air pollution in epidemiological studies. LUR has been successfully applied to model annual mean concentrations of $NO_2$, $NO_x$, $PM_{2.5}$, black carbon, the soot content of $PM_{2.5}$ and VOCs in different settings. The performance of the method in urban areas is typically better or equivalent to geo-statistical methods (such as kriging) and dispersion models. LUR combines monitoring of air pollution and development of stochastic models using GIS-based predictor variables. A schematic is shown in **Figure 2**. Monitoring campaigns are typically conducted spatially at about 20-100 locations spread over the study area, and temporally via 1-4 surveys of 1-2 weeks duration.

The GIS-based predictor variables needed in the stochastic models include traffic representations, population density, land use, physical geography (e.g. altitude) and climate. A typical land use multivariate LR model starts with an initial pool of 30-80 potential predictors (variables). Reduction in the number of predictors is realized by eliminating variables that are highly correlated with other variables or due to lack of interpretability. Typically, a significantly smaller number of variables end up being used in the model.
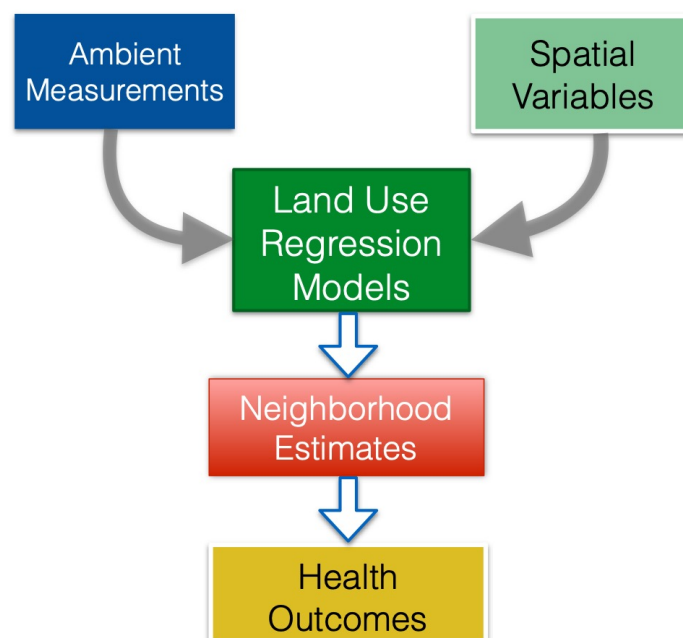


*Figure 2* LUR models use measurements to predict neighborhood estimates
by correlating with the spatial predictor variables.

Establishing a monitoring programme involves deciding whether to use routine or purposefully designed networks for the ambient measurements. While using routine (pre-existing) networks is significantly less costly, it does not offer the possibility of selecting the locations of the monitoring stations. With purposefully designed networks, the number and distribution of monitoring sites is customized for the domain of interest, in addition to temporal aspects including the number, dates, and durations of the campaigns.

**Figure 3** lists some commonly used predictor variables, which fall into the following categories: **(i)** traffic, **(ii)** population or address density, **(iii)** land use, **(iv)** altitude and topography, **(v)** meteorology, and **(vi)** location. Most of these variables are accessible within a GIS framework. Attention should be paid to the uncertainty associated with these variables arising from potential problems with geographic data sets such as accessibility, completeness and precision. It should be noted that the technology is advancing at such rate that many previously encountered issues may have been resolved.
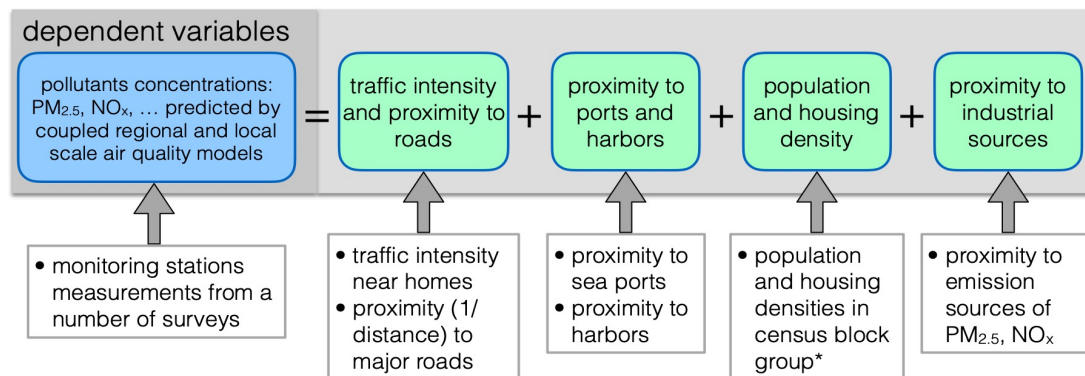


*Figure 3* In LUR models, the dependent variables (neighborhood estimates) are expressed in terms of the predictor variables, shown on the right of the equals sign.

Commonly, standard LR techniques are used to develop the prediction models. A mathematical representation is shown in **Figure 4**. The coefficient βi associated with independent variable Xi is characterized by a p-value, which measures the probability for the coefficient. The closer the p-value is to zero, the more important is the predictor variable in the LUR model. The overall model performance is quantified using the R-squared value, which measures how well, over a range 0-100, the model fits the observations. For a perfect fit, $R^2=1$.



$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \cdots + \beta_n X_n + \epsilon$$
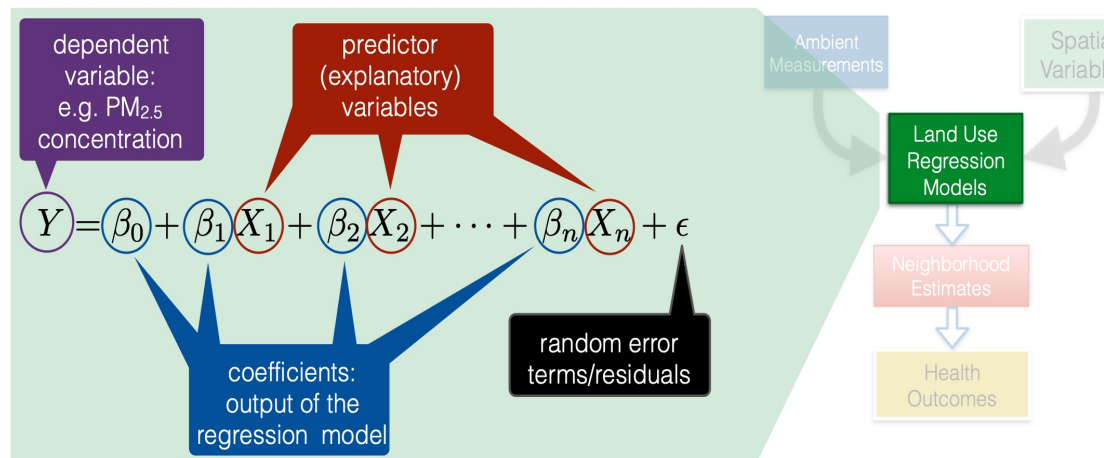
**Figure 4** *In LUR models, the dependent variables (Y) are expressed in terms of the predictor variables ($X_{i,i=1,2,..,n}$). The outputs of the regression model are the coefficients βi and information about the error ε.*

A key advantage of LUR models is that they are capable of capturing small-scale variability in community health studies. Additionally, they are less resource intensive than other methods, as land use data is widely available. LUR models still face several challenges.

They require accurate monitoring data at a large number of sites. Their lack of ability to connect specific sources of emissions to concentrations hinders their potential for developing pollution control  strategies. Their application in regions where a significant portion of the population lives in high-rise buildings may seriously misclassify exposure, especially in high-rise buildings near major roads. LUR models often employ circular buffer zones. This imposes some level of isotropy, which may not be representative. When used in health studies, LUR models are not transferable from one region to another. They also do not address multi-pollutant aspects of air pollution. They also lack the fine scale temporal resolution needed for short-term exposure studies. In addition, they estimate outdoor air pollution as opposed to indoor or personal. Current and future research efforts are focused on tackling some of these challenges, in addition to the incorporation of some meteorological conditions and emission data into the pool of predictor variables.

### 3.5.2    Lagrangian dispersion computational models

As opposed to statistical methods, dispersion models rely on physically-based spatio-temporal[5] simulation of the transport of mass, momentum, energy, and chemical species.

Transport of pollutants originating from the emission sources is carried out by numerically solving the associated transport equation, which requires knowledge of the meteorological conditions. In the absence of chemical reactions, this transport is governed by advection and diffusion (mixing). Accounting for the advection of pollutant particles requires knowledge of the local velocity, while accounting for mixing requires knowledge of the local turbulent mixing diffusivity, which in turn depends on the velocity field and other thermophysical properties.

In addition to accurate representation of the spatio-temporal meteorological variables, the locations, emissions rates, and schedules of all the emission sources must be reliably measured. **Figure 5** shows how all the components that make up a dispersion model come into play.
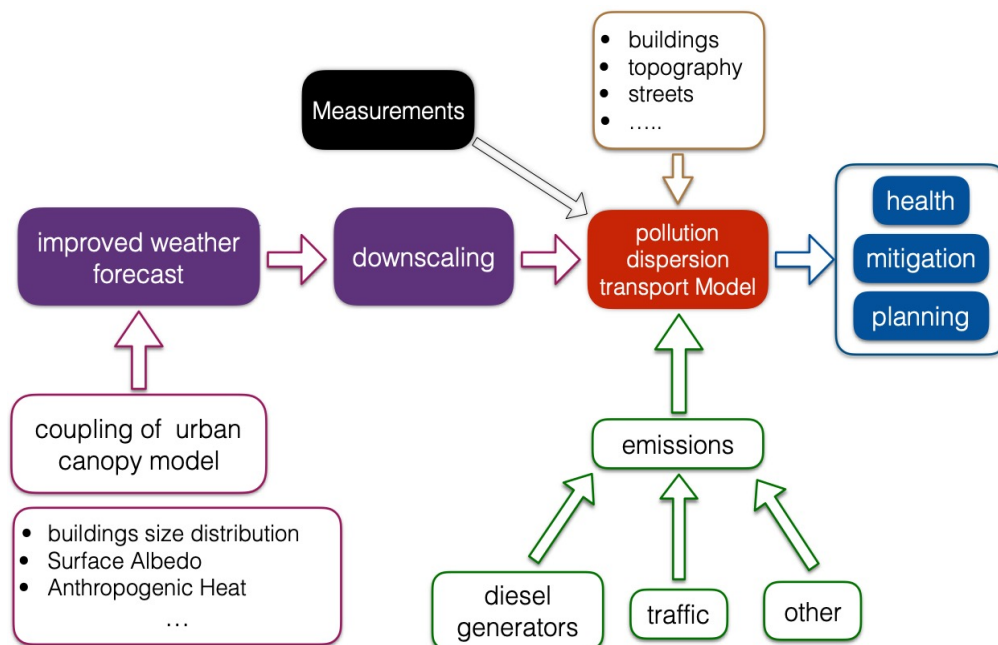


**Figure 5** *A schematic showing the components that make up a dispersion model.*

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[5] Spatio-temporal means that the variables are represented in a four-dimensional space with the axes: x, y, z, and t.

Dispersion models predict the time-varying three-dimensional spatial distribution of pollutant concentration in a user-controlled simulation environment. As such, they enable investigation of what-if scenarios and exploration of mitigation strategies. For example, all of the following questions can be answered using dispersion models: What is the exposure of all those living on the 8th floor? How will elevating all the emission stacks by 5 m impact the ground pollution levels under different weather conditions? In the next five years, when 1,000 buildings will be torn down and 1,500 erected, how can exposure be reduced? An example is shown in **Figure 6**, where the impact of extending the stack height of six diesel generators on the $NO_x$ colormaps at 30 m above ground is explored as a way to reduce residents' exposure in a neighborhood in Beirut.

Three-dimensional dispersion computational models may be either Lagrangian or Eulerian. While Eulerian models solve the transport equations on a grid, Lagrangian models follows particles in time as they are advected by the velocity field. There are numerous advantages from using Lagrangian models as opposed to Eulerian models. These advantages include not having to deal with the non-linear advection term, which is often dealt with using upwind schemes in Eulerian methods.
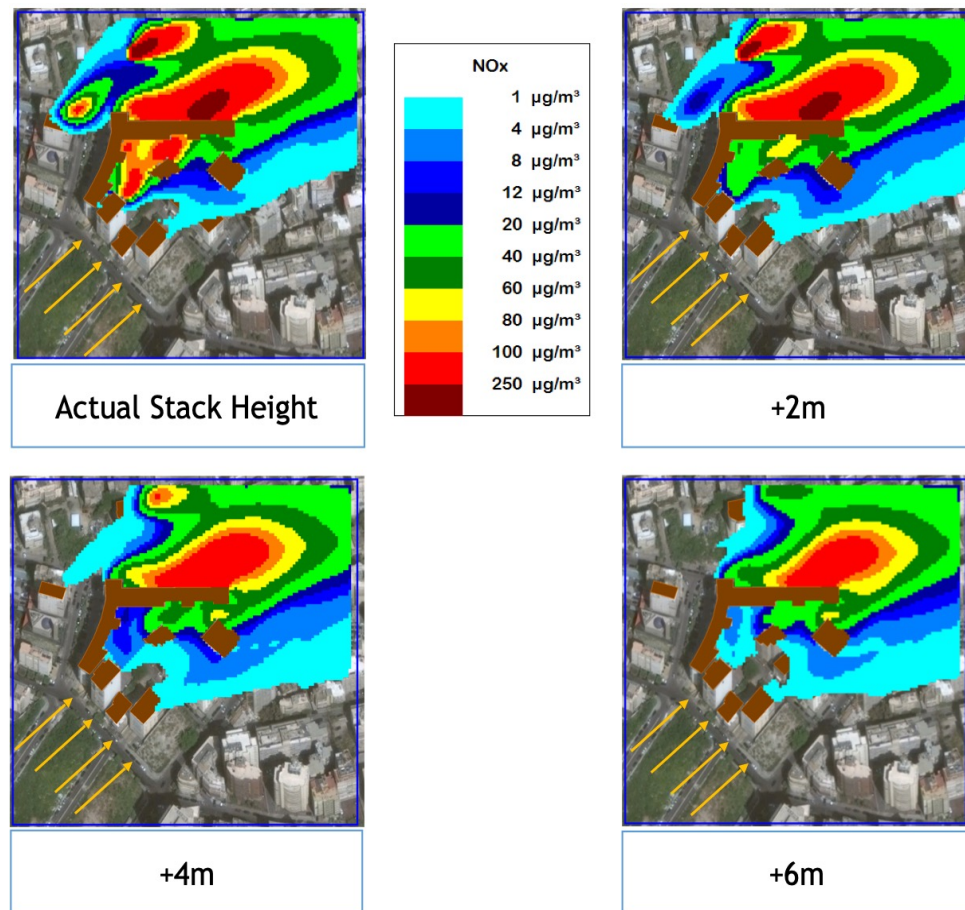


*Figure 6* Colormaps of the $NO_x$ distribution 30m above ground in a Beirut neighbourhood for different generator stack elevations.

While dispersion models have the advantages of predicting the time-varying three-dimensional distribution of pollutant concentrations and enabling exploration of what-if scenarios, they face the challenge of uncertainties that impact the accuracy of their results. These include uncertainties in **(i)** the emission sources (rates, spatial distribution, schedule), **(ii)** the downscaled fields of the thermophysical properties (velocity, temperature, etc.), and **(iii)** the mixing coefficients. These uncertainties can in some cases be reduced by assimilating observations into the dispersion model. Data assimilation and uncertainty quantification have become indispensable tools that transform dispersion modelling into a powerful predictive framework.

## 3.6   Input data requirements

The LUR method combines monitoring of air pollution with stochastic models using GIS-based predictor variables. Monitoring takes place at 20-100 locations spread over the study area and is temporally limited to 2-4 surveys of typically 1-2 weeks duration each. A list of commonly used predictor variables is presented in **Table 1**. Note that spatial predictor variables are available in GIS tools such as ARCGIS or QGIS, though these can be improved by taking measurements. Some variables may require additional effort. For traffic, for example, a challenge is the accessibility of traffic intensity data. Traffic counts are typically only available for a small number of streets, mainly for major roads and highways. In the absence of detailed data, traffic models can be used to assign traffic counts to other roads, and in some cities modeled data are available from transport and highway authorities. Alternatively, the length of specific road types can be used.

Predictor variables in LUR models are usually computed for circular zones around each monitoring site, using buffer functions in the GIS. The buffer sizes should be selected to take account of known dispersion patterns. These include impacts of major roads and inner-city area. Concentrations of traffic-related air pollutants decline exponentially with distance from the road. Beyond about 100 m from a major urban road, or 500 m from a major freeway, variability is limited. In street canyons, marked accumulation of air pollution may occur, especially against the windward side of buildings, with the result that concentrations may differ substantially from one side of the road to another. Other aspects of inner-city areas include oxygen-limited formation of $NO_2$ (from NO) in street canyons, and the drop of pollution concentration virtually to background levels behind a row of uninterrupted buildings.

The pollution dispersion transport model takes as an input the digitized representation of the buildings, topography, and streets, as seen in **Figure 7** for the case of Beirut city. It also takes as an input the emission sources data and the downscaled fields of velocity and other thermophysical properties such as temperature and density. The time-varying 3D fields of velocity and other thermophysical properties can be obtained using a weather forecast tool. For example, the WRF model can be coupled with an urban canopy model (UCM) to produce more accurate predictions in urban environments. The UCM requires an accurate description of building sizes distribution, surface albedo, and anthropogenic heat.

Modelling pollution dispersion at smaller scales (2-1000 m) requires another round of downscaling of the meteorological mesoscale conditions onto a well resolved domain. Well resolved means that the geometrical representation of the domain must accurately capture all features within the desired resolution. Thus, to model dispersion at the urban canopy scale (2-5 m), the numerical representation of the domain must accurately capture the topography and buildings to within the required resolution.

*Table 1* *Common predictor variables used in LUR methods.*

| Category | Predictor variables |
| --- | --- |
| Traffic | Traffic intensity |
| | Percentage traffic jam |
| | Number of trucks |
| | Road length |
| Land cover | Residential |
| | Non-residential |
| | Agriculture |
| | Parks |
| | Water bodies |
| | Area of open space |
| Distance to | Major roads |
| | Sea |
| | Petroleum facilities |
| | Factories |
| Population | Number of buildings |
| | Population |
| | Household density |
| Geo | Physical geography |
| | Altitude |
| Meteorological | Meteorological region |
| | Climate |
| Sampling | Sampling height |
| Emissions | Total primary emissions of pollutant |
| | Pollutant emissions from major road vehicle sources |
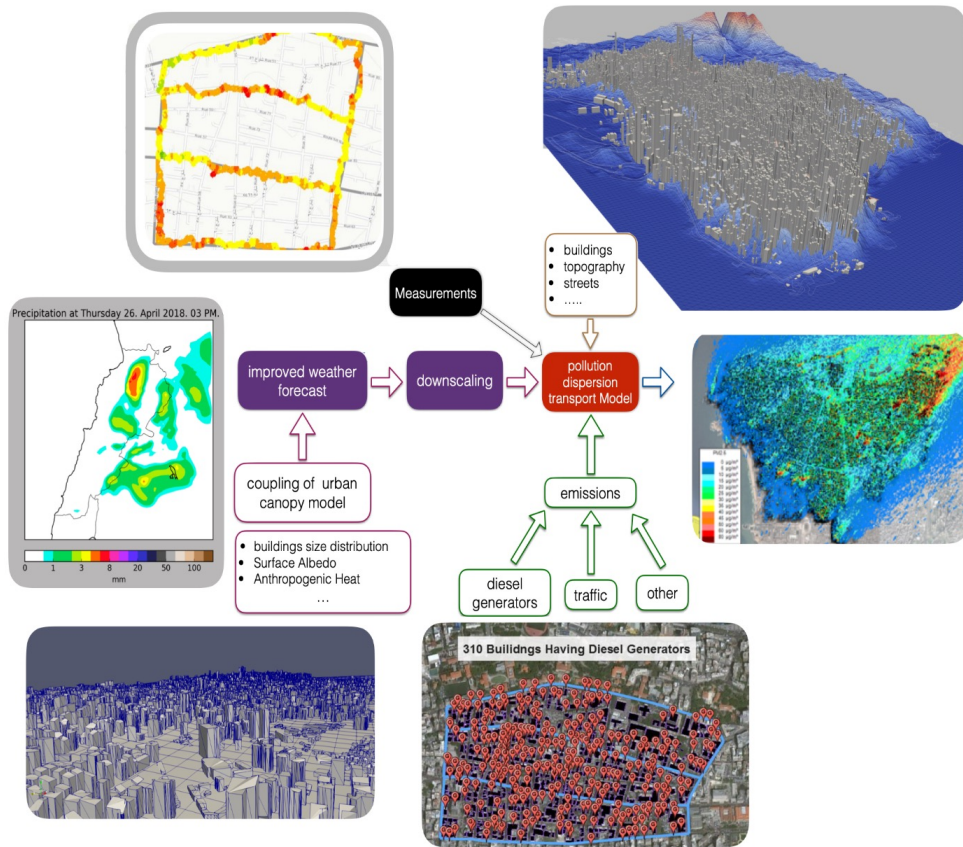
*Figure 7* *Digitized representation (not to scale) of topography, buildings, and streets in Beirut city.*

In addition to the downscaled thermophysical fields and the digitized topography, buildings and streets, an accurate emission inventory must be in place for the dispersion model to work.
It is recommenced to build the emissions inventory in a GIS environment due to the many ensuing advantages. An example is shown in **Figure 8**, which shows a sample of the data collected on diesel generators in a neighborhood in Beirut.
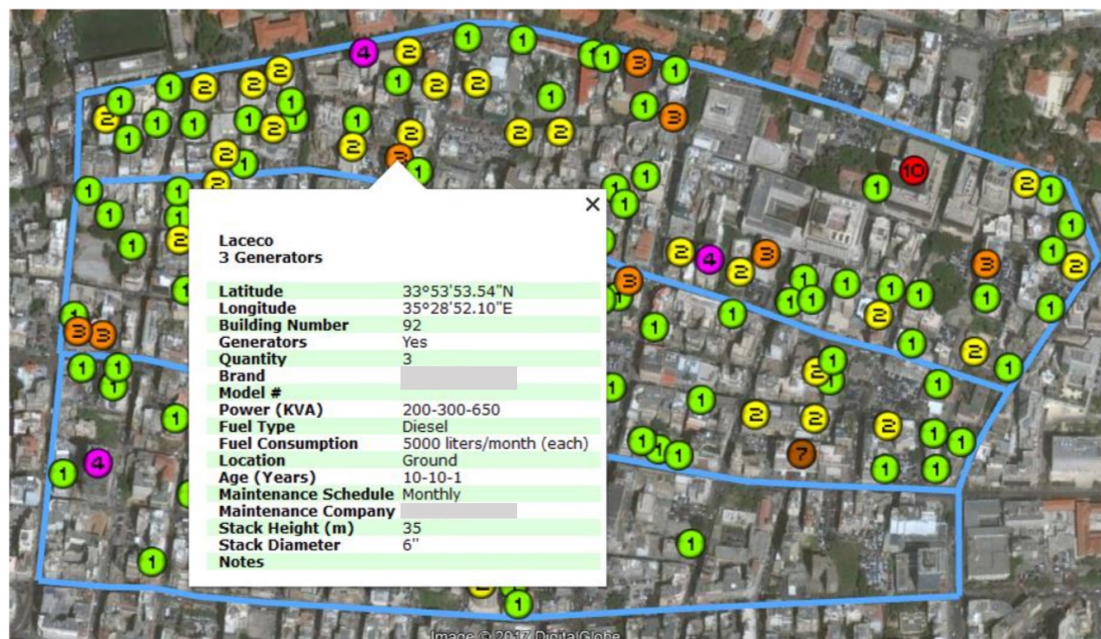
**Figure 8** *An example of an emission inventory in a GIS environment showing diesel generators in the Hamra neighbourhood of Beirut.*

In regions where access to emission inventory data is not possible, statistical methods can be used to infer emission data. These methods must however be constrained and complemented. Complementing the statistical inference of emission data by information such as land use is key to the realistic representation of the emissions. For example, any statistical inference of emissions must acknowledge the fact that there are no emissions sources in a park. Constraining inferred emissions data is also essential to ensure that key quantities such as total fuel consumption are not under- or over-estimated.

# O4

## 4. Recommendations

In the GCC region, emission estimates are either absent or only available for a few countries. This is mainly due to a lack of commitment to this important task and of the capacity to carry it out. Without detailed and reliable emission inventories, there is little opportunity to develop strategic plans for how to deal regionally, nationally, or locally with air pollution problems and to monitor the effect of such plans. Good quality emission inventories are the foundation on which optimized emission prevention and control strategies can be developed at different scales.

For example, addressing regional issues such as tropospheric $O_3$ formation and increasing atmospheric loads of PM (especially $PM_{2.5}$) requires high quality emission inventories in order to develop regionally coordinated abatement strategies. This is especially true given that the distribution of air pollutants in the region is strongly affected by seasonal sandstorms.

Hence, this manual provides guidance for the development of national emission inventories that are comparable at the regional level. It is recommended to develop emission inventories at the national and regional levels under a common framework for reporting and common reporting timeframes

1. At the national level, it is recommended to:

    1. Compile emission inventories at regular intervals including but not restricted to year-to-year variations; if countries are to report emission inventories using the tools provided in this guidance manual, countries that already have in place their own systems for collection of emissions inventories following the EMEP methodology can submit their final estimations using the EMEP coding
    2. Obtain/develop country or region-specific emission factors for key categories
    3. Use emission inventories to inform new policy and regulations and/or assess and design regulations and controls to reduce emissions
    4. Use emission inventories to monitor the effectiveness of policies and regulations
    5. Complement dispersion modelling of ambient levels of criteria pollutants based on calculated emissions with monitoring data

2. At the regional level, it is recommended to:

    1. Use this guidance as a common framework for emission inventories and establish quality assurance/quality control programmes to increase the quality of emission inventories in GCC countries
    2. Use this guidance to assess pollution transport, evaluate local contributions, and establish an airshed management system

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