Supplement of

Long-term historical trends in air pollutant emissions in Asia: Regional Emission inventory in ASia (REAS) version 3

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Supplementary information and data related to methodology of REASv3

Contents

S1. Introduction

This document provides detailed information related to methodologies of Regional Emission inventory in ASia (REAS) version 3 (hereafter REASv3 in this document) developed as a supplementary material of the main manuscript entitled “Long-term historical trends in air pollutant emissions in Asia: Regional Emission inventory in ASia (REAS) version 3”. In this document, first and second versions of REAS are often cited and expressed as REASv1 (Ohara et al., 2007) and REASv2 (Kurokawa et al., 2013), respectively. The framework of REASv3 such as target species, countries and regions, and emission sources was summarized in Sect. 2. Sects. 3, 4, 5, 6, and 7 provide details of activity data and emission factors including settings of emission controls for stationary combustion, industrial production, non-combustion sources of NMVOC, road transport, and other transport, respectively. The details related to methodology for non-combustion sources of NH_3 were given in Sect. 8. Grid allocation and monthly variation factors for spatial and temporal distribution were described in Sect. 9. In Sect. 10, details of methodology and settings for estimation of uncertainties were provided.

Note that this document is for REASv3.2 which is an updated version of REASv3.1 (Kurokawa et al., 2019). The differences between REASv3.2 and REASv3.1 and causes of the discrepancies were provided in another document entitled “Differences between REASv3.2 and REASv3.1” developed as an additional supplement of the main manuscript.

S2. Framework of REASv3

S2.1 Target species

Target species of REASv3 are summarized in Table 2.1. In REASv3, NMVOC species were divided into 19 chemical species categories as presented in Table 2.2. Codes of each species used in emission tables and gridded data of REASv3 are also provided in the tables.

Table 2.1. Target species of REASv3.

Species code	Species
SO2	Sulfur dioxide
NOX	Nitrogen oxides (as NO_2)
CO_	Carbon monoxide
NMV	Non-methane volatile organic compounds
NH3	Ammonia
CO2	Carbon dioxide
PM10_	Primary PM_{10}
PM2.5	Primary $PM_{2.5}$
BC_	Black carbon
OC_	Primary organic carbon

Table 2.2. NMVOC species categories defined in REASv3.

Species number code	NMVOC species
01	Ethane
02	Propane
03	Butanes
04	Pentanes
05	Other alkanes
06	Ethylene
07	Propene
08	Terminal alkenes
09	Internal alkenes
10	Acetylene
11	Benzene
12	Toluene
13	Xylenes

14	Other aromatics
15	Formaldehyde
16	Other aromatics
17	Ketones
18	Halocarbons
19	Others
20	Total

S2.2 Target years

Target years of REASv3 are 1950-2015 (each year). In future updated versions, the oldest target year is basically fixed, but data in later years (after 2016) are planned to be added.

S2.3 Target countries and regions

Table 2.3 provides list of countries and sub-regions included in the inventory domain of REASv3. Codes of region, countries, and sub-regions used in the main manuscript, emission tables and gridded data of REASv3 are also provided in the table.

Table 2.3. Region, country, and sub-region included in the inventory domain of REASv3 with codes used in the main manuscript and files of emission tables and gridded data provided from the REAS website (https://www.nies.go.jp/REAS/).

Region name/ Region code	Country name: Sub-region name	Country and sub-region code CCCRR CCC: Country code RR: Sub-region code
China/ CHN	China: Whole Country	CHNWC
	China: Beijing	CHNBJ
	China: Tianjin	CHNTJ
	China: Hebei	CHNHE
	China: Shanxi	CHNSX
	China: Inner Mongolia	CHNNM
	China: Liaoning	CHNLN
	China: Jilin	CHNJL
	China: Heilongjiang	CHNHL

	China: Shanghai	CHNSH
	China: Jiangsu	CHNJS
	China: Zhejiang	CHNZJ
	China: Anhui	CHNAH
	China: Fujian	CHNFJ
	China: Jiangxi	CHNJX
	China: Shandong	CHNSD
	China: Henan	CHNHA
	China: Hubei	CHNHB
	China: Hunan	CHNHN
	China: Guangdong	CHNGD
	China: Guangxi	CHNGX
	China: Hainan	CHNHI
	China: Chongqing	CHNCQ
	China: Sichuan	CHNSC
	China: Guizhou	CHNGZ
	China: Yunnan	CHNYN
	China: Tibet	CHNXZ
	China: Shaanxi	CHNSN
	China: Gansu	CHNGS
	China: Qinghai	CHNQH
	China: Ningxia	CHNNX
	China: Xinjiang	CHNXJ
	China: Hong Kong	CHNHK
	China: Macau	CHNMC
India/ IND	India: Whole Country	INDWC
	India: Andhra Pradesh	INDAP
	India: Bihar, Jharkhand	INDBJ
	India: North East (Arunachal Pradesh/Assam/Manipur/ Meghalaya/Mizoram/Nagaland/Sikkim/Tripura)	INDAN
	India: Gujarat	INDGU
	India: Haryana	INDHA
	India: Karnataka/Goa	INDKG
	India: Kerala	INDKE
	India: Madhya Pradesh/Chhattisgarh	INDMC

	India: Maharashtra	INDMA
	India: Orissa	INDOR
	India: Punjab/Chandigarh	INDPU
	India: Rajasthan	INDRA
	India: Tamil Nadu	INDTN
	India: Utter Pradesh/Uttaranchal	INDUU
	India: West Bengal	INDWB
	India: Himachal Pradesh/Jammu and Kashmir	INDHJ
	India: Delhi	INDDE
Japan/ JPN	Japan: Whole Country	JPNWC
	Japan: Hokkaido-Tohoku (Hokkaido/Aomori/Iwate/ Miyagi/Akita/Yamagata/Fukukshima)	JPNHT
	Japan: Kanto (Ibaraki/Tochigi/Gunma/Saitama/Chiba/ Tokyo/Kanagawa)	JPNKN
	Japan: Chubu (Niigata/Toyama/Ishikawa/Fukui/ Yamanashi/Nagano/Gifu/Shizuoka/Aichi)	JPNCB
	Japan: Kinki (Mie/Shiga/Kyoto/Osaka/Hyogo/Nara/ Wakayama)	JPNKK
	Japan: Chugoku-Shikoku (Tottori/Shimane/Okayama/ Hiroshima/Yamaguchi/Tokushima/Kagawa/Ehime/Kochi)	JPNCS
	Japan: Kyushu-Okinawa (Fukuoka/Saga/Nagasaki/ Kumamoto/Oita/Miyazaki/Kagoshima/Okinawa)	JPNKO
Other East Asia / OEA	Democratic People’s Republic of Korea, Whole Country	PRKWC
	Republic of Korea, Whole Country	KORWC
	Mongolia: Whole Country	MNGWC
	Taiwan: Whole Country	TWNWC
Southeast Asia/ SEA	Brunei: Whole Country	BRNWC
	Cambodia: Whole Country	KHMWC
	Indonesia: Whole Country	IDNWC
	Laos: Whole Country	LAOWC
	Malaysia: Whole Country	MYSWC
	Myanmar: Whole Country	MMRWC
	Philippines: Whole Country	PHLWC
	Singapore: Whole Country re	SGPWC
	Thailand: Whole Country	THAWC

	Vietnam: Whole Country	VNMWC
Other South Asia/ OSA	Afghanistan: Whole Country	AFGWC
	Bangladesh: Whole Country	BGDWC
	Bhutan: Whole Country	BTNWC
	Maldives: Whole Country	MDVWC
	Nepal: Whole Country	NPLWC
	Pakistan: Whole Country	PAKWC
	Sri Lanka: Whole Country	LKAWC

S2.4 Target emission sources

S2.4.1 Combustion sources

Table 2.4 provides list of sub-sector categories of combustion sources defined in REASv3. Aggregated sector categories used in the main manuscript and emission tables of REASv3 are presented as “Sector code”. IEA codes show relationships between sub-sector categories of REASv3 and the International Energy Agency (IEA) World Energy Balances (IEAWEB) (IEA, 2017). Fuel types defined in REASv3 are provided in Sect S3.1.1. See Sects. S3, S6, and S7 for details of stationary combustion, road transport, and other transport sectors, respectively.

Several emission sources related to transformation sectors except for power plants were included in Table 2.4. Sources categorized as energy sectors in IEAWEB are only considered as combustion sources. For coke ovens (not as the energy sector), emissions were estimated based on coal input for SO_2 and NO_x and coke production for CO, NMVOC, CO_2, and PM species. In REASv3, for coke ovens as energy transformation sectors, contributions from both combustion and non-combustion processes were included in the emissions. In other words, their emissions were not estimated separately. Similarly, the following sources include both combustion and non-combustion emissions which were not estimated separately:

- Charcoal production plants
- Manufacture of other solid fuels
- Gas works

In addition, CO emissions from pig iron, crude steel, and sinter production for all countries, those from brick production except for China, Japan, Republic of Korea, and Taiwan, emissions of PM species from sinter and pig iron production for China, and those from brick production for all countries estimated based on their production amounts include contributions from both combustion and non-combustion sources (not estimated separately).

Table 2.4. Sub-sector categories of combustion sources considered in REASv3 with sector codes used in the main manuscript and emission tables of REASv3 and IEA codes showing relationships between sub-sector categories of REASv3 and the IEAWEB.

Sector code	Sub-sector category	IEA code
Power Plants/ PP	Power plants (point sources/area sources)	MAINELEC/AUTOELEC/ MAINCHP/AUTOCHP/ MAINHEAT/AUTOHEAT/ THEA/TBOILER/TELE
	Power plants (energy)	EPOWERPLT
Industry/ IND	Coke ovens	TCOKEOVS
	Charcoal production plants	TCHARCOAL
	Manufacture of other solid fuels	TPATFUEL/TBKB/TNONSPEC
	Coke ovens (energy)	ECOKEOVS
	Charcoal production plants (energy)	ECHARCOAL
	Manufacture of other solid fuels (energy)	EMINES/EPATFUEL/EBKB/ ENONSPEC
	Petroleum refineries (energy)	EREFINER
	Manufacture of other liquid fuels (energy)	EOILGASEX/ECOALLIQ/EGTL
	Gas works	TGASWKS
	Gas works (energy)	EGASWKS
	Manufacture of other gaseous fuels (energy)	ELNG/EGTL
	Chemical and petrochemical industry	CHEMICAL
	Iron and steel industry	IRONSTL
	Blast furnace	TBLASTFUR
	Blast furnace (energy)	EBLASTFUR
	Non-ferrous metal industry	NONFERR
	Cement industry	NONMET
	Lime industry	
	Brick industry	
	Other non-metallic minerals industries	
	Construction industry	CONSTRUC
	Transport equipment industry	TRANSEQ
	Machinery industry	MACHINE
	Mining and quarrying industry	MINING
	Food and tobacco industry	FOODPRO

	Paper, pulp and printing industry	PAPERPRO
	Wood and wood products industry	WOODPRO
	Textile and leather industry	TEXTILES
	Other industries	INONSPEC
Road transport/ ROAD	Road transport	ROAD
Other transport/ OTRA	Rail	RAIL
	Pipeline transport	PIPLINE
	Other transport*[1]	TRNONSPE
Residential/ RESI	Residential	RESIDENT
Other domestic/ ODOM	Commercial and public services	COMMPUB
	Agriculture*[2]	AGRICULT
	Others	ONONSPEC

*[1]Aviation and navigation (both for domestic and international) are not included.

*[2]Forestry is included, but fishing is not included.

S2.4.2 Non-combustion sources: Industrial production and other transformation

Table 2.5 provides list of sub-sector categories of non-combustion sources defined in REASv3 with target species and notes for each sub-sector category. See Sect. S4 for details of industrial processes and other transformation. See Sects. S5 and S8 for industrial processes related to NMVOC and NH_3, respectively. Note that, as described in Sect S2.4.1, non-combustion emissions from coke production, those of CO from pig iron, crude steel, and sinter productions (for all countries and regions) and from brick production (except for China, Japan, Republic of Korea, and Taiwan), and those of PM species from sinter and pig iron production (for China) and from brick production (for all countries) were not estimated separately. For these sources, estimated emission in REASv3 include contributions from both combustion and non-combustion processes.

Table 2.5. Sub-sector categories of non-combustion sources from industrial production and other transformation considered in REASv3.

Sub-sector category	Target species	Notes
Pig iron production	CO, PM species	Iron and steel industry
Crude steel production	CO, NMVOC, PM species	

Sinter production	CO, PM species	
Rolled steel production	NMVOC	
Copper production	SO_2, PM species	Non-ferrous metal industry
Zinc production	SO_2, PM species	
Lead production	SO_2, PM species	
Almina production	SO_2, PM species	
Aluminium production	SO_2, PM species	
Cement production	CO_2, PM species	Non-metallic minerals industry
Lime production	CO_2, PM species	
Brick production	PM species	
Sulphuric acid production	SO_2	Inorganic chemicals industry
Carbon black production	NMVOC, PM species	
Ethylene production	NMVOC	Organic chemicals industry
Polyethylene production	NMVOC	
Styrene production	NMVOC	
Polystyrene production	NMVOC	
Polyvinylchloride production	NMVOC	
Propylene production	NMVOC	
Polypropylene production	NMVOC	
Polyvinylchloride processing	NMVOC	
Polystyrene processing	NMVOC	
Bread production	NMVOC	Other industries considered for NMVOC
Beer production	NMVOC	
Asphalt production	NMVOC	
Pulp and paper production	NMVOC	
Ammonia	NH_3	Synthetic fertilizer industry considered for NH_3
Ammonium nitrate	NH_3	
Urea	NH_3	
Coke production	CO, NMVOC, CO_2, PM species	Manufacture of solid fuels
Petroleum refineries	SO_2, NMVOC, PM species	Manufacture of liquid fuels For NMVOC, contributions were included in extraction processes. See Sect. S2.4.3.

S2.4.3 Non-combustion sources of NMVOC

Non-combustion sources for NMVOC emissions considered in REASv3 are extraction processes, solvent use, industrial processes, waste disposal and evaporative emissions from road vehicles. Sub-categories of extraction processes and solvent use are summarized in Tables 2.6 and 2.7, respectively. Definitions of the sub-sectors are the same as with those of Klimont et al. (2002a). See Table 2.5, Sects. S5.1.7 and S6.3 for industrial processes, waste disposal, and evaporative emissions from road vehicles, respectively. See Sect. S5 for details of non-combustion sources of NMVOC.

Table 2.6. Sub-sector categories of extraction processes considered in REASv3.

Sub-category
Gas production
Gas distribution
Crude oil production
Crude oil handling
Petroleum refineries[a]
Service station
Transport and depots

a. Except for NMVOC, contributions were included in industrial processes. See Sect. S2.4.2.

Table 2.7. Sub-sector categories of solvent use considered in REASv3.

Sub-category
Dry cleaning
Decreasing operation
Vehicle treatment
Domestic use of solvents
Asphalt blowing
Paint production
Ink production
Tire production
Synthetic rubber production
Textile industry
Preservation of wood
Adhesive application
Printing[a]
Paint application[b]

a. Contributions from following activities were included: packing, offset printing, publication, and screen printing. b. Contributions from following purposes were included: architecture, domestic usage, automobile manufacture, vehicle refinishing, and other industrial application.

S2.4.4 Non-combustion sources of NH_3

Non-combustion sources of NH_3 emissions considered in REASv3 are manure management of livestock, fertilizer application, industrial processes, human, and latrines as summarized in Table 2.8. See Sect. S8 for details of non-combustion sources of NH_3.

Table 2.8. Sub-sector categories of non-combustion sources of NH_3 considered in REASv3.

Sub-category
Manure management[a]
Fertilizer application[b]
Industrial processes[c]
Human[d]
Latrines

a. Contributions from manure management including housing, storage and yards were included. Those from manure applied to soils were included in fertilizer application. b. Contributions from both synthetic fertilizer and animal manure used as fertilizer were included. c. See Sect. S2.4.2. d. Contributions from perspiration and respiration were included.

S2.5 Spatial and temporal resolution

In REASv3, only large power plants are treated as point sources and gridded data of other emission sources are provided with a horizontal resolution of 0.25° × 0.25°. For temporal resolution, monthly emissions are estimated in REASv3 by allocating annual emissions to each month using monthly proxy data. Details of methodologies and data used for spatial and temporal allocation are described in Sect. S9.

Table 2.9 provides sub-sector categories included in aggregated sector codes for gridded data in REASv3.

Table 2.9. Sector codes for gridded data in REASv3 and sub-sector categories included in each code.

Sector categories code	Sub-sector categories included in each sector code
POWER_PLANTS_POINT	Power plants (points) in Table 2.4
POWER_PLANTS_NON-POINT[a]	Power plants (area sources and energy) in Table 2.4
INDUSTRY[a]	Combustion sources of industry sector in Table 2.4
	Non-combustion sources of industrial production and other transformation sector in Table 2.5
ROAD_TRANSPORT	Road transport sector in Table 2.4
	Evaporative NMVOC emissions from road vehicles described in Sect. S6.3
OTHER_TRANSPORT	Other transport sector in Table 2.4
DOMESTIC[a]	Residential and other domestic sectors in Table 2.4
EXTRACTION	NMVOC emissions from extraction processes in Table 2.6
SOLVENTGS	NMVOC emissions from solvent use in Table 2.7
WASTE	NMVOC emissions from waste disposal described in Sect. S5.1.7
MANURE_MANAGEMENT	NH_3 emissions from manure management described in Sect. S8.1
FERTILIZER	NH_3 emissions from fertilizer application described in Sect. S8.2
MISC	NH_3 emissions from human and latrines described in Sects. S8.4 and S8.5.

a. For CO_2 gridded data of POWER_PLANTS_NON-POINT, INDUSTRY, and DOMESTIC, emissions excluding biofuel (-NON-BF) and those from biofuel (-BF) are provided separately.

S3. Stationary combustion

S3.1 Activity data

S3.1.1 Definition of fuel types

Table 3.1 describes fuel types considered in stationary combustion sources of REASv3. Emissions of air pollutants were estimated individually for each fuel type. In Fig. 4 of the main manuscript and Figs. S2, S4, S6, S8, S10, and S12 of the supplement, fuel types are aggregated to several categories. Definition of the categories is also provided in Table 3.1. For each fuel type, definitions are mostly the same as those of the International Energy Agency (IEA) World Energy Balances (IEAWEB) (IEA, 2017). Exceptions are "Raw coal", "Cleaned coal", "Other washed coal", and "Other coking products" which are defined only for China in the China Energy Statistical Yearbook (CESY) (National Bureau of Statistics of China, 1986, 2001-2017). Definition of "Bituminous coal", "Kerosene", and “Diesel oil” in Table 3.1. is the same as that of "Other bituminous coal", "Other kerosene", and “Gas/diesel oil excl. biofuels” of IEAWEB, respectively. For hard (brown) coal, if there is no detailed information, corresponding fuel type is considered as "Bituminous coal" ("Lignite"). For other fuel types not included in Table 3.1, emissions from combustion were ignored in REASv3.

Table 3.1. List of detailed fuel types considered in REASv3 and definition of aggregated categories used in the main manuscript and the supplement.

Aggregated categories (code)	Aggregated categories (description)	Detailed fuel types
COAL	Primary coal	Coking coal Anthracite Bituminous coal Raw coal Cleaned coal Other washed coal Sub-bituminous coal Lignite
DC	Secondary coal	Coke oven coke Gas coke Coal tar Patent fuel Brown coal briquettes (BKB) Other coking products
NGAS	Natural gas	Natural gas
OGAS	Other gas fuels	Gas works gas Coke oven gas Blast furnace gas Other recovered gases
LF	Light oil fuels	Refinery gas Liquefied petroleum gas (LPG) Natural gas liquids Motor gasoline Naphtha Kerosene
MD	Diesel oil	Diesel oil
HF	Heavy oil fuels	Crude oil Heavy fuel oil Petroleum coke Other oil products
BF	Biofuel	Fuelwood Crop Residue

		Animal waste Biogas Biogasoline Biodiesels Charcoal
OTH	Other fuels	Municipal waste (renewable) Municipal waste (non-renewable) Industrial waste

S3.1.2 Data sources of fuel consumption and assumptions to estimate missing historical data

In REASv3, fuel consumption data were primarily obtained from IEAWEB, CESY, the United Nations (UN) Energy Statistics Database (UN, 2016), and UN data, which is a web-based data service of the UN (http://data.un.org/). However, all these sources do not include data for the entire target period of REASv3, that is from 1950-2015. Furthermore, past data for sectors do not contain as many categories. In this sub-section, data sources and assumptions for estimating missing historical data used in REASv3 are summarized in Table 3.2 including how to distribute total or sub-total data to detailed sub-sectors and how to extrapolate data until 1950. Note that descriptions for fuel consumption data in transport sector are also included in this sub-section.

Table. 3.2. Data sources and assumptions for estimating missing historical data used in REASv3 for each country and region.

(a) China

<table>
<tr>
<td>Data sources and treatments</td>
<td>

Fuel consumption for each region except for Tibet, Hong Kong and Macau were obtained from CESY during 1985-2015 and those before 1984 were extrapolated to 1950 using data for whole China during 1950-2015. See Sect. S3.1.3 for regional fuel consumption data in China.
Data of whole country were taken from IEAWEB during 1971-2015 and extrapolated to 1950. Those of Tibet were taken from REASv2 (based on GAINS ASIA at that time) during 2000-2008 and extrapolated using data of whole country. See (n) and (o) of this sub-section for Hong Kong and Macau, respectively.

</td>
</tr>
<tr>
<td>Assumptions for estimating missing historical data</td>
<td>

Assumptions for modifying IEAWEB during 1971-2015 are as follows:

Energy industry own use sector:

Data of bituminous coal and natural gas before 1989 were distributed to sub-sectors based on relative ratios of fuel consumption data in 1990.
Fuel consumption data of coke oven gas in 1990 were extrapolated to 1980 using trends of coke oven gas production in IEAWEB during 1980-1990 and then, extrapolated to 1971 based on trends of coke oven coke production in IEAWEB during 1971-1980.

Industry sector:

Data of coking coal, gas works gas, coke oven gas, refinery gas, and LPG/other bituminous coal and crude oil/natural gas, other kerosene, diesel oil, and heavy fuel oil before 1989/1984/1979 were distributed to sub-sectors based on relative ratios in 1990/1985/1980.
Fuel consumption data of coke oven gas in 1980 were extrapolated to 1971 using trends of coke oven gas production in IEAWEB during 1971-1980.

Transport sector:

Data of diesel oil before 1989 were distributed to road transport, domestic navigation, and agriculture/forestry based on relative ratios of corresponding fuel consumption in 1990.

See "Assumption for data extrapolation" in this sub-section how to extrapolate the data of IEAWEB to 1950.

</td>
</tr>
</table>

(b) India

Data sources and treatments	● Data of whole country were taken from IEAWEB during 1971-2015 and extrapolated to 1950. ● See Sect. S3.1.4 for regional fuel consumption data in India.
Assumptions for estimating missing historical data	● No major modifications were done for IEAWEB during 1971-2015. ● See "Assumption for data extrapolation" in this sub-section how to extrapolate the data of IEAWEB to 1950.

(c) Japan

Data sources and treatments	● Data of whole country were taken from IEAWEB during 1960-2015 and extrapolated to 1950. ● See Sect. S3.1.5 for regional fuel consumption data in Japan.
Assumptions for estimating missing historical data	● Assumptions for modifying IEAWEB during 1960-2015 are as follows: ➢ Industry sector: ✧ Data of hard coal and coke oven coke/natural gas and LPG/crude oil/heavy fuel oil before 1974/1981/1965/1969 were distributed to sub-sectors based on relative ratios of fuel consumption data in 1975/1982/1966/1970. ➢ Residential and other sectors: ✧ Data of heavy fuel oil before 1969 were distributed to sub-sectors based on relative ratios in 1970. ➢ Other kerosene and diesel oil: ✧ Data of total final consumption before 1969 were distributed to sub-sectors based on relative ratios in 1970. ● See "Assumption for data extrapolation" in this sub-section how to extrapolate the data of IEAWEB to 1950 except for following procedures: ➢ Consumption of hard coal, brown coal, patent fuel, coke oven coke, gas works gas, natural gas, and primary solid biofuels in residential sector were extrapolated to 1950 using the Historical Statistics of Japan (Japan Statistical Association, 2006). ➢ Consumption of primary solid biofuels in paper, pulp and printing industry before 1981 were extrapolated to 1950 based on trends of production amounts of paper and pulp in Japan (Economy, Trade and Industry Statistics Association, 1998).

(d) Republic of Korea

Data sources and treatments	● Data of whole country were taken from IEAWEB during 1971-2015 and extrapolated to 1950.
Assumptions for estimating missing historical data	● Assumptions for modifying IEAWEB during 1971-2015 are as follows: ➢ Industry sector: ✧ Data of coke oven coke/other kerosene, diesel oil, and heavy fuel oil/natural gas before 2001/1980/1992 were distributed to sub-sectors based on relative ratios of fuel consumption data in 2002/1981/1993. ➢ Transport and other sectors: ✧ Data of diesel oil and heavy fuel oil before 1980 were distributed to sub-sectors based on relative ratios in 1981. ➢ Residential and other sectors: ✧ Data of primary solid biofuels before 1989 were distributed to sub-sectors based on relative ratios in 1990. ● See "Assumption for data extrapolation" in this sub-section how to extrapolate the data of IEAWEB to 1950.

(e) Taiwan

Data sources and treatments	● Data of whole country were taken from IEAWEB during 1971-2015 and extrapolated to 1950.
Assumptions for estimating missing historical data	● Assumptions for modifying IEAWEB during 1971-2015 are as follows: ➢ Residential and other sectors: ✧ Data of diesel oil/heavy fuel oil before 1979/1981 were distributed to sub-sectors based on relative ratios of fuel consumption data in 1980/1982. ● See "Assumption for data extrapolation" in this sub-section how to extrapolate the data of IEAWEB to 1950.

(f) Indonesia

Data sources and treatments	● Data of whole country were taken from IEAWEB during 1971-2015 and extrapolated to 1950.
Assumptions for estimating missing historical data	● Assumptions for modifying IEAWEB during 1971-2015 are as follows: ➢ Industry sector: ✧ Data of other bituminous coal and sub-bituminous coal before 1999 were distributed to sub-sectors based on relative ratios of consumption data of sub-bituminous coal in 2000. ✧ Data of natural gas/diesel oil and heavy fuel oil before 1980/1988 were distributed to sub-sectors based on relative ratios of fuel consumption data in 1981/1989. ✧ Fuel consumption data of primary solid biofuels in 1990 were extrapolated to 1971 using trends of primary solid biofuels consumption data in the other sector in IEAWEB during 1971-1990. ➢ Transport, residential and other sectors: ✧ Data of heavy fuel oil after 2000 were distributed to sub-sectors based on relative ratios in 1999. ● See "Assumption for data extrapolation" in this sub-section how to extrapolate the data of IEAWEB to 1950.

(g) Myanmar

Data sources and treatments	● Data of whole country were taken from IEAWEB during 1971-2015 and extrapolated to 1950.
Assumptions for estimating missing historical data	● Assumptions for modifying IEAWEB during 1971-2015 are as follows: ➢ Industry sector: ✧ Data of other bituminous coal/diesel oil before 2010/2011 were distributed to sub-sectors based on relative ratios of fuel consumption data in 2011/2012. ● See "Assumption for data extrapolation" in this sub-section how to extrapolate the data of IEAWEB to 1950.

(h) Philippines

Data sources and treatments	● Data of whole country were taken from IEAWEB during 1971-2015 and extrapolated to 1950.
Assumptions for estimating missing historical data	● Assumptions for modifying IEAWEB during 1971-2015 are as follows: ➢ Industry sector: ✧ Data of diesel oil and heavy fuel oil before 1979 were distributed to sub-sectors based on relative ratios of fuel consumption data in 1980. ● See "Assumption for data extrapolation" in this sub-section how to extrapolate the data of IEAWEB to 1950.

(i) Singapore

Data sources and treatments	● Data of whole country were taken from IEAWEB during 1971-2015 and extrapolated to 1950.
Assumptions for estimating missing historical data	● Assumptions for modifying IEAWEB during 1971-2015 are as follows: ➢ Residential and other sectors: ✧ Data of natural gas before 2005 were distributed to sub-sectors based on relative ratios of fuel consumption data in 2006. ● See "Assumption for data extrapolation" in this sub-section how to extrapolate the data of IEAWEB to 1950.

(j) Thailand

Data sources and treatments	● Data of whole country were taken from IEAWEB during 1971-2015 and extrapolated to 1950.
Assumptions for estimating missing historical data	● Assumptions for modifying IEAWEB during 1971-2015 are as follows: ➢ Industry sector: ✧ Data of other bituminous coal/natural gas before 1988/2001 were distributed to sub-sectors based on relative ratios of fuel consumption data in 1989/2002. ● See "Assumption for data extrapolation" in this sub-section how to extrapolate the data of IEAWEB to 1950.

(k) Vietnam

Data sources and treatments	● Data of whole country were taken from IEAWEB during 1971-2015 and extrapolated to 1950.
Assumptions for estimating missing historical data	● Assumptions for modifying IEAWEB during 1971-2015 are as follows: ➢ Industry ✧ Data of anthracite, diesel oil and heavy fuel oil during 1980-2009 were distributed to sub-sectors based on relative ratios of corresponding fuel consumption data in 2010. ✧ Data of natural gas before 2009 were distributed to sub-sectors based on relative ratios in 2010. ✧ Data of other bituminous coal and lignite before 2009 were distributed to sub-sectors based on relative ratios of anthracite consumption data in 2010. ✧ Data of other bituminous coal and sub-bituminous coal after 2011 were distributed to sub-sectors based on relative ratios of anthracite consumption data in corresponding years of 2011-2015. ➢ Hard coal, diesel oil, and heavy fuel oil ✧ Data of total final consumption before 1979 were distributed to sub-sectors based on relative ratios in 1980. ● See "Assumption for data extrapolation" in this sub-section how to extrapolate the data of IEAWEB to 1950.

(l) Mongolia

Data sources and treatments	● Data of whole country were taken from IEAWEB during 1985-2015 and extrapolated to 1950.
Assumptions for estimating missing historical data	● No major modifications were done for IEAWEB during 1985-2015. ● See "Assumption for data extrapolation" in this sub-section how to extrapolate the data of IEAWEB to 1950.

(m) Cambodia

Data sources and treatments	● Data of whole country were taken from IEAWEB during 1995-2015 and extrapolated to 1950.
Assumptions for estimating missing historical data	● No major modifications were done for IEAWEB during 1995-2015. ● See "Assumption for data extrapolation" in this sub-section how to extrapolate the data of IEAWEB to 1950.

(n) Hong Kong, Democratic People's Republic of Korea, Brunei, Malaysia, Bangladesh, Nepal, Pakistan, and Sri Lanka

Data sources and treatments	● Data of whole country were taken from IEAWEB during 1971-2015 and extrapolated to 1950.
Assumptions for estimating missing historical data	● No major modifications were done for IEAWEB during 1995-2015. ● See "Assumption for data extrapolation" in this sub-section how to extrapolate the data of IEAWEB to 1950.

(o) Macau, Laos, Afghanistan, Bhutan, and Maldives

Data sources and treatments	● Data of whole country were taken from UN data during 1990-2015 and extrapolated to 1950.
Assumptions for estimating missing historical data	● No major modifications were done for UN data during 1990-2015. ● Data before 1990 were extrapolated to 1950 using trends of fuel consumption estimated using UN Energy Statistics Database as follows: Consumption = Production + Import – Export + Changes in stocks ● Biofuel consumption data before 1970 were extrapolated to 1950 using trends of population numbers.

Assumption for data extrapolation

As described above, fuel consumption data before 1959 and 1970 were not included in IEAWEB for Japan and other countries, respectively. The missing historical fuel consumption data were estimated by extrapolation using trends of related data for each sub-sector. Trend factors used in REASv3 are summarized in Table 3.3.

Table. 3.3. Trend factors for extrapolating fuel consumption data to 1950 in each sub-sector.

Sub-sectors	Trend factors and data sources
Power plants including energy sector	● Trend factors: Amounts of generated power for all fuel types ● Data sources: ➢ Each region of China: China Data Online ➢ Other countries and regions: Mitchell (1998)
Coke ovens and blast furnace including energy sector	● Trend factors: Amounts of pig iron production for all fuel types ● Data sources: See Sect. S4.1.1
Charcoal production plants	● Trend factors: Amounts of charcoal production for all fuel types ● Data sources: Data after 1961 were obtained from FAOSTAT

	(http://www.fao.org/faostat/en) and trends between 1950 and 1960 were assumed based on Fernandes et al. (2007).
Petroleum Refineries including energy sector	● Trend factors: Amounts of total crude oil consumption for all fuel types ● Data sources: Total crude oil consumption was estimated using Mitchell (1998) as follow: Consumption = Production + Import – Export
Iron and steel	● Trend factors: Total amounts of pig iron and crude steel production for all fuel types ● Data sources: See Sect. S4.1.1
Non-ferrous metals	● Trend factors: Total amounts of copper, lead, zinc, and primary aluminum production for all fuel types ● Data sources: See Sect. S4.1.2
Non-metallic minerals industry (cement, lime, and brick)	● Trend factors: Amounts of cement production for all fuel types ● Data sources: See Sect. S4.1.3
Railway	● Trend factors: Length of railway line for all fuel types ● Data sources: Mitchell (1998)
Road transport	● Trend factors: Total annual mileages of vehicles for each fuel type ● Data sources: See Sect. S6.1.1
Others	● Trend factors and data sources: ➢ Coal fuels except for coke fuels: Total coal consumption estimated using Mitchell (1998) as follows: Consumption = Production + Import – Export ➢ Coke fuels and gas fuels except for natural gas: The same trends as those for coke ovens ➢ Natural gas: Total natural gas consumption estimated using Mitchell (1998) ➢ Oil fuels: The same trends as those for petroleum refineries ➢ Biofuels: See Sect. S3.1.8 ➢ Charcoal: The same trends as those for charcoal production plants ➢ Other fuels: Fuel consumption data were not extended to 1950.

S3.1.3 Regional fuel consumption data in China

REASv3 used CESY for fuel consumption data of regions in China defined in Table 2.1 except for Hong Kong and Macau. However, in CESY, only total data are available in industry and transport sectors which need to be distributed to sub-sectors. In REASv3, weighting factors for the distribution were prepared for each region. Basic methodology and data used for the weighting factors are described briefly in this sub-section. Note that all motor gasoline listed in both industry and transport sectors of CESY are assumed to be consumed in road transport sector based on IEAWEB.

Industry sector

For most regions, total consumption data in industry sector were divided into sub-sectors based on weighting factors prepared using energy data in statistical yearbook of each region. Availabilities of detailed data for the weighting factors are different among regions and summarized in Table 3.4 except for Shanghai, Jiangsu, Zhejiang, Shandong, Hainan and Sichuan where no energy data are available in statistical yearbook of each region.

Table. 3.4. Data sources and treatments of weighting factors for each region to distribute total fuel consumption in industry sector to each sub-sector.

Regions	Data sources and treatments
Beijing	● Data of major fuel types were taken from Beijing Statistical Yearbook. ● For the year when statistics are not available, data in 2001/2005/2007/2010/2014 were used before 2000/for 2004/for 2008/for 2011/for 2015.
Tianjin	● Data of major fuel types were taken from Tianjin Statistical Yearbook. ● For the year when statistics are not available, data in 2001/2010/2013 were used before 2000/for 2011/after 2012.
Hebei	● Consumption of main energy sources were taken from Hebei Statistical Yearbook and used for all fuel types. ● For the year when statistics are not available, data in 2005/2010/2013 were used before 2004/for 2011/after 2012.
Shanxi	● Data of coal, coke, and diesel oil were taken from Shanxi Statistical Yearbook. For other fuels, weighting factors were based on data of REASv2 (based on GAINS ASIA at that time).

	● For the year when Shanxi Statistical Yearbook are not available, data in 2000/2010/2013/2014 were used before 1999/for 2011/for 2012/for 2015. For REASv2 (available during 2000-2008), data in 2000/2008 were used before 1999/after 2009.
Inner Mongolia	● Data of major fuel types were taken from Inner Mongolia Statistical Yearbook. ● For the year when statistics are not available, data in 2001/2007/2010/2013 were used before 2000/for 2006/for 2011/after 2012.
Liaoning	● Data of major fuel types were taken from Liaoning Statistical Yearbook. ● For the year when statistics are not available, data in 2001/2010/2013 were used before 2000/for 2011/after 2012.
Jilin	● Data of major fuel types were taken from Jilin Statistical Yearbook. ● For the year when statistics are not available, data in 2000/2002/2005/2010/2013 were used before 1999/for 2001/for 2004/for 2011/after 2012.
Heilongjiang	● Data of major fuel types were taken from Heilongjiang Statistical Yearbook. ● For the year when statistics are not available, data in 2005/2010/2013 were used before 2004/for 2011/after 2012.
Shanghai	See descriptions below this table.
Jiangsu	See descriptions below this table.
Zhejiang	See descriptions below this table.
Anhui	● Data of major fuel types were taken from Anhui Statistical Yearbook. ● For the year when statistics are not available, data in 2000/2002/2005/2010/2013 were used before 1999/for 2001/for 2004/for 2011/after 2012.
Fujian	● Data of major fuel types were taken from Fujian Statistical Yearbook. ● For the year when statistics are not available, data in 2001/2010/2013 were used before 2000/for 2011/after 2012.
Jiangxi	● Data of major fuel types were taken from Jiangxi Statistical Yearbook. ● For the year when statistics are not available, data in 2000/2010/2013 were used before 1999/for 2011/after 2012.
Shandong	See descriptions below this table.

Henan	● Data of major fuel types were taken from Henan Statistical Yearbook. ● For the year when statistics are not available, data in 2001/2010/2013 were used before 2000/for 2011/after 2012.
Hubei	● Data of coal and diesel oil were taken from Hubei Statistical Yearbook. For other fuels, weighting factors were based on data of REASv2 (based on GAINS ASIA at that time). ● For the year when Hubei Statistical Yearbook are not available, data in 2000/2010/2013 were used before 1999/for 2011/after 2012. For REASv2 (available during 2000-2008), data in 2000/2008 were used before 1999/after 2009.
Hunan	● Data of major fuel types were taken from Hunan Statistical Yearbook. ● For the year when statistics are not available, data in 2001/2005/2010/2013 were used before 2000/for 2004/for 2011/after 2012.
Guangdong	● Data of coal were taken from Guangdong Statistical Yearbook. For other fuels, weighting factors were based on data of REASv2 (based on GAINS ASIA at that time). ● For the year when Guangdong Statistical Yearbook are not available, data in 2000/2010/2013/2014 were used before 1999/for 2011/for 2012/for 2015. For REASv2 (available during 2000-2008), data in 2000/2008 were used before 1999/after 2009.
Guangxi	● Data of total energy consumption were taken from Guangxi Statistical Yearbook for all fuel types. ● For the year when statistics are not available, data in 1995/2000/2014 were used before 1997/for 1998 and 1999/for 2015.
Hainan	See descriptions below this table.
Chongqing	● Data of major fuel types were taken from Chongqing Statistical Yearbook. ● For the year when statistics are not available, data in 2001/2010/2013 were used before 2000/for 2011/after 2014.
Sichuan	See descriptions below this table.
Guizhou	● Data of major fuel types were taken from Guizhou Statistical Yearbook. ● For the year when statistics are not available, data in 2000/2010/2014 were used before 1999/for 2011/for 2015.
Yunnan	● Data of coal, coke, and oil were taken from Yunnan Statistical

	Yearbook. For other fuels, weighting factors were based on data of REASv2 (based on GAINS ASIA at that time). ● For the year when Yunnan Statistical Yearbook are not available, data in 2000/2013 were used before 1999/after 2014. For REASv2 (available during 2000-2008), data in 2000/2008 were used before 1999/after 2009.
Tibet	● Fuel consumption data were not from CESY. (See Sect. S3.1.2)
Shaanxi	● Data of coal, coke, and diesel oil were taken from Shaanxi Statistical Yearbook. For other fuels, weighting factors were based on data of REASv2 (based on GAINS ASIA at that time). ● For the year when Shanxi Statistical Yearbook are not available, data in 2002/2005/2010/2013 were used before 2001/for 2004/for 2009 and 2011/after 2012. For REASv2 (available during 2000-2008), data in 2000/2008 were used before 1999/after 2009.
Gansu	● Data of major fuel types were taken from Gansu Statistical Yearbook. ● For the year when statistics are not available, data in 2001/2010/2013/2014 were used before 2000/for 2011/for 2012/for 2015.
Qinghai	● Data of coal were taken from Qinghai Statistical Yearbook. For other fuels, weighting factors were based on data of REASv2 (based on GAINS ASIA at that time). ● For the year when Qinghai Statistical Yearbook are not available, data in 2001/2010/2013 were used before 2000/for 2011/after 2012. For REASv2 (available during 2000-2008), data in 2000/2008 were used before 1999/after 2009.
Ningxia	● Data of major fuel types were taken from Ningxia Statistical Yearbook. ● For the year when statistics are not available, data in 2000/2010/2013 were used before 1999/for 2011/after 2012.
Xinjiang	● Data of major fuel types were taken from Xinjiang Statistical Yearbook. ● For the year when statistics are not available, data in 2001/2007/2009/2013 were used before 2000/for 2008/for 2010 and 2011/after 2012.
Hong Kong	Fuel consumption data were not from CESY. (See Sect. S3.1.2)
Macau	Fuel consumption data were not from CESY. (See Sect. S3.1.2)

For Shanghai, Jiangsu, Zhejiang, Shandong, Hainan and Sichuan, weighting factors were assumed based on sub-sector level fuel consumption data developed using the China total data described in Sect. S3.1.2 and related regional data as follows:

- Weighting factors to distribute fuel consumption in whole China to each region were prepared for each sub-sector and commonly used for all fuel types. The weighting factors for each sub-sector used in REASv3 are as follows:
  - Amounts of steel production in each region (see Sect. S4.1.1) were used for iron and steel sub-sector.
  - Total amounts of copper, lead, zinc, and primary aluminum production in each region (see Sect. S4.1.2) were used for non-ferrous metals sub-sector.
  - Amounts of cement production in each region (see Sect. S4.1.3) were used for non-metallic minerals sub-sector in IEAWEB. (Fuel consumption in non-metallic minerals were further distributed to cement, lime, and brick sub-sectors in REASv3. See Sect. S3.1.7.)
  - Amounts of coal production in each region taken from China Data Online were used for coal mines (in energy sector) and mining and quarrying sub-sectors.
  - Amounts of paper and paperboard production in each region taken from China Data Online were used for paper, pulp and prints sub-sector.
  - Amounts of textile production in each region (see Sect. S5.1.2) were used for textile and leather sub-sector.
  - GDP of each region taken from China Data Online were used for other sectors.
- Using the China total data and the weighting factors, the tentative regional fuel consumption data (TRFCD) were developed. Then, the fuel consumption ratio of each sub-sector to industry sector total was calculated for Shanghai, Jiangsu, Zhejiang, Shandong, Hainan and Sichuan using the TRFCD of each region. Finally, fuel consumption in industry sector of each region in CESY was distributed to sub-sectors using the corresponding ratios. When categories of fuel types are different between the TRFCD and CESY, following procedures were adopted:
  - For raw coal, cleaned coal, and other washed coal in CESY, the ratio for total of anthracite, coking coal and other bituminous coal in the TRFCD were used.
  - For other coking products and other petroleum products in CESY, the ratio for coke oven coke and heavy fuel oil in the TRFCD were used, respectively.

Transport sector

For transport sector, no detailed data are available even in statistical yearbook of each region. Therefore, weighting factors for each region were assumed in the similar procedure for industry sector as follows:

- As mentioned in the first paragraph of this sub-section, all motor gasoline consumption (including those in industry sector) is distributed to road transport sector.
- All solid coal fuels are assumed to be used in railway sector.
- Natural gas consumption before and after 1995 was distributed to pipeline transport and road transport sectors, respectively.
- All heavy fuel oil consumption is distributed to domestic navigation sector.
- For diesel oil, using the same methodology for industry sector, diesel oil consumption data in road transport, railway, and domestic navigation sectors in each region were developed and then, weighting factors were assumed. For regional diesel oil consumption data, those in railway and domestic navigation sectors were taken from REASv2 (based on GAINS ASIA at that time) during 2000-2008 and data in 2000 and 2008 were used before 1999 and 2009, respectively. See Sect. S6.1.2 for diesel oil consumption in each region in road transport sector.
- Consumption of all other fuels is distributed to non-specified transport sector.
- Assumptions of motor gasoline, solid coal fuels, natural gas and heavy fuel oil described above were based on IEAWEB.

S3.1.4 Regional fuel consumption data in India

As defined in Table 2.1, REASv3 has 17 sub-regions for India. Therefore, fuel consumption data of country total based on IEAWEB need to be divided for each sub-region. Table 3.5 provides weighting factors used to allocate country total data to the 17 sub-regions.

Table. 3.5. Weighting factors for allocating country total fuel consumption data to the 17 sub-regions in India.

Sectors and fuel types	Weighting factors and data sources
Power plants including energy sector	● Weighting factors: Total generation capacities in each region ● Data sources: World Electric Power Plants Database (Platts, 2018)
Iron and steel	● Weighting factors: Amounts of crude steel production for all fuel types ● Data sources: See Sect. S4.1.1
Non-ferrous metals	● Weighting factors: Total amounts of copper, lead, zinc, and primary

	aluminum production for all fuel types ● Data sources: See Sect. S4.1.2
Non-metallic minerals industry (cement, lime, and brick)	● Weighting factors: Amounts of cement production for all fuel types ● Data sources: See Sect. S4.1.3
Road	● See Sect. S6.1
Rail	● Weighting factors: Length of railway line for all fuel types ● Data sources: Factors after 2005 were estimated from TERI (2013, 2018) and those in 2005 were used before 2004.
Biofuels	● See Sect. S3.1.8
Industry and energy sectors (default)	● Weighting factors and data sources: ➢ Factors for LPG, motor gasoline, kerosene, diesel oil, heavy fuel oil, and naphtha during 1998-2013 were estimated from TERI (2013, 2018) and those in 1998 and 2013 were used before 1997 and after 2014, respectively. ➢ Factors for other fuels after 1999 were estimated from "Fuel Consumed" in Annual Survey of Industries (Ministry of Statistics & Programme Implementation, http://www.csoisw.gov.in/cms/en/1023-annual-survey-of-industries.aspx) and those in 1999 were used before 1998.
Residential and other domestic sectors	● Weighting factors and data sources: ➢ Factors for kerosene and LPG during 1983-1999 were estimated from TERI (2013, 2018) and those in 1983 were used before 1982. The factors in 2010 were estimated based on Census of India 2011 (Chandramouli, 2011) and used after 2011. Factors between 1999 and 2010 were interpolated. ➢ Data of LPG were also used for natural gas. For other fuels, those of kerosene were used.

S3.1.5 Regional fuel consumption data in Japan

REASv3 has 6 sub-regions for Japan as defined in Table 2.1 and the same as the case of India, fuel consumption data of country total based on IEAWEB need to be divided to each sub-region. Table 3.6 provides weighting factors used to allocate country total data to the 6 sub-regions.

Table 3.6. Weighting factors for allocating country total fuel consumption data to the 6 sub-regions in Japan.

Sectors and fuel types	Weighting factors and data sources
Power plants including energy sector	● Weighting factors: Total generation capacities in each region ● Data sources: World Electric Power Plants Database (Platts, 2018)
Non-ferrous metals	● Weighting factors: Total amounts of copper, lead, zinc, and primary aluminum production for all fuel types ● Data sources: See Sect. S4.1.2
Road	● See Sect. S6.1
Others	● Weighting factors: ➢ Factors for each sector and fuel type during 1990-2015 were estimated using energy consumption statistics of each prefecture in corresponding years of 1990-2015. ➢ Factors in 1990 were used for those before 1989. ● Data sources: ➢ Website of the Agency for National Resources and Energy https://www.enecho.meti.go.jp/statistics/energy_consumption/ec002/results.html (in Japanese)

S3.1.6 Fuel consumption in power plants

General methodology

In REASv3, power plants with following criteria were treated as point sources:

- Power plants which were treated as point sources in REASv2 (see Kurokawa et al., 2013).
- Power plants which entered commercial operation after 2008 and whose total generating capacities of units in each power plant were larger than 300MW.

Then, fuel consumption in power plants sector was estimated as follows:

1) Fuel consumption in each power plant (point source) was estimated. (see “Fuel consumption in each power plant” below)
2) (A) Total of the fuel consumption in each power plant was calculated in each country and region.
3) If (A) was larger than (B) fuel consumption in total power plant sector in a corresponding country and region, data of each power plants prepared in 1) were adjusted by the ratio of (B) to (A). In this case, fuel consumption of power plants as area sources was assumed to be zero.

4) IF (A) was smaller than (B), the value of (B) minus (A) was assumed to be fuel consumption in area sources. In this case, there is no change for the data of each power plant developed in 1).

Fuel consumption in each power plant

In REASv2, power plants whose annual CO_2 emissions in the Carbon Monitoring for Action (CARMA) Database (Wheeler and Ummel, 2008) were more than 1 Mt in 2000 and/or 2007 were treated as point sources. Before 2007, REASv3 used the same power plants as point sources with some revisions for such as generation capacities, fuel types, etc. using the updated World Electric Power Plants Database (Platts, 2018). For fuel consumption, data between 2000 and 2007 were basically the same as those in REASv2. Before 2000, fuel consumption of each power plant in operation was assumed to be the same as that in 2000 which will be adjusted based on total fuel consumption in power plants sector as described in "General methodology" above. (Note that power plants which were constructed and retired before 2000 were not considered in REASv3.) After 2008, REASv3 included power plants which entered commercial operation after 2008 as new point sources based on the WEPP (see also "General methodology" above). Although major information was available including fuel types used in each power plant, there are no data of fuel consumption in the WEPP. Thus, in REASv3, annual fuel consumption per generation capacity for each fuel type was estimated first using data in 2000 and 2007 for each country. The data were estimated for power plants which started operation before 1999 and after 2000, separately. Then, using the generation capacities data obtained from the WEPP, fuel consumption in each power plant was estimated.

S3.1.7 Fuel consumption in non-metallic minerals

REASv3 defined cement, lime, brick, and non-specified sub-sectors in the non-metallic minerals category in stationary combustion sources. However, energy statistics used in REASv3 including IEAWEB and regional statistical yearbook of China provide fuel consumption in total non-metallic minerals industry which needs to be distributed to each sub-sector.

In REASv3, all primary coal fuels were assumed to be used in cement, lime, and brick production. For China, Hua et al. (2016), Wang et al. (2012), and Streets et al. (2006) give coal consumption in cement (1980-2012), brick (1950-2015), and lime (2001) industries, respectively. Using these data and production amounts of cement, lime and brick, coal consumption per unit of production of cement, lime, and brick was estimated, respectively. Then, coal consumption data in non-metallic minerals in each region were distributed to each sub-sector based on production amounts of cement, lime, and brick in each region and corresponding coal consumption per united of production. Similarly, Maithel (2013) provides coal consumption in cement and brick industries in Pakistan during 2001-2010 and with production amounts of cement and brick, fuel consumption in non-metallic minerals industry were distributed to each sub-sector. For other countries, due to lack of information, averaged coal consumption per unit of production of cement, lime, and brick for China was used for other East and Southeast Asian countries. For other countries in South Asia, averaged coal consumption per unit of production of cement and brick for Pakistan and that of lime for China was used. Then, with production data of cement, lime, and brick, fuel consumption in non-metallic minerals were distributed to each sub-sector. See Sects. S4.1.3, S4.1.4, and S4.1.5 for production data of cement, lime, and brick, respectively.

For other fuels, in REASv3, coke oven coke and heavy fuel oil were assumed to be used in cement industry and others including gas fuels and diesel oil were allocated to the non-specified sub-sector.

S3.1.8 Biofuels

China

CESY provides biofuel consumption data of fuelwood, crop residue, and biogas in each region during 1998-2007 which were used in REASv3. Before 1997, data were extended to 1980 using trends of each fuel consumption data in REASv1 and then extended to 1950 based on trends of biofuel consumption in East Asia obtained from Fernandes et al. (2007). After 2007, fuelwood, crop residue, and biogas consumption in total China were extrapolated to 2015 using trends of primary solid biofuels consumption in IEAWEB. Then, consumption of each fuel in each region in 2007 were tentatively extrapolated to 2015 using trends of rural population numbers in each region. Finally, fuelwood, crop residue, and biogas consumption in total China estimated during 2008-2015 were distributed to each region using the tentatively extrapolated data in each region.

India

Primary solid biofuels in IEAWEB were assumed to be total of fuelwood, crop residue and animal waste in India during 1971-2015. Before 1970, the primary solid biofuels consumption was extrapolated to 1950 using trends of biofuel consumption in South Asia obtained from Fernandes et al. (2007). Then, relative ratios of fuelwood, crop residue, and animal waste consumption in 17 sub-regions to consumption of the primary solid biofuels in total India were calculated for 1990 and 2010 using data in Streets and Waldhoff (1998) and Census of India 2011 (Chandramouli, 2011), respectively and interpolated between 1991 and 2009. Before 1989 and after 2011, the ratios of 1990 and 2010 were assumed to be constant, respectively. Finally, fuel consumption of fuelwood, crop residue, and animal waste in each sub-region during 1950-2015 were calculated.

Japan

Primary solid biofuels consumption in IEAWEB were assumed to be fuelwood consumption in Japan during 1982-2015. Before 1981, as described in Sect. S3.1.2, fuel consumption in residential and paper, pulp and printing industry sectors was extrapolated to 1950 using the Historical Statistics of Japan (Japan Statistical Association, 2006) and trends of production amounts of paper and pulp in Japan, respectively.

Macau, Laos, Afghanistan, Bhutan, and Maldives

See Sect. S3.1.2 for methodology and data sources. Only fuelwood and charcoal were included for this group.

Other countries

Primary solid biofuels data in IEAWEB were assumed to be total of fuelwood, crop residue and animal waste consumption in each country and extrapolated to 1950 using trends of biofuel consumption in East or Southeast or South Asia obtained from Fernandes et al. (2007). For distribution to each fuel type, consumption ratios of fuelwood, crop residue, and animal waste in 1990 obtained from Streets and Waldhoff (1998) were used during 1950-2015.

S3.2 Emission factors and settings of emission controls

S3.2.1 SO_2

Sulfur contents in fuels

In REASv3, default settings were taken from those of REASv1 during 1980-2000 generally based on RAINS ASIA at that time, Streets et al. (2000), Kato and Akimoto (1992) and Kato et al. (1991). For countries using default settings, data in 1980 and 2000 were used before 1979 and after 2001, respectively. For China, India, Japan, Republic of Korea, and Taiwan, additional country-specific settings were considered as described in Table 3.7.

Table 3.7. Settings and assumptions of sulfur contents in fuels for China, India, Japan, Republic of Korea, and Taiwan.

Countries	Settings and assumptions
China	● Coal: ➢ During 1985-2000: Data were taken from REASv1 based on Kato and Akimoto (1992) in 1985 and China Coal Industry Yearbook 2002 (State Administration for Coal Safety, 2003) in 1990 and 1995. In 2000, data in 1995 were adjusted so that the national average sulfur contents were 1.08% after Lu et al. (2010). Data in other years were interpolated. ➢ During 2001-2005: Data were taken from REASv2 where settings of power plants in 2005 were based on Zhao et al. (2008) and national average sulfur contents were adjusted to 1.02% after Lu et al. (2010). Data between 2000 and 2005 were interpolated. ➢ Before 1984 and after 2006, settings in 1980 and 2005 were used, respectively. ● Oil ➢ Before 1985, data were obtained from Kato et al. (1991) and those in 1995 were based on information from Tsinghua University (1.5% for heavy fuel oil and 0.58%, 0.35%, and 0.163% for diesel oil in north, northeast, and other areas, respectively) for REASv1. Data between 1986-1994 were interpolated and after 1996, data in 1995 were used.
India	● Data were taken from REASv1 based on Reddy and Venkataraman (2002) for coal, heavy fuel oil, and light fuels and Kato et al. (1991) for others. The same data were used for the entire target period of REASv3.
Japan	● Coal: Data during 1960-1996 were taken from Li and Dai (2000). The value in 1960 was 1.06% and gradually decreased to 0.60% in 1996. It was assumed that the value was reduced by 10% from 1996 to 2010 referring a report of MOEJ (2012). Data between 1996 and 2010 were interpolated and those in 1960 and 2010 were used before 1959 and after 2011, respectively. ● Heavy fuel oil and crude oil: Settings during 1965-2010 for power plants were based on Iwaya (2013). Those for industry were based on Kato et al. (1991), Streets et al. (2000), and Imura et al. (1999). Data

	in 1965 and 2010 were used before 1964 and after 2011, respectively. ➢ Heavy fuel oil for power plants: The values before 1965 were 2.6% and decreased almost constantly to 0.80% in 1975. Then the values were gradually decreased to 0.75% in 1990 and the values was used after 1990. ➢ Heavy fuel oil for industry: The values before 1965 were 2.60% and assumed to be decreased gradually to 1.4% in 1975, 1.1% in 1985, and 1.0% in 2000. The values after 2000 were assumed to be constant. ➢ Crude oil for power plants: The value before 1965 were 2.8% and decreased almost linearly to 0.20% in 1975. After 1975, values were between 0.15% and 0.20%. ● Diesel: Settings were based on regulations of diesel oil in Japan as follows: 1.2% before 1975, 0.50% during 1976-1991, 0.20% during 1992-1996, 0.05% during 1997-2003, and 0.005% after 2004.
Republic of Korea and Taiwan	● Data during 1980-2000 were taken from REASv1 based on Kato et al. (1991), RAINS ASIA, and Streets et a. (2000) and those in 1975 were obtained from Kato et al. (1991). Data between 1976-1981 were interpolated and those in 1975 and 2000 were used before 1974 and after 2001, respectively.

Emission factors

SO_2 emissions from coal and oil fuels were calculated using sulfur contents in fuels and ratios of sulfur emitted as SO_2. Settings of REASv3 for the fraction of sulfur in the fuel that is emitted as SO_2 were taken from REASv1 and REASv2 based on Kato and Akimoto (1992), Kato et al. (1991) and RAINS ASIA as follows:

- Power plants (point sources): 0.95
- Power plants (area sources)): 0.90 for Japan, Republic of Korea, and Taiwan; 0.775 for other countries and regions.
- Industry sector: 0.775
- Coke ovens: 0.0685
- Iron and steel: 0.1483
- Transport sector: 0.775
- Domestic sector: 0.60
- Coke oven coke for all sectors: 0.885

- Oil fuels for all sectors: 1.0

For coke ovens, activity data are coal input and it is considered that the estimated SO_2 emissions include both combustion and non-combustion sources.

For gas fuels such as coke oven gas and blast furnace gas, light fuels such as LPG, and other fuels except for primary biofuels such as charcoal and municipal wastes, emission factors were derived from Kato and Akimoto (1991). Those for fuelwood and crop residue were taken from Garg et al. (2001) and those for animal waste were from Gadi et al. (2003).

In cement plants, effects of absorption of SO_2 by cements need to be considered. In REASv3, the absorption rates for China were obtained from Li et al. (2017) and those for other countries were based on Kato et al. (1991).

Settings of emission controls

Settings and assumptions for reduction of SO_2 emissions from combustion sources by abatement equipment adopted in REASv3 are summarized in Table 3.8. For other sources not described in Table 3.8, no emission controls were considered.

Table 3.8. Settings and assumptions of emission controls of SO_2

Countries	Settings and assumption
China	● Power plants: Effects of flue-gas desulfurization (FGD) were considered after 2000 as follows: ➢ Settings during 2000-2008 were taken from REASv2 based on national introduction rates of FGD from Lu et al. (2010) and those of each province from Zhao et al. (2008). ➢ After 2008, increases of penetration of FGD were assumed referring Liu et al. (2015) and Li et al. (2017). In 2015, the introduction rates were assumed to be 100% in power plants considered as point sources and 90% for other power plants. Removal efficiencies of FGD units were assumed to be 0.75 before 2003 and 0.90 after 2010 and the values were interpolated during 2004-2009. ● Industry: Effects of FGD were roughly assumed as follows: ➢ Referring Li et al. (2017), it was assumed that regulations started from (A) Beijing and Shanghai, then (B) Shandong, Hebei, and Guangdong, and finally (C) other provinces. ➢ Regulations of industrial boiler were strengthened after 2014

	referring Zheng et al. (2018). ➢ For (A), it was assumed that introduction of FGD started from 2000 and penetration rates in 2010 were 40% which is a setting for China in 2020 in Business-as-usual scenario of Wang et al. (2014). For the penetration rates, linear trends were assumed during 2000-2013. ➢ For (B) and (C), it was assumed that penetration of FGD started 2 and 4 years after (A), respectively and reduction effects were assumed to be smaller than (A) by 10% and 15%, respectively. It was assumed that removal efficiencies of FGD units were 0.75 for (A), 0.70 for (B) and 0.65 for (C). ➢ In 2015, total reduction rates of SO_2 emissions were assumed to be 75%, 63%, and 52% for (A), (B), and (C), respectively.
Japan	● Power plants: Referring MRI (2015), Kato et al. (1991), and MOEJ (2000), effects of FGD were considered after 1968 as follows: ➢ In 1990 and after 2000, introduction rates of FGD in power plants as point sources were assumed to be 95% and 100%, respectively. It was assumed that removal efficiencies of FGD units were 0.95 after 1990. Trends of total reduction rates during 1968 and 1990 were assumed based on MOEJ (2000) and those between 1990 and 2000 were interpolated. ➢ For introduction rates of FGD in power plants as area sources, it was assumed to be 95% after 2000 and the trends before 1990 were estimated based on those of point sources. ● Other sectors: Referring Kato et al. (1991), total reduction rates of SO_2 emissions were assumed as follows: ➢ For large industries including sulphuric acid plants, 80% of reduction rates of power plants as area sources were adopted. ➢ For other industries, reduction rates were assumed to be 50% of large industries. ➢ For commercial and public services, 50% of reduction rates of other industries were adopted.
Republic of Korea	● Effects of FGD were roughly assumed as follows: ➢ Power plants: Referring Ebata et al. (1997) and Wang et al. (2014), it is assumed that introduction of FGD was from 1990. The penetration rates in power plants as point sources in 2000,

	2005, and 2010 were 90%, 97%, and 98%, respectively. Data between 1990, 2000, 2005, and 2010 were interpolated and data in 2010 were used after 2011. Effects of FGD on power plants as area sources were assumed to be 5% lower than point sources. Removal efficiencies of FGD units were roughly assumed to be 0.90 in 1990 and 0.95 after 2000 and the values were interpolated during 1991-1999. ➢ Industry: It was assumed that introduction of FGD started from 1990 and penetration rates of FGD were 80% and 85% in 2005 and 2010, respectively based on Wang et al. (2014). Data between 1990, 2005, and 2010 were interpolated and data in 2010 were used after 2011. It was assumed that removal efficiencies of FGD units were 0.95 for large industries and half of the values were adopted for other industries.
Taiwan	● Effects of FGD were roughly assumed as follows: ➢ Power plants: Due to lack of information, the same reduction rates of Republic of Korea were adopted after 1995. But according to Ebata et al. (1997), introduction of FGD started earlier than Republic of Korea. It was assumed that penetration rates in 10% and 30% in 1980 and 1990, respectively and data between 1980, 1990, and 1995 were interpolated. ➢ Industry: Similar to power plants, the same reduction rates of Republic of Korea were adopted after 2000 and it was assumed that introduction of FGD started from 1985. Data between 1985 and 2000 were interpolated.
Thailand	● Effects of FGD were assumed as follows: ➢ Power plants as point sources: Referring UN Environment (2018), reduction rates were assumed for four power plants as follows: Mae Moh (0.8-0.97 in 1978-2015), BLCP Power (0.84 from 2006), National Power Supply (0.75 from 1999), and GHECO-One (0.952 from 2012).
Other countries	● Effects of FGD were assumed as follows: ➢ Power plants as point sources: Reduction rets (0.7-0.9) were assumed if units have information of installed FGD equipment in World Electric Power Plants Database (Platts, 2018). ➢ Countries which have power plants with FGD and number of such

	power plants in 2015 (in parentheses) in REASv3 were as follows: India (10), Indonesia (5), Laos (1), Malaysia (4), Vietnam (10), and Sri Lanka (2).

S3.2.2 NO_x

Default emission factors

Table 3.9 summarized default emission factors used in REASv3 for fuel combustion in power plants, industry, and residential sectors. Specific settings for coke ovens, iron and steel industry, cement industry, and emission controls were described below the table.

Table 3.9. Default emission factors of NO_x from fuel combustion in power plants, industry and residential sectors. Unit is t/PJ expressed as NO_2.

Fuel type	Power plants	Industry	Residential
Hard coal[h]	345[a]	260[e]	78[g]
Raw coal[i]	See Table 3.10.	203[f]	61.1[g]
Cleaned coal[i]		162[f]	48.5[g]
Other washed coal[i]		509[f]	153[g]
Sub-bituminous coal	524[a]	A	B
Lignite	433[a]	A	B
Coke oven coke[j]	345	260	78
Natural gas	105[b]	53[b]	37[b]
Gas works gas	10.5[b]	7.4[b]	5.25[b]
Coke oven gas	77.8[b]	55[b]	38[b]
Blast furnace gas	10.5[b]	7.4[b]	38[b]
LPG	79[b]	56[b]	33[b]
Kerosene	485[b]	167[b]	25[b]
Diesel oil	632[b]	222[b]	74[b]
Crude oil	249[b]	145[b]	49[b]
Heavy fuel oil	249[b]	145[b]	49[b]
Fuelwood	45[c]		
Crop residue	91.1[c]		
Animal waste	91.1[c]		
Charcoal	100[d]		

a. AP-42 (US EPA, 1995). b. Kato and Akimoto (1992). c. Streets and Waldhoff (1998), d. Revised 1996 IPCC guidelines (IPCC, 1997). e. Estimated based on ratios of emission factors between power plants and industry in Kato and Akimoto (1992). f. Estimated referring Zhang et al. (2007). g. 30% of emission factors of industry were adopted based on Kato and Akimoto (1992). h. Emission factors were commonly used for coking coal, anthracite and bituminous coal. i. Only defined for China. j. Emission factors for hard coal were adopted. A. Estimated based on ratios of emission factors between power plants and industry in Kato and Akimoto (1992) considering differences of net calorific values. B. 30% of emission factors of industry were adopted.

Coke ovens

For coal input to coke ovens, emission factor was 1.0 t/kt taken from Kato and Akimoto (1992). It is considered that NO_x emissions estimated using this emission factor include contributions from both combustion and non-combustion processes.

Iron and steel industry

In iron and steel industry, emission factors for cokes, coke oven gas, and blast furnace gas were taken from Kato and Akimoto (1992) as follows:

- Coke oven coke: 4.0 t/kt for China and 2.5 t/kt for other countries
- Coke oven gas: 141 t/PJ
- Blast furnace gas: 76.4 t/PJ

For other fuel types, default emission factors were used.

Cement industry

For China, emission factors of coal combustion in each cement kiln type were obtained from Lei et al. (2011a) as follows: 15.3 t/kt for precalciner kilns, 18.5 t/kt for other rotary kilns, and 1.7 t/kt for shaft kilns. Coal consumption in each cement kiln type were estimated based on Lei et al. (2011a) and Hua et al. (2016). For other fuel types, default emission factors in industry were used.

For Japan, NO_x emissions were not estimated based on fuel consumption, but using amount of cement production in each kiln type. Emission factors (t/kt of clinker produced) were taken from AP-42 (US EPA, 1995) as follows: 3.7 for wet process kilns, 3.0 for long dry process kilns, 2.4 for preheater process kilns and 2.1 for preheater/precalciner kilns. Ratio of clinker to cement was assumed to be 0.85 based on Cement handbook (Japan Cement Association, 2019). (See Sect. S4.1.3 for production data by different kiln types.)

For other countries and regions, default emission factors in industry were used for all fuel types.

Settings of emission controls

Settings and assumptions for reduction of NO_x emissions from combustion sources by abatement equipment adopted in REASv3 are summarized in Table 3.10. For other sources not described in Table 3.10, no emission controls were considered.

Table 3.10. Settings and assumptions of emission controls of NO_x

Countries	Settings and assumption
China	● Power plants ➢ Referring Zhang et al. (2007) and Liu et al. (2015), emission factors [t/PJ] for coal fired power plants were assumed considering effects of low-NO_x burner based on capacity and years as follows: ✧ 227: Larger than 300 MW or equal to 300 MW after 1995. ✧ 300: Smaller than 300 MW but equal to or larger than 100 MW after 1997. ✧ 393: Equal to 300 MW before 1995 or Smaller than 300 MW but equal to or larger than 100 MW before 1997. ✧ 369: Less than 100 MW. ✧ 300: Power plants as area sources (no information of capacity) before 2000. The values were assumed to be decreased by 10% until 2010 and by 15% until 2015. ➢ Penetration rates of selective catalytic reduction (SCR: efficiency 73%) and selective non-catalytic reduction (SNCR: efficiency 30%) for each province in 2011 were taken from Chen et al. (2014). Referring Chen et al. (2014), Li et al. (2017), and Zheng et al. (2018), national introduction rates were assumed to be 12%, 18%, and 75% in 2010, 2011, and 2015 and reduction rates for as point sources were estimated. For area sources, 50% of reduction rates of point sources were adopted. ● Industry ➢ Referring Li et al. (2017), effects of De-NO_x system were considered for precalciner kilns in cement plants and penetration rates were roughly assumed to be 0% in 2010, 50% in 2014 and 90% in 2015.
Japan	● Power plants: Referring MRI (2015), JMF and ICETT (2003), and MOEJ (2000), effects of low-NO_x burner and SCR were considered as follows: ➢ Effects of low-NO_x burner were considered after 1970 and reduction efficiencies were assumed to be 15%, 35%, and 50% in 1975, 1980, and after 2005, respectively. Data between 1970, 1975, 1980, and 2005 were interpolated.

	➢ Effects of SCR were considered after 1974 and introduction rates in coal, oil, and gas power plants as point sources were assumed to be 80%, 40%, and 72% in 2002 and 90%, 45%, and 80% after 2010, respectively. Trends of the introduction rates during 1974 -2002 were assumed based on MOEJ (2000) and reduction rates during 2002-2010 were interpolated. For power plants as area sources, reduction rates were assumed to be 85% of point sources. ● Industry: Effects of low-NO_x burner and SCR were roughly assumed referring MRI (2015) and Kato et al. (1991) as follows: ➢ It was assumed that trends of introduction rates of low-NO_x burner were the same as for those of power plants, but reduction efficiencies were 50% of those for power plants as point sources. ➢ For large industries such as cement, iron and steel, it was assumed that trends of penetration rates of SCR were the same as those of power plants, but reduction efficiencies were 50% of those for power plants as point sources. For other industries, reduction rates were assumed to be 50% of those for large industries.
Republic of Korea/Taiwan	● For power plants, introduction rates of low-NO_x burner were 84% and 86% in 2005 and 2010, respectively and those of SCR (SNCR) were 56% (5%) and 68% (5%) in 2005, and 2010, respectively based on Wang et al. (2014). It was roughly assumed that low-NO_x burner, SCR, and SNCR were installed from 1990 and their penetration rates in 2015 were 90%, 73%, and 5%, respectively. Reduction rates between 1990, 2005, 2010, and 2015 were interpolated. ● Due to lack of information, the same settings for Republic ok Korea were adopted to Taiwan.
Others	● Effects of low-NO_x burner and De-NO_x system were assumed as follows: ➢ Power plants as point sources: Reduction rets (0.3-0.5) were assumed if units have information of installed De-NO_x system in World Electric Power Plants Database (Platts, 2018). ● Countries which have power plants with De-NO_x equipment and number of such power plants in 2015 (in parentheses) in REASv3 were as follows: India (11), Indonesia (5), Malaysia (6), Philippines (4), Singapore (4), Thailand (9), Vietnam (4), Pakistan (1), and Sri Lanka (2).

S3.2.3 CO

Default emission factors

Table 3.11 summarized default emission factors used in REASv3 for fuel combustion in power plants, industry and residential sectors. Specific settings for coal combustion and, iron and steel industry, cement and other non-metallic minerals industries were described below the table.

Table 3.11. Default emission factors of CO from fuel combustion in power plants, industry and residential sectors. Unit is t/PJ.

Fuel type	Power plants	Industry	Residential
Hard coal[e]	20[a]	See "Emission factors for coal combustion" below.	
Raw coal[f]	20[a]		
Cleaned coal[f]	20[a]		
Other washed coal[f]	20[a]		
Sub-bituminous coal	20[a]		
Lignite	20[a]		
Coke oven coke	20[a]	150[a]	2000[a]
Natural gas	20[a]	30[a]	50[a]
Gas works gas	20[a]	150[a]	150[a]
Coke oven gas	20[a]	150[a]	150[a]
Blast furnace gas	20[a]	150[a]	150[a]
LPG	15[a]	10[a]	326[a]
Kerosene	15[a]	15[a]	179[a]
Diesel oil	15[a]	15[a]	20[a]
Crude oil	15[a]	15[a]	20[a]
Heavy fuel oil	15[a]	15[a]	20[a]
Fuelwood	255.5[b]	2555[c]	5110[d]
Crop residue	354.5[b]	3545[c]	7090[d]
Animal waste	330[b]	3300[c]	6600[d]
Charcoal	400[b]	4000[a]	7000[a]

a. The global atmospheric pollution forum air pollutant emission inventory manual (SEI, 2012). b. Emission factors of power plants were assumed to be 10% of industry sector. c. Emission factors of industry sector were assumed to be 50% of residential sector. d. Streets and Waldhoff (1999). e. Emission factors were commonly used for coking coal, anthracite and bituminous coal. f. Only defined for China.

Emission factors for coal combustion

(a) Industry sector except for cement and other non-metallic minerals industries

Due to lack of information of detailed boiler and furnace types in industry sub-sectors in each country, CO emission factors of industry sector were roughly assumed in REASv3 as follows:

- 5.75 t/kt: average of emission factors for fluidized bed furnace and automatic stoker boiler based on AP-42 (US EPA, 1995).
    - Default emission factors for Japan, Republic of Korea, and Taiwan
    - Emission factors for large industries in China
- 18.6 t/kt: Emission factors for other industries in China estimated referring Streets et al. (2006) and data for fluidized bed furnace, automatic stoker, and hand-feed stoker in AP-42 (US EPA, 1995).
- 8.5 t/kt: Emission factors based on automatic stoker in AP-42 (UE EPA, 1995) were adopted for large industries in other countries.
- 66.25 t/kt: Emission factors based on average of automatic stoker and hand-feed stoker in AP-42 (UE UPA, 1995) for other industries in other countries.
- It was assumed that emission factors in China were decreased by 25% from 2000 to 2015 linearly assuming improvement in combustion efficiency.

(b) Residential sector

Emission factors for China, India, and other countries were assumed as follows:

- 75 t/kt for China obtained from Streets et al. (2006) for stove in residential sector.
- 275 t/kt for India taken from Pandey et al. (2014) for traditional stove in residential sector.
- 2.61 kt/PJ for other countries as default emission factor derived from the global atmospheric pollution forum air pollutant emission inventory manual (SEI, 2012)

Coke production and iron and steel industry

In REASv3, CO emissions from coke production and iron and steel industry were also estimated using production amounts of coke oven coke, sinter, pig iron, and crude steel (see Sects. S4.2.1 and S4.2.8). CO emission factors for coal consumption in coke ovens, those for coal and coke fuels in blast furnace, and coke furls and gas fuels in iron and industry sectors were assumed to be zero assuming their contributions were included in the emissions estimated based on production amounts described in Sects S4.2.1 and S4.2.8. These mean that CO emissions from combustion sources in coke production and iron and steel industry were not estimated separately in REASv3.

Cement industries

For China, emission factors of coal combustion in each cement kiln type were obtained from Lei et al. (2011a) as follows: 17.8 t/kt for precalciner kilns, 17.8 t/kt for other rotary kilns, and 155.7 t/kt for shaft kilns. Coal consumption in each cement kiln type were estimated based on Lei et al. (2011a) and Hua et al. (2016). For other fuel types, default emission factors in industry were used.

For Japan, CO emissions were not estimated based on fuel consumption, but using amount of cement production in each kiln type. Emission factors (t/kt of clinker produced) were taken from AP-42 (US EPA, 1995) as follows: 0.06 for wet process kilns, 0.11 for long dry process kilns, 0.49 for preheater process kilns and 1.8 for preheater/precalciner kilns. Ratio of clinker to cement was assumed to be 0.85 based on Cement handbook (Japan Cement Association, 2019). (See Sect. S4.1.3 for production data by different kiln types.)

For other countries and regions, 63.8 t/kt were used for emission factors for coal consumption in cement industry based on average of emission factors for precalciner kilns, other rotary kilns, and shaft kilns taken from AP-42 (US EPA, 1995). For other fuel types, default emission factors in industry were used.

Other non-metallic minerals industries

For lime industry, 155.7 t/kt were commonly used for coal combustion in all countries and default emission factors were used for other fuel types. For brick industry, 150 t/kt were used for coal combustion in China and default emission factors were adopted for Japan, Republic of Korea, and Taiwan. For other countries, emissions from brick industry were not estimated based on fuel combustion, but using amount of brick production. Emission factor 2.0 t/kt of brick produced was assumed based on Weyant et al. (2014) (See Sect. S4.2.5). For other sources, default emission factors were used.

S3.2.4 PM species

Default emission factors

Tables 3.12-14 summarized default emission factors of PM_{10}, $PM_{2.5}$, BC, and OC used in REASv3 for fuel combustion in power plants, industry, and residential sectors (Note that emissions of PM species from gas fuels were neglected in REASv3). Specific settings for biofuels, iron and steel industry, cement and other non-metallic minerals industries were described below the table.

Table 3.12. Default emission factors of PM_{10}, $PM_{2.5}$, BC, and OC from fuel combustion in power plants. Unit is t/kt.

Fuel type	PM_{10}	$PM_{2.5}$	BC	OC
Hard coal[f]	12.0[a]	5.08[c]	0.072[a]	0.0[a]
Raw coal[g]	46.0[b]	12.0[b]	0.024[b]	0.0[b]
Cleaned coal[g]	46.0[b]	12.0[b]	0.024[b]	0.0[b]
Other washed coal[g]	46.0[b]	12.0[b]	0.024[b]	0.0[b]
Sub-bituminous coal	29.0[a]	9.3[c]	0.174[a]	0.0[a]
Lignite	29.0[a]	9.3[c]	0.174[a]	0.0[a]
Coke oven coke[h]	12.0	5.08	0.072	0.0
Diesel oil	0.49[a]	0.186[d]	0.147[a]	0.0441[a]
Crude oil[i]	1.1	0.775	0.088	0.033
Heavy fuel oil	1.1[a]	0.775[d]	0.088[a]	0.033[a]
Fuelwood	2.2[e]	1.79[e]	0.11[e]	0.44[e]
Crop residue[j]	2.2	1.79	0.11	0.44
Animal waste[j]	2.2	1.79	0.11	0.44
Charcoal	4.1[e]	3.32[e]	0.205[e]	0.82[e]

a. Bond et al. (2004). b. Lei et al. (2011b). c. $PM_{2.5}/PM_{10}$ ratios were estimated based on AP-42 (US UPA, 1995). d. $PM_{2.5}/PM_{10}$ ratios were estimated based on Klimont et al. (2002b). e. Emission factors of PM_{10}, BC, and OC for fuelwood and charcoal were taken from Bond et al. (2004). $PM_{2.5}/PM_{10}$ ratios were estimated based on the global atmospheric pollution forum air pollutant emission inventory manual (SEI, 2012). f. Emission factors were commonly used for coking coal, anthracite and bituminous coal. g. Only defined for China. h. Emission factors for hard coal were adopted. i. Emission factors for heavy fuel oil were adopted. j. Emission factors for fuelwood were adopted.

Table 3.13. Default emission factors of PM_{10}, $PM_{2.5}$, BC, and OC from fuel combustion in industry sector. Unit is t/kt.

Fuel type	PM_{10}	$PM_{2.5}$	BC	OC
Hard coal[f]	4.2[a]	1.79[c]	0.84[a]	0.168[a]
Raw coal[g]	7.21[b]	2.17[b]	0.412[b]	0.0868[b]
Cleaned coal[g]	7.21[b]	2.17[b]	0.412[b]	0.0868[b]
Other washed coal[g]	7.21[b]	2.17[b]	0.412[b]	0.0868[b]
Sub-bituminous coal	17.0[a]	7.23[c]	0.85[a]	1.7[c]
Lignite	17.0[a]	7.23[c]	0.85[a]	1.7[c]
Coke oven coke[h]	4.2	1.79	0.84	0.168
Kerosene	0.9[a]	0.341[d]	0.117[a]	0.09[a]
Diesel oil	0.49[a]	0.186[d]	0.147[a]	0.0441[a]
Crude oil[i]	1.1	0.775	0.088	0.033
Heavy fuel oil	1.1[a]	0.775[d]	0.088[a]	0.033[a]
Fuelwood	6.1[e]	4.95[e]	0.555[e]	3.22[e]
Crop residue[j]	6.1	4.95	0.555	3.22
Animal waste[j]	6.1	4.95	0.555	3.22
Charcoal	4.1[e]	3.32[e]	0.205[e]	0.82[e]

a. Bond et al. (2004). b. Estimated based on Lei et al. (2011b) and Streets et al. (2006). c. $PM_{2.5}/PM_{10}$ ratio was estimated based on the global atmospheric pollution forum air pollutant emission inventory manual (SEI, 2012). OC/BC ratio was assumed based on ABC Emission Inventory Manual (Shrestha et al., 2013). d. $PM_{2.5}/PM_{10}$ ratios were estimated based on Klimont et al. (2002b). e. Emission factors of PM_{10}, BC, and OC for fuelwood and charcoal were taken from Bond et al. (2004). $PM_{2.5}/PM_{10}$ ratios were estimated based on the global atmospheric pollution forum air pollutant emission inventory manual (SEI, 2012). f. Emission factors were commonly used for coking coal, anthracite and bituminous coal. g. Only defined for China. h. Emission factors for hard coal were adopted. i. Emission factors for heavy fuel oil were adopted. j. Emission factors for fuelwood were adopted.

Table 3.14. Default emission factors of PM_{10}, $PM_{2.5}$, BC, and OC from fuel combustion in residential sector. Unit is t/kt.

Fuel type	PM_{10}	$PM_{2.5}$	BC	OC
Hard coal[i]	7.4[a]	4.49[a]	1.02[a]	2.15[a]
Raw coal[j]	8.82[b]	6.86[b]	1.56[b]	3.29[b]
Cleaned coal[j]	8.82[b]	6.86[b]	1.56[b]	3.29[b]

Other washed coal[j]	8.82[b]	6.86[b]	1.56[b]	3.29[b]
Sub-bituminous coal	4.6[c]	2.79[c]	0.636[c]	1.334[c]
Lignite	4.6[c]	2.79[c]	0.636[c]	1.334[c]
Coke oven coke[k]	7.4	4.49	1.02	2.15
LPG	0.52[d]	0.197[d]	0.0676[d]	0.052[d]
Kerosene	0.9[d]	0.341[d]	0.117[d]	0.09[d]
Diesel oil	0.49[d]	0.186[d]	0.147[d]	0.044[d]
Crude oil[l]	1.1	0.775	0.088	0.033
Heavy fuel oil	1.1[d]	0.775[d]	0.088[d]	0.033[d]
Fuelwood	5.76[e], 4.80[f]	5.58[e], 4.60[f]	1.12[e], 0.85[f]	4.46[e], 3.20[f]
Crop residue	7.21[e], 6.01[f]	6.98[e], 5.75[f]	1.05[e], 0.95[f]	3.98[e], 3.70[f]
Animal waste	9.8[g]	9.8[g]	0.4[g]	3.1[g]
Charcoal	4.1[h]	3.32[h]	0.205[h]	0.82[h]

a. Estimated based on PM_{10} emission factors for residential sectors in Bond et al. (2004) and ratios of $PM_{2.5}$, BC, and OC to PM_{10} in Lei et al. (2011b). b. Estimated based on emission factors for stove in Lei et al. (2011b). c. Emission factor for PM_{10} derived from Bond et al. (2004) and ratios of $PM_{2.5}$, BC, and OC to PM_{10} were from those for hard coal. d. Bond et al. (2004) for PM_{10}, BC, and OC and $PM_{2.5}/PM_{10}$ ratios were estimated based on Klimont et al. (2002b). e. Estimated based on Lei et al. (2011b) and used for East Asian countries. f. Estimated based on Pandy et al. (2014) and used for Southeast and South Asian countries. g. Estimated based on Pandy et al. (2014) and commonly used for all countries. h. Emission factors of PM_{10}, BC, and OC were taken from Bond et al. (2004). $PM_{2.5}/PM_{10}$ ratios were estimated based on the global atmospheric pollution forum air pollutant emission inventory manual (SEI, 2012). i. Emission factors were commonly used for coking coal, anthracite and bituminous coal. j. Only defined for China. Values were gradually decreased from 1990 until their two third by 2005 referring Lei et al. (2011b). k. Emission factors for hard coal were adopted. l. Emission factors for heavy fuel oil were adopted.

Coke production and iron and steel industry

The same as for CO, in REASv3, emissions of PM species from coke ovens were also estimated base on production amounts of coke oven coke (see Sect. S4.2.8). Emission factors of PM species for coal consumption in coke ovens were assumed to be zero assuming their contribution were included in the emissions estimated based on production amounts of coke described in Sect. S4.2.8. For China, emissions of PM species from iron and steel production were also estimated base on production amounts of sinter, pig iron, and crude steel (see Sect. S4.2.1). It was assumed that emission factors for sinter and pig iron production obtained from Lei et al (2011b) include emissions from coal combustion. Therefore, emission factors of PM species for coal combustion in iron and steel industry were assumed to be zero for China.

Cement industry

Emissions of PM species in China and Japan were not estimated based on fuel consumption, but using amount of cement production in each kiln type. For China, emission factors (t/kt of cement produced) of PM_{10}/$PM_{2.5}$/BC/OC were estimated based on Hua et al. (2016) and Lei et al. (2011a, b) as follows: 44.8/19.2/0.115/0.192 for precalciner kilns, 37.3/14.9/0.0894/0.149 for other rotary kilns, and 8.9/3.2/0.0192/0.032 for shaft kilns. For Japan, emission factors of PM_{10}/$PM_{2.5}$/BC/OC (t/kt of clinker produced) were taken from AP-42 (US EPA, 1995) and Kupiainen and Klimont (2004) as follows: 15.6/4.55/0.0273/0.0455 for wet process kilns, 35.9/15.4/0.0924/0.154 for long dry process kilns, 54.6/23.4/0.140/0.234 for preheater process kilns and preheater/precalciner kilns. Ratio of clinker to cement was assumed to be 0.85 based on Cement handbook (Japan Cement Association, 2019). (See Sect. S4.1.3 for production data by different kiln types.). For other countries and regions, default emission factors in industry were used for all fuel types. See Sect. S4.2.3 for non-combustion emissions from cement production.

Brick industry

Emissions of PM species from brick production were not estimated based on fuel combustion, but using amount of brick production. Emission factors of PM_{10}/$PM_{2.5}$/BC/OC were assumed referring Lei et al. (2011b), Weyant et al. (2014), and Klimont et al. (2017) as follows:

- China: 0.71/0.27/0.108/0.0945 t/kt of brick produced
- Japan, Republic of Korea, and Taiwan: 0.473/0.18/0.002/0.0035 t/kt of brick produced
- Other countries: 0.5/0.19/0.15/0.007 t/kt of brick produced

Settings of emission controls

Settings and assumptions for reduction of emissions of PM species from combustion sources by abatement equipment adopted in REASv3 are summarized in Table 3.15. For other sources not described in Table 3.15, no emission controls were considered. Note that the reduction rates of $PM_{2.5}$ were applied to BC and OC.

Table 3.15. Settings and assumptions of emission controls of PM species.

Countries	Settings and assumption
China	● Power plants ➢ Effects of control technologies by cyclones, wet scrubbers, electrostatic precipitators (ESP), and fabric filters during 1990-2015 were estimated based on their penetration rates in Lei et al. (2011b) and Zhao et al. (2014). ➢ Reduction rates of PM_{10}/$PM_{2.5}$ were assumed to be 0.84/0.62, 0.92/0.78, and 0.98/0.94, and in 1990, 2000, and 2015, respectively. It was assumed that reduction rates before 1970 were zero and the values between 1970 and 1990 were interpolated. ● Industry ➢ Iron and steel industry: See Sect. S4.2.1 ➢ Coke ovens: See Sect. S4.2.8. ➢ Non-ferrous metals industry: See Sect. S4.2.2 ➢ Cement industry: See Sect. S4.2.3. ➢ Lime industry: See Sect. S4.2.4. ➢ Brick industry: See Sect. S4.2.5. ➢ Other industries: Due to lack of information, reduction rates were roughly assumed as follows: Reduction rates of PM_{10} and $PM_{2.5}$ in 1990 were 0.55 and 0.25 referring settings of cement industry. Those in 2015 were 0.77 and 0.53 referring Wang et al. (2014) for settings of industry in 2010. It was assumed that reduction rates before 1980 were zero and the values between 1980, 1990, and 2015 were interpolated.
India	● Due to lack of information, referring Sadavarte and Venkataraman (2014), Pandey et al. (2014), Guttikunda and Jawahar (2014), and Reddy and Venkataraman (2002), reduction rates of PM_{10}/$PM_{2.5}$ for power plants and industries during 1980-2015 were roughly assumed

	as follows: ➢ Power plants: 0.0/0.0, 0.45/0.40, 0.85/0.81, and 0.87/0.85 in 1980, 1985, 2000, and 2015, respectively. Values between 1980, 1985, 2000, and 2015 were interpolated. ➢ Iron and steel and cement industries: 0.0/0.0, 0.47/0.46, and 0.85/0.83 in 1980, 1995, and 2015, respectively. Values between 1980, 1995, and 2015 were interpolated. ➢ Other industries: 0.0/0.0, 0.40/0.30, and 0.45/0.40 in 1980, 1995, and 2015, respectively. Values between 1980, 1995, and 2015 were interpolated.
Japan	● Referring MRI (2015) and other literatures such as Shimoda (2016), Suzuki (1990) and Goto (1981), following assumptions were considered for control equipment of PM species: ➢ Introduction of control equipment for power plants was expanded from 1957. ➢ Introduction of bag filter was expanded from 1960. ➢ From 1968, installation of ESP in power plants became mandatory. ➢ Introduction of high quality ESP was expanded from 1975. ➢ Regulations for PM species were strengthened from 1995. ● Based on above assumption, reduction rates of PM_{10}/$PM_{2.5}$ for power plants were assumed as follows: 0.37/0.27, 0.9/0.88, and 0.995/0.99 in 1960, 1975, and after 2000, respectively. It was assumed that reduction rates before 1956 were zero and the values between 1950, 1960, 1975, and 2000 were interpolated. ● For industry, reduction rates of PM_{10}/$PM_{2.5}$ after 2000 were assumed to be 0.99/0.985 for iron and steel and cement industries and 0.98/0.96 for other industries. Trends between 1950 and 2000 were assumed to be the same as for those of power plants.
Republic of Korea/Taiwan	● Power plants: Based on Wang et al. (2014), reduction rates of PM_{10} and $PM_{2.5}$ after 2005 were assumed to be 0.985 and 0.97, respectively. Referring Ebata et al. (1997), it was assumed that penetration rates of control equipment of PM species in 1990 were already high. Reduction rates in 1990 were assumed to be 0.9 and 0.88 for PM_{10} and $PM_{2.5}$, respective and zero before 1970. Values between 1970, 1990, and 2005 were interpolated.

	● Industry: Based on Wang et al. (2014), reduction rates of $PM_{10}/PM_{2.5}$ in 2005 and in 2010 were assumed to be 0.944/0.905 and 0.948/0.910, respectively. It was roughly assumed that reduction rates of $PM_{10}/PM_{2.5}$ in 2015 were 0.968/0.935, respectively and zero before 1970. Values between 1970, 2005, 2010, and 2015 were interpolated. ● Due to lack of information, the same settings for Republic of Korea were adopted.
Thailand	● Power plants: Referring Thao Pham et al. (2008), reduction rates of PM_{10} and $PM_{2.5}$ in 2000 were assumed to be 0.84 and 0.80, respectively. For trends of reduction rates, it was roughly assumed that reduction rates of PM_{10} and $PM_{2.5}$ were increased to 0.90 and 0.88 in 2015, respectively and zero before 1980. Values between 1980, 2000, and 2015 were interpolated. ● Industry: Referring Thao Pham et al. (2008), for iron and steel and cement industries, reduction rates of PM_{10} and $PM_{2.5}$ in 2005 were assumed to be 0.82 and 0.80, respectively. For trends of reduction rats, it was roughly assumed that reduction rates of PM_{10} and $PM_{2.5}$ in 2015 were 0.85 and 0.83, respectively and zero before 1980. Values between 1980, 2000, and 2015 were interpolated. For other industries, 50% of reduction rates of iron and steel and cement industries were adopted.
Others	● Due to lack of information, settings of Thailand during 1980-2005 were adopted for those of Indonesia, Malaysia, Myanmar, Philippines, Vietnam, and Mongolia during 1990-2015 and the same settings of Thailand were used for Singapore. ● For Laos and Sri Lanka, reduction rates of 0.95/0.92 for $PM_{10}/PM_{2.5}$ were used for large power plants equipped with ESP based on information from World Electric Power Plants Database (Platts, 2018),

S3.2.5 Other species and sources

NMVOC

Emission factors for fossil fuel combustion were taken from REASv2 based on Wei et al. (2008) for East Asian countries and the global atmospheric pollution forum air pollutant emission inventory manual (SEI, 2012) for Southeast and South Asian countries. For fuelwood, crop residue, and animal waste, emission factors were estimated as follows:

- Fuelwood
  - 3.13 t/kt based on Wei et al. (2008) for East Asian countries
  - 15.9 t/kt based on Sharma et al. (2015) for Southeast and South Asian countries
- Crop residue
  - 8.36 t/kt based on Wei et al. (2008) for East Asian countries
  - 13.3 t/kt based on Sharma et al. (2015) for Southeast and South Asian countries
- Animal waste
  - 10.4 t/kt based on Sharma et al. (2015) for all countries
- Charcoal
  - 100 t/PJ taken from IPCC (1997) for all countries

Emission factors described above were for total NMVOC. In REASv3, total NMVOC emissions were allocated to 19 NMVOC species categories defined in Sect. S2.1. The speciation was conducted based on speciation profiles for each sub-sector and fuel type provided by D. G. Streets (private communication) generally based on Klimont et al. (2002a) used for REASv1 and REASv2. The speciation profiles were commonly used for all countries and periods.

NH_3

Emission factors for fossil fuel combustion were taken from REASv1 based on EMEP/CORINAIR Emission Inventory Guidebook (EEA, 1996). For biofuel, 1.29 t/kt for fuelwood and 0.97 t/kt for charcoal were obtained from ABC Emission Inventory Manual (Shrestha et al., 2013). Due to lack of information, the emission factor for fuelwood was adopted to crop residue and animal waste.

CO_2

Emission factors for fuel combustion except for fuelwood, crop residue, and animal wastes were obtained from 2006 IPCC Guidelines for National Greenhouse Gas Inventories (IPCC, 2006). Default emission factors were used except for those of coal combustion in China where lower values were adopted referring Guan et al. (2012). Emission factors for fuelwood, crop residue, and animal wastes were 83.1, 87.0, and 76.9 kt/PJ derived from Streets and Waldhoff (1999).

Agriculture

For emissions from fuel combustion in agriculture sub-sector, emission factors of industry sector were used except for following settings for diesel oil referring Bond et al. (2004) and ABC Emission Inventory Manual (Shrestha et al., 2013):

- 50.3 t/kt for NO_x
- 16.0 t/kt for CO
- 2.0 t/kt for PM_{10}
- 1.72 t/kt for $PM_{2.5}$
- 1.14 t/kt for BC
- 0.36 t/kt for OC

Charcoal production

Activity data to estimate emissions from charcoal production as energy transformation sectors is wood input. Fuelwood consumption data developed based on methodologies described in Sect. S3.1 were used. Emission factors of NO_x, CO, and NMVOC were taken from Revised 1996 IPCC guidelines (IPCC, 1997) and those of others were based on Akagi et al. (2011).

S4. Stationary non-combustion: Industrial production and other transformation

Descriptions for evaporative NMVOC emissions and NH_3 emissions from non-combustion sources are provided in Sects. S5 and S8, respectively.

S4.1 Activity data

S4.1.1 Iron and steel production

Activity data to estimate non-combustion emissions from iron and steel production industry in REASv3 are production amounts of pig iron, crude steel, sinter, and hot rolled products. National total production of pig iron, crude steel, and hot rolled products were obtained from Steel Statistical Yearbook (World Steel Association, https://www.worldsteel.org/steel-by-topic/statistics/steel-statistical-yearbook.html) during 1968-2015 and extrapolated to 1950 using trends of pig iron and crude steel production in Mitchell (1998). For crude steel, production data by each process, oxygen-blown converter, electric furnace, and open-hearth furnace were separately obtained. Sinter production data were taken from Steel Statistical Yearbook during 1977-1992. For China, sinter production data were available during 2000-2015 and those between 1992 and 2000 were interpolated. Then, missing data between 1950 and 2015 were estimated based on trends of pig iron production in each country.

For regional distribution in China, production amounts of steel during 1950-2015 and pig iron during 1983-2015 in each region were available in China Data Online and China Statistical Yearbook (National Bureau of Statistics of China, 1986-2016), respectively. Pig iron data before 1982 were extrapolated for each region using the trends of steel production in China Data Online. Then, using the steel data, production amounts of crude steel and hot rolled products in China total were distributed to each region. Similarly using the regional pig iron data, sinter and pig iron production amounts in whole China were distributed to each region. For India, ratios of crude steel production in 17 sub-regions were estimated using Minerals Yearbook (United States Geological Survey (USGS)) and Indiastat during 2000-2015. Using the regional data, production amounts of pig iron, crude steel, singer, and hot rolled products in India total were distributed to each sub-region. For Japan, ratios of steel production amounts in 6 sub-regions during 2003 and 2011 were estimated using statistics of major factories (https://www.japanmetaldaily.com/statistics/crudemateworks/details/index.html) and production data of pig iron, crude steel, singer, and hot rolled products in India total were distributed to each sub-region.

S4.1.2 Non-ferrous metal production

In REASv3, non-combustion emissions from copper, zinc, lead, and aluminum production were considered in non-ferrous metal production processes. Activity data were production amounts of primary copper, zinc, lead, alumina, aluminum, and secondary aluminum obtained from Minerals Yearbook during 1960-2015 (USGS) and extrapolated to 1950 using trends of corresponding production data in Mitchell (1998). For China, India, and Japan, national total data need to be distributed to each sub-region. Weighting factors for the distribution were estimated during 1995-2015 using annual generation capacities of major plants in Minerals Yearbook (USGS). Before 1994, the weighting factors for 1995 were used.

S4.1.3 Cement production

Activity data for non-combustion emissions from cement industry are production amounts of cement. For China, regional data were basically available in China Data Online during 1950-2015. However, not all regions had complete data during the period and sometimes interpolation and extrapolation procedures were necessary. Therefore, in REASv3, regional data were used for weighting factors to distribute national total data of cement production to each sub-region. For Japan, national cement production during 1990-2015 were obtained from Minerals Yearbook (USGS) and extrapolated to 1950 using trends of corresponding data in the Historical Statistics of Japan (Japan Statistical Association, 2006). For the distribution to each sub-region, first, weighting factors in 2004 and 2018 were estimated using production amounts by major cement plants. Then, those during 2005-2015 were interpolated and data in 2004 were used before 2003. In addition to total amounts, production data by different kiln types were available in China (Hua et al., 2016) and Japan (Japan Cement Association, http://www.jcassoc.or.jp/cement/2eng/index.html). For other countries, national total production during 1960-2015 were obtained from Minerals Yearbook (USGS). For extrapolation to 1950, in REASv3, trends of national CO_2 emissions from cement production taken from CDIAC (Carbon Dioxide Information Analysis Center) (Marland et al., 2008). For regional data in India, weighting factors during 1984 and 2009 were estimated using regional production data in TERI Energy & Environment Data Diary and Yearbook (TERI, 2013, 2018). Before 1983 and after 2010, data in 1984 and 2009 were used, respectively.

S4.1.4 Lime production

Activity data for non-combustion emissions from lime industry are production amounts of lime. Data were obtained from Minerals Yearbook during 1960-2015 (USGS) and were extrapolated to 1950 using trends of cement production estimated in REASv3.

S4.1.5 Brick production

Activity data for non-combustion emissions from brick industry are production amounts of brick. However, unlike the other products in non-metallic minerals industry, brick production data were not available in most international and national statistics. For Japan, national production data during 1950-2007 were taken from Hiragushi (2009) and Japan Statistical Yearbook (Statistics Bureau, 2010-2018) and were distributed to 6 sub-regions using total fuel consumption in non-metallic minerals sector. For other countries, first, default data were prepared taken from REASv2 and GAINS ASIA at that time during 1990-2015 and extrapolated to 1950 using trends of cement production in each country. For China, Vietnam, Bangladesh, India, and Pakistan, national production data in 1990, 2000, 2005, and 2010 were obtained from Klimont et al. (2017) and interpolated during 1990-2010 and extrapolated to 2015 using trends of the default data. For China, data between 1980-1990 were extrapolated based on trends of production in Zhang (1997) and those before 1980 were extrapolated using trends of the default data. For regional distribution, fuel consumption data in brick production in each region (see Sects. S3.1.3 and S3.1.7) were used for weighting factors. For India, data between 1983-1990 were extrapolated based on trends of production in Industrial Commodity Statistical Yearbook taken from UN data, which is a web-based data service of the UN (http://data.un.org/) and those before 1983 were extrapolated using trends of the default data. For regional distribution, common weighting factors during 1950-2015 were estimated based on Maithel et al. (2012). For Vietnam, Bangladesh, and Pakistan, data before 1990 were extrapolated using trends of the default data. For Nepal, production data in 2006 were obtained from Maithel (2013) and extrapolated during 1950-2015 using trends of the default data. For Rep. of Korea, Indonesia, Myanmar, the default data were used during 1990-2015 and before 1990, data were extrapolated to 1985 using trends of production in Industrial Commodity Statistical Yearbook and then extended to 1950 using trends of the default data. For other countries, the default data were directly used.

S4.1.6 Sulphuric acid production

Activity data to estimate non-combustion emissions from sulphuric acid plants are amounts of total sulphuric acid production in each country and region. For China, national total production data during 1950-2015 were obtained from China Data Online and distributed to each region using regional data during 1983-2015 in China Statistical Yearbook (National Bureau of Statistics of China, 1986-2016). Before 1983, data in 1983 were used as weighting factors for the regional distribution. For Japan, national production data were taken from statistics provided by the Sulphuric Acid Association of Japan (http://www.ryusan-kyokai.org/) during 1983-2015 and extrapolated to 1950 using trends of sulphuric acid production in Mitchell (1998). Weighting factors for regional distribution were estimated using annual generation capacities of major plants in 2015 in Minerals Yearbook (USGS). For other countries, national total production data were provided by the Sulphuric Acid Association of Japan during 1980-2015 and extrapolated to 1950 using trends of sulphuric acid production in Mitchell (1998). For India, national total data were distributed to 17 sub-regions using data of REASv2 during 2000-2008 based on GAINS ASIA at that time. For the weighting factors, data in 2000 and 2008 were used before 2000 and 2008, respectively.

S4.1.7 Carbon black production

In REASv3, non-combustion emissions from carbon black production were only considered for China, India, Japan, and, Rep. of Korea. Similar to brick production, default data were prepared taken from REASv2 and GAINS ASIA at that time during 1990-2015 and extrapolated to 1950 using GDP in each country and region. For GDP, regional data in China during 1950-2015 were obtained from China Data Online. For other countries, data during 1970-2015 were derived from UN data, which is a web-based data service of the UN (http://data.un.org/) and extrapolated to 1960 using OECD Data (https://data.oecd.org/gdp/gross-domestic-product-gdp.htm) and then extrapolated to 1950 using trends of total population.

For China, national total production in 2010 were obtained from Wei et al. (2011) and were extrapolated during 1950-2015 and distributed to each region using the default data as weighting factors. For India, national production data during 1983-2003 were taken from Industrial Commodity Statistical Yearbook taken from the UN data and similar to China, the data were extrapolated during 1950-2015 and distributed to each region using the default data. For Japan and Rep. of Korea, national production data during 1964-2014 were obtained from Mineral Yearbook (USGS) and extrapolated during 1950-2015 and data in Japan were distributed to 6 sub-regions using the default data.

S4.1.8 Other transformation sectors

Coke ovens

In REASv3, activity data to estimate emissions from coke ovens as energy transformation sectors are coal input for SO_2 and NO_x and coke production for CO, NMVOC, CO_2, and PM species. Coal consumption was taken from data developed based on methodologies described in Sect. S3.1. For coke production, national data were obtained from the International Energy Agency (IEA) World Energy Balances (IEA, 2017) during 1960-2015 for Japan and 1971-2015 for other countries. The data were extrapolated to 1950 based on trends of pig iron production before 1959 and 1970 for Japan and other countries, respectively. For China, regional production data during 1990-2015 were available in the China Energy Statistical Yearbook (CESY) (National Bureau of Statistics of China, 1986, 2001-2017) and used to distribute national total production data to each sub-region. Before 1990, data in 1990 were used. For India and Japan, weighting factors for the regional distribution were based on regional pig iron production data in each country.

Petroleum refineries

Activity data to estimate emissions from petroleum refineries as energy transformation sectors is crude oil input. Consumption data of crude oil developed based on methodologies described in Sect. S3.1 were used.

S4.2 Emission factors and settings of emission controls

S4.2.1 Iron and steel production

Emission factors

In REASv3, emissions of CO, NMVOC, CO_2, and PM species were estimated using production amounts of sinter, pig iron, crude steel, and rolled steel. Default emission factors are summarized in Table 4.1 and emission factors of PM species for China are provided in Table 4.2. Note that emission factors of CO for all countries and those of PM species for China include contributions from both combustion and non-combustion emissions. (See also Sects. S3.2.3 and S3.2.4.)

Table 4.1. Default emission factors of CO, NMVOC, CO_2, PM_{10}, $PM_{2.5}$, BC, and OC from production of sinter, pig iron, crude steel, and rolled steel. It was assumed that both combustion and non-combustion emissions are included in emission factors of CO. Unit is t/kt-produced.

	Sinter	Pig iron	Crude steel/ OHF[a]	Crude steel/ BOF[a]	Crude steel/ EF[a]	Rolled steel
CO	22.0[b]	40.5[c]	34.5[d]	69.0[b]	9.0[b]	-
NMVOC[e]	-	-	0.055	0.055	0.055	0.025
CO_2[f]	-	-	-	-	80.0	-
PM_{10}[g]	1.555	0.490	8.760	14.63	10.18	-
$PM_{2.5}$[g]	0.691	0.300	6.330	10.45	7.550	-
BC[h]	0.005	0.018	-	-	-	-
OC[h]	0.026	-	-	2.090	0.180	-

a. OHF: Open-hearth furnace, BOF: Basic oxygen furnace, and EF: Electric furnace. b. AP-42 (US EPA, 1995), c. Streets et al. (2006), d. 50% of BOF was adopted. e. Klimont et al. (2002a). f. IPCC (2006). g. Klimont et al. (2002b). h. Kupiainen and Klimont (2004).

Table 4.2. Emission factors of PM_{10}, $PM_{2.5}$, BC, and OC from production of sinter, pig iron, crude steel, and rolled steel for China. It was assumed that both combustion and non-combustion emissions are included (except for emission factors of PM species for crude steel production). Unit is t/kt-produced.

	Sinter	Pig iron	Crude steel/ OHF[a]	Crude steel/ BOF[a]	Crude steel/ EF[a]	Rolled steel
CO[b]	22.00	40.50	27.10[d]	54.20	9.000	-
PM_{10}[c]	6.050	9.650	19.10	14.63	8.120	-
$PM_{2.5}$[c]	2.620	6.000	13.80	10.45	6.020	-
BC[c]	0.0262	0.600	0.138	-	-	-
OC[c]	0.131	0.120	0.690	2.090	0.120	-

a. OHF: Open-hearth furnace, BOF: Basic oxygen furnace, and EF: Electric furnace. b. Streets et al. (2006). c. Lei et al. (2011b). d. 50% of BOF was adopted.

For CO, the gas from blast furnace and basic oxygen furnace is collected and recycled in modern factories (Streets et al., 2006) and in REASv1, corresponding CO emissions in Japan were neglected. In REASv3, following settings were roughly assumed:

- China: Emission factors in Table 4.2 were used during 1950-2000 and 50% of the value was adopted in 2015. Emission factors between 2000 and 2015 were interpolated.
- Japan: Default emission factors were used before 1960 and 10% of the value was adopted after

1990. Emission factors between 1960 and1990 were interpolated.

- Republic of Korea and Taiwan: Default emission factors were used before 1975 and 10% of the value was adopted after 2005. Emission factors between 1975 and 2005 were interpolated.

Settings of emission controls

For iron and steel production, emission controls were only considered for PM species. Settings and assumptions for reduction of emissions in China by abatement equipment adopted in REASv3 are summarized in Table 4.3. For other countries, the same settings for combustion emissions in iron and steel industry were adopted. (See Table 3.15 in Sect. S3.2.4.)

Table 4.3. Settings and assumptions of emission controls of PM species for iron and steel production in China.

Countries	Settings and assumption
China	● Referring Wu et al. (2017), reduction rates of $PM_{10}/PM_{2.5}$ for sinter production, pig iron, BOF, and EF in 2000, 2005, 2010, and 2015 were assumed as follows ➢ Sinter: 0.780/0.592, 0.892/0.809, 0.946/0.916, and 0.956/0.939 ➢ Pig iron: 0.850/0.715, 0.910/0.844, 0.954/0.936, and 0.961/0.945 ➢ BOF: 0.850/0.715, 0.870/0.758, 0.955/0.937, and 0.959/0.943 ➢ EF: 0.782/0.568, 0.834/0.678, 0.900/0.815, and 0.977/0.968 ● It was assumed that reduction rates were zero in 1980 and values between 1980, 2000, 2005, 2010, and 2015 were interpolated.

S4.2.2 Non-ferrous metal production

In REASv3, emissions of SO_2, PM_{10}, and $PM_{2.5}$ were estimated using production amounts of copper, zinc, lead, and aluminum.

SO_2

Default emission factors were taken from Kato and Akimoto (1992) as follows:

- Copper: 2.0 kt/kt- produced
- Zinc: 1.0 kt/kt-produced
- Lead: 0.32 kt/kt-produced

In some countries, SO_2 emitted from non-ferrous metal plants were collected and used for materials of sulphuric acid. In that case, the amounts of collected SO_2 need to be reduced from SO_2 emissions calculated by default emission factors. In REASv3, amounts of sulphuric acid produced using SO_2 collected from non-ferrous metal plants were obtained from the Sulphuric Acid Association of Japan based on reports of International Fertilizer Industry Association, the British Sulphur Cooperation Limited, Sulphuric Acid Notebook of Japan, and Kato et al. (1991). In addition, the same reduction rates of SO_2 by emission control equipment for non-ferrous metal industry were adopted.

PM_{10} and $PM_{2.5}$

Default emission factors t/kt-produced were obtained from Lei et al. (2011b) for China and Klimont et al. (2002b) for other countries as follows:

China:

- Copper, Zinc, and Lead: 276.0 for PM_{10} and 246.0 for $PM_{2.5}$
- Aluminum (primary): 26.51 for PM_{10} and 18.28 for $PM_{2.5}$
- Aluminum (secondary): 6.98 for PM_{10} and 5.20 for $PM_{2.5}$

Other countries:

- Copper, Zinc, and Lead: 13.8 for PM_{10} and 12.3 for $PM_{2.5}$
- Aluminum (primary): 27.26 for PM_{10} and 18.5 for $PM_{2.5}$
- Aluminum (secondary): 6.97 for PM_{10} and 5.195 for $PM_{2.5}$

For emission controls, the same settings for combustion emissions in industry sectors were adopted except for China. (See Table 3.15 in Sect. S3.2.4.) For China, reduction rates were assumed as follows:

- Referring Zhao et al. (2014), reduction rates of PM_{10}/$PM_{2.5}$ in 2010 and 2015 were 0.910/0.882 and 0.945/0.906, respectively and values between 2010 and 2015 were interpolated.
- Trends of reduction rates between 1980 and 2010 were assumed to be the same as settings for combustion emissions in other industries. (See Table 3.15 in Sect. S3.2.4.)

S4.2.3 Cement production

In REASv3, emissions of CO_2 and PM species for all countries and those of NO_x and CO for Japan were estimated using production amounts of cement. For emission of NO_x and CO in Japan and those of PM species in China and Japan, emission factors for combustion emissions were described in Sects. S3.2.2, S3.2.3 and S3.2.4, respectively. In this sub-section, emission factors for non-combustion emissions were described.

Default emission factor of CO_2 was 0.52 t/t-clinker produced based on IPCC (2006). Clinker to cement ratios were roughly assumed as follows:

- China: 0.72 before 2005 and 0.6 in 2015 based on Gao et al. (2017). Values between 2005 and 2005 were interpolated.
- India: 0.83 before 1990 and 0.77 after 2005 based on Barcelo (2014). Values between 1990 and 2005 were interpolated.
- Japan: 0.85 base on Cement handbook (Japan Cement Association, 2019)
- Others: 0.9 before 1990 and 0.85 after 2005 based on Barcelo (2014). Values between 1990 and 2005 were interpolated.

For PM species, default emission factors of PM_{10}, $PM_{2.5}$, BC, and OC t/kt-produced were assumed as follows:

- China: 34.3, 9.8, 0.0588, and 0.098 were taken from Hua et al. (2016) and Lei et al. (2011a).
- Others: 16.0, 4.64, 0.0278, and 0.0464 were derived from AP-42 (US EPA, 1995) and Lei et al. (2011a).

For emission controls, the same settings for combustion emissions in cement industry were adopted except for China. (See Table 3.15 in Sect. S3.2.4.) For China, reduction rates were assumed as follows:

- Referring Hua et al. (2016), reduction rates of $PM_{10}/PM_{2.5}$ during 1980-2012 were estimated for each year. Values were 0.565/0.218, 0.586/0.250, 0.746/0.527, and 0.973/0.916 in 1980, 1990, 2000, and 2012, respectively.
- It was roughly assumed that reduction rates of $PM_{10}/PM_{2.5}$ in 2015 were 0.98/0.97 and zero in 1975. Values between 1975 and 1980 and those between 2010 and 2015 were interpolated.

S4.2.4 Lime production

In REASv3, emissions of CO_2 and PM species were estimated using production amounts of lime. Default emission factors of CO_2 were taken from IPCC (2006) and those of PM species were derived from Klimont et al. (2002b) and Kupiainen and Klimont (2004) as follows:

- CO_2: 750 t/kt-produced
- PM_{10}: 12.0 t/kt-produced
- $PM_{2.5}$: 1.4 t/kt-produced
- BC: 0.028 t/kt-produced
- OC: 0.014 t/kt-produced

For emission controls of PM species, the same settings for combustion emissions in industry sectors were adopted except for China. (See Table 3.15 in Sect. S3.2.4.) For China, reduction rates were assumed as follows:

- Referring Zhao et al. (2014), reduction rates of $PM_{10}/PM_{2.5}$ in 2010 and 2015 were 0.766/0.670

and 0.782/0.697, respectively and values between 2010 and 2015 were interpolated.

- Trends of reduction rates between 1985 and 2010 were assumed to be the same as settings between 1980 and 2005 for combustion emissions in other industries. (See Table 3.15 in Sect. S3.2.4.)

S4.2.5 Brick production

In REASv3, emissions of CO and PM species were estimated using production amounts of brick.

For CO, note that emissions in China, Japan, Republic of Korea, and Taiwan were estimated using fuel consumption as described in Sect. S3.2.3. For other countries, emissions were estimated with production amounts of brick and emission factor 2.0 t/kt-produced was taken from Weyan et al. (2014).

For PM species, default emission factors of PM_{10}, $PM_{2.5}$, BC, and OC t/kt-produced were assumed as follows:

- China: 0.71, 0.27, 0.108, and 0.0945 were taken from Lei et al. (2011b).
- Japan, Republic of Korea, and Taiwan: Emission factors of tunnel kiln 0.4773, 0.18, 0.002, and 0.0035 were obtained from Klimont et al. (2017).
- Others: Emission factors of Bull's trench kiln 0.5, 0.19, 0.15, and 0.007 were based on Weyant et al. (2014).

For emission controls of PM species, the same settings for combustion emissions in industry sectors were adopted except for China. (See Table 3.15 in Sect. S3.2.4.) For China, reduction rates were assumed as follows:

- Referring Zhao et al. (2014), reduction rates of $PM_{10}/PM_{2.5}$ in 2010 and 2015 were 0.425/0.208 and 0.362/0.143, respectively and values between 2010 and 2015 were interpolated.
- Trends of reduction rates between 1985 and 2010 were assumed to be the same as settings for combustion emissions in other industries. (See Table 3.15 in Sect. S3.2.4.)

S4.2.6 Sulphuric acid production

In REASv3, emissions of SO_2 were estimated using production amounts of sulphuric acid. Default emission factors were taken from Kato et al. (1991) as follows:

- 20.0 t/kt-produced for China, Japan, Republic of Korea, and Taiwan
- 33.0 t/kt-produced for other countries.

For emission controls, the same settings for combustion emissions in large industries were adopted for Japan, Republic of Korea, and Taiwan and those for other industries were applied for China. For other countries, no emission controls were considered.

S4.2.7 Carbon black production

In REASv3, emissions of NMVOC and PM species were estimated using production amounts of carbon black. Default emission factor of NMVOC was taken from Klimont et al. (2002a) and those of PM species were derived from Klimont et al. (2002b) and Kupiainen and Klimont (2004) as follows:

- NMVOC: 90 t/kt-produced
- PM_{10}: 1.60 t/kt-produced
- $PM_{2.5}$: 1.44 t/kt-produced
- BC: 1.10 t/kt-produced
- OC: 0.00 t/kt-produced

For emission controls of PM species, the same settings for combustion emissions in industry sectors were adopted for all countries. (See Table 3.15 in Sect. S3.2.4.)

S4.2.8 Other transformation sectors

Coke ovens

In REASv3, emissions of CO, NMVOC, CO_2, and PM species were estimated using production amounts of coke oven coke.

For CO, emission factors were taken from Streets et al. (2006) as follows:

- 1.6 t/kt-produced for machinery coke ovens
- 15.6 t/kt-produced for indigenous coke ovens

Production amounts of coke oven coke in different technologies were only considered for China. Ratios of production amounts between machinery and indigenous coke ovens in each province in 2005 and 2006 were taken from China Industrial Economy Statistics Yearbook (National Bureau of Statistics, 2006-2007) and were extrapolated based on national ratios during 1990-2011 obtained from Huo et al. (2012a). It was roughly assumed that ratios of machinery coke ovens in 1970 were zero and gradually increased from 2011 to 2015. Data between 1970 and 1990 were interpolated. Due to lack of information, emission factors for machinery coke ovens were adopted for all other countries. As described in Sect. S3.2.3, emission factors were assumed to include contribution from combustion emissions.

Default emission factors of NMVOC was taken from Klimont et al. (2002a) and that of CO_2 was obtained from IPCC (2006) as follows:

- NMVOC: 1.44 t/kt-produced
- CO_2: 560 t/kt-produced

For PM species, default emission factors of PM_{10}, $PM_{2.5}$, BC, and OC t/kt-produced were assumed as follows:

- China: 8.79, 5.22, 1.57, and 1.83 were taken from Lei et al. (2011b).
- Others: 3.36, 2.00, 0.75, and 0.54 were taken from Klimont et al. (2002b) and Kupiainen and Klimont (2004).

As described in Sect. S3.2.4, emission factors were assumed to include contribution from combustion emissions. For emission controls of PM species, the same settings for combustion emissions in iron and steel industry were adopted except for China. (See Table 3.15 in Sect. S3.2.4.) For China, reduction rates were assumed as follows:

- Referring Zhao et al. (2014), reduction rates of PM_{10}/$PM_{2.5}$ in 2010 and 2015 were estimated for machinery and indigenous coke ovens as follows:
    - Machinery: 0.773/0.560 and 0.803/0.624 in 2010 and 2015, respectively.
    - Indigenous: 0.193/0.140 and 0.200/0.156 in 2010 and 2015, respectively.
    - Values between 2010 and 2015 were interpolated.
- Trends of reduction rates between 1985 and 2010 were assumed to be the same as settings for combustion emissions in other industries. (See Table 3.15 in Sect. S3.2.4.)

Petroleum refineries

In REASv3, emissions of SO_2, NMVOC and PM species were estimated using consumption amounts of crude oil in oil refinery industry. Default emission factors were derived from Kato and Akimoto (1992) for SO_2, Klimont et al. (2002a) for NMVOC, Klimont et al. (2002b) and Kupiainen and Klimont (2004) for PM species as follows:

- SO_2: 0.46S t/kt (S: Sulfur contents in fuel in wt%)
- NMVOC: 2.34 t/PJ
- PM_{10}: 1.20 t/kt
- $PM_{2.5}$: 0.96 t/kt
- BC: 0.00015 t/kt
- OC: 0.00 t/kt

For emission controls of SO_2 and PM species, the same settings for combustion emissions in industry sectors were adopted for all countries. (See Table 3.15 in Sect. S3.2.4.)

S4.2.9 Speciation of NMVOC emissions

Emission factors described in Sect. S4.2 were for total NMVOC. In REASv3, total NMVOC emissions were allocated to 19 NMVOC species categories defined in Sect. S2.1. The speciation was conducted based on speciation profiles for each sub-sector provided by D. G. Streets (private communication) generally based on Klimont et al. (2002a) used for REASv1 and REASv2. The speciation profiles were commonly used for all countries and periods.

S5. Non-combustion sources of NMVOC

In this section, activity data, emission factors, and their sources used to estimate evaporative NMVOC emissions in REASv3 are described. See Sect. S2.4.3 for sub-sector categories defined in REASv3. For Japan, NMVOC emissions from evaporative sources were derived from the Ministry of the Environment Japan (MEOJ, 2017a) and thus, activity data and emission factors of Japan were not compiled in REASv3 (see Sect. S5.3.1 for Japan).

S5.1 Activity data

In REASv3, activity data of REASv2 during 2000-2008 estimated based on Klimont et al. (2002a) were used as "default".

S5.1.1 Extraction processes

In REASv3, emissions from gas production and distribution, oil production and handling, petroleum refineries, service stations, and transport and depots are included in those from extraction processes. Data sources and treatments of activity data for each sub-sector category used in REASv3 were summarized in Table 5.1.

Table 5.1. Data sources and treatments of activity data for sub-sectors of extraction processes.

Sub-sector categories	Data sources and treatments of activity data
Gas production and distribution	● Activity data: Natural gas production ● Data sources and treatments: ➢ China: Regional data during 1985-2015 were taken from the China Energy Statistical Yearbook (CESY) (National Bureau of Statistics of China, 1986, 2001-2017). Before 1985, data were extrapolated to 1971 using the International Energy Agency (IEA) World Energy Balances (IEAWEB) (IEA, 2017) and to 1950 using Mitchell (1998). ➢ India: National total data were obtained from IEAWEB and extrapolated to 1950 using Mitchel (1998). For regional distribution, weighting factors were calculated using regional data taken from TERI (2013, 2018). ➢ Other countries: National total data were derived from IEAWEB or the United Nations (UN) Energy Statistics Database (UN, 2016) and

	extrapolated to 1950 using Mitchel (1998).
Crude oil production and handling	● Activity data: Crude oil production ● Data sources and treatments: ➢ China: Regional data during 1950-2015 were derived from China Data Online. ➢ India: National total data were obtained from IEAWEB and extrapolated to 1950 using Mitchel (1998). For regional distribution, weighting factors were calculated using regional data taken from TERI (2013, 2018). ➢ Other countries: National total data were derived from IEAWEB or the UN Energy Statistics Database (UN, 2016) and extrapolated to 1950 using Mitchel (1998).
Petroleum refineries	● Activity data: Consumption of crude oil in petroleum refineries ● Data sources and treatments: See Sect. S3.1.
Service stations	● Activity data: Consumption of gasoline in road transport sector ● Data sources and treatments: See Sect. S3.1.
Transport and depots	● Activity data: Consumption of gasoline and diesel in road transport sector ● Data sources and treatments: See Sect. S3.1.

S5.1.2 Solvent use

In this sub-section, activity data of NMVOC evaporative emissions from solvent use except for printing (See Sect. S5.1.3) and paint application (See Sect. S5.1.4) were described. Data sources and treatments of activity data for each sub-sector category used in REASv3 were summarized in Table 5.2. (See Sect. S4.1.7 for data sources of GDP used in this sub-section.)

Table 5.2. Data sources and treatments of activity data for sub-sectors of solvent use.

Sub-sector categories	Data sources and treatments of activity data
Dry cleaning	● Activity data: Textiles cleaned ● Data sources and treatments: ➢ China: National total data in 2012 were taken from Wu et al. (2016) and extrapolated during 1950-2015 using trends of GDP. For regional distribution, urban population (see descriptions for domestic use of solvents in this table) were used as weighting factors.

	➢ India: National data in 2010 were based on Sharma et al. (2015) and extrapolated during 1950-2015 using trends of GDP. For regional distribution, urban population were used as weighting factors. ➢ Other countries: Default data were used and extrapolated during 1950-2015 using trends of GDP.
Degreasing operation	● Activity data: Solvent used ● Data sources and treatments: ➢ China: National total data in 2005 were taken from Wei et al. (2008). Regional distribution and extrapolation during 1950-2015 were conducted based on GDP. ➢ Other countries and regions: Default data were used during 2000-2008 and extrapolated during 1950-2015 using trends of GDP.
Vehicle treatment	● Activity data: Cars registered ● Data sources and treatments: See Sect. S6.1.1.
Domestic use of solvents	● Activity data: Urban and rural population ● Data sources and treatments: ➢ China: National and regional total population were obtained from China Data Online. Regional urban population data were calculated using proportion of urban population during 2005-2015 in China Statistical Yearbook (National Bureau of Statistics of China, 1986–2016) and the proportion data in 2005 for each region were used to estimated urban population before 2004. Then rural population in each region during 1950-2015 were calculated. ➢ India: National total population were taken from UN (2018). Regional ratios and proportion of urban population during 1951-2011 were estimated using data in Indiastat. Then, urban and rural population in each region were calculated. ➢ Other countries: National urban and rural population during 1950-2015 were derived from UN (2018). For Taiwan, population data were taken from Worldometer (https://www.worldometers.info/).
Asphalt blowing	● Activity data: Asphalt produced ● Data sources and treatments: ➢ China: National total data in 2012 were taken from Wu et al. (2016) and extrapolated to 1950 using trends of Bitumen consumption in IEAWEB and GDP. Regional distribution was based on GDP. ➢ Other countries and regions: National and regional data were taken

	from default and extrapolated to 1950 using trends of Bitumen consumption in IEAWEB and GDP.
Paint production	● Activity data: Paint produced ● Data sources and treatments: ➢ China: National total data during 2011-2013 were taken from Zheng et al. (2017). ➢ Other countries and regions: National data were taken from Industrial Commodity Statistical Yearbook. ➢ All countries and regions: Extrapolation for missing data and regional distribution were based on GDP.
Ink production	● Activity data: Ink produced ● Data sources and treatments: ➢ China: National total data during 2011-2013 were taken from Zheng et al. (2017). ➢ Other countries and regions: National data were taken from Industrial Commodity Statistical Yearbook. ➢ All countries and regions: Extrapolation for missing data and regional distribution were based on GDP.
Tire production	● Activity data: Tire produced ● Data sources and treatments: ➢ China: National total data during 2011-2013 were taken from Zheng et al. (2017). ➢ India: National data in 2010 were derived from Sharma et al. (2015). ➢ Other countries: National data were taken from Industrial Commodity Statistical Yearbook. ➢ All countries and regions: Extrapolation for missing data and regional distribution were based on GDP.
Synthetic rubber production	● Activity data: Synthetic rubber produced ● Data sources and treatments: ➢ China: National total data during 2011-2013 were taken from Zheng et al. (2017). ➢ India: National data in 2010 were derived from Sharma et al. (2015). ➢ Indonesia: National data in 2010 were obtained from Permadi et al. (2017). ➢ Other countries: National data were taken from Industrial Commodity Statistical Yearbook.

	➢ All countries and regions: Extrapolation for missing data and regional distribution were based on GDP.
Textile industry	● Activity data: Textile produced ● Data sources and treatments: ➢ China: National total data during 2011-2013 were derived from Zheng et al. (2017). ➢ Other countries and regions: National and regional data were taken from default. ➢ All: Extrapolation for missing data and regional distribution for China were based on GDP.
Preservation of wood	● Activity data: Wood treated ● Data sources and treatments: ➢ All: National and regional data were taken from default and extrapolated during 1950-2015 using trends GDP.
Adhesive application	● Activity data: Adhesive consumed ● Data sources and treatments: ➢ China: National total data in 2005 and 2010 were taken from Wei et al. (2008; 2011). ➢ India: National data in 2010 were derived from Sharma et al. (2015). ➢ Indonesia: National data in 2010 were obtained from Permadi et al. (2017). ➢ Other countries: National data were taken from default. ➢ All countries and regions: Extrapolation for missing data and regional distribution were based on GDP.

S5.1.3 Printing

In REASv3, NMVOC evaporative emissions from following four printing activities are considered: packing, offset printing, publication, and screen printing. Activity data are ink consumption for each purpose. In this sub-section, data sources and treatments of activity data used in REASv3 were described.

National total ink consumption data were calculated as default for this sub-section using production, export, and import amounts taken from Industrial Commodity Statistical Yearbook and missing data were extrapolated based on GDP. For China, national total ink consumption in 2005, 2010, and 2012 were derived from Wei et al. (2008, 2011) and Wu et al. (2016) and interpolated during 2005 and 2012. Before 2005 and after 2012, the data were extrapolated based on the default data. For Indonesia, national total ink consumption data in 2010 were obtained from Permadi et al. (2017) and extrapolated during 1950-2015 based on the default data. For India, national ink consumption amounts in 2010 are available for packing, offset printing, publication, and screen printing in Sharma et al. (2015). The data were extrapolated during 1950-2015 based on the default data. For distribution of total ink consumption to each purpose except for India and regional distribution of national total data in China and India, activity data of REASv2 during 2000-2008 were used as weighting factors. Before 1999 and 2009, data in 2000 and 2008 were used respectively.

S5.1.4 Paint application

In REASv3, NMVOC evaporative emissions from paint application were considered for following purposes: architecture, domestic usage, automobile manufacture, vehicle refinishing, and other industrial applications. In this sub-section, data sources and treatments of activity data used in REASv3 were described.

National total paint consumption data during 2000-2009 were taken from a report of Information Research Limited and missing data were extrapolated during 1950-2015 based on GDP. For China, national total paint application data in 2005, 2010, and 2012 were derived from Wei et al. (2008, 2011) and Wu et al. (2016) and interpolated during 2005 and 2012. Before 2005 and after 2012, the data were extrapolated based on GDP. For India and Indonesia, national total paint consumption data in 2010 were obtained from Sharma et al. (2015) and Permadi et al. (2017), respectively and extrapolated during 1950-2015 based on GDP. The total paint consumption data were distributed to each purpose described above except for automobile manufacture using activity data of REASv2 during 2000-2008 as weighting factors. Before 1999 and after 2010, data in 2000 and 2008 were used respectively.

For automobile manufacture, activity data are production number of small and large vehicles. Production data of passenger vehicles (treated as small vehicles), bus and trucks (considered as large vehicles) in Asian countries during 2013-2015 were derived from the Japan Automobile Manufacture Association, Inc. (http://www.jama-english.jp/). Data of India and Republic of Korea were extrapolated to 1999 using data taken from Global Note (https://www.globalnote.jp/). Production number of passenger and duty vehicles were obtained from Michell (1998) and missing data were interpolated. For China, regional data during 1980-2015 were obtained from China Statistical Yearbook (National Bureau of Statistics of China, 1986–2016) and extrapolated to 1950 using national data in China Data Online.

S5.1.5 Chemical industry

Activity data of NMVOC evaporative emissions from chemical industry were described in this sub-section. Data sources and treatments for each sub-sector category used in REASv3 were summarized in Table 5.3. (See Sect. S3.1 for energy consumption in chemical industry sub-sector and Sect. S4.1.7 for data sources of GDP used in this sub-section.)

Table 5.3. Data sources and treatments of activity data for sub-sectors of Chemical industry.

Sub-sector categories	Data sources and treatments of activity data
Ethylene production	● Activity data: Ethylene produced ● Data sources and treatments: ➢ China: Regional data during 2004-2015 were extrapolated to 1978 using national data both obtained from China Statistical Yearbook (National Bureau of Statistics of China, 1986–2016). The data were extrapolated to 1950 based on total energy consumption in chemical industry sub-sector. ➢ India: National data in 2010 were derived from Sharma et al. (2015) and Industrial Commodity Statistical Yearbook during 1983-2003. Data between 2003 and 2010 were interpolated and missing data were extrapolated based on total energy consumption in chemical industry sub-sector. For regional distribution, the default data were used as weighting factors. ➢ Other countries and regions: National data before 1983 were taken from Industrial Commodity Statistical Yearbook and TOZAI BOEKI TSUSHINSHA (2014a). Missing data were interpolated and extrapolated based on total energy consumption in chemical industry.
Polyethylene production	● Activity data: `Polyethylene produced ● Data sources and treatments: ➢ China: National data before 1985 were taken from Industrial Commodity Statistical Yearbook and TOZAI BOEKI TSUSHINSHA (2014b). For regional distribution, data of ethylene were used as weighting factors. ➢ Other countries and regions: National data before 1983 were taken from Industrial Commodity Statistical Yearbook and TOZAI BOEKI TSUSHINSHA (2014a). For regional distribution in India, the default

	data were used as weighting factors.
Styrene production	● Activity data: Styrene produced ● Data sources and treatments: ➢ National data during 2008-2013 in China and those during 2009-2015 were obtained from TOZAI BOEKI TSUSHINSHA (2014b; a). Extrapolation during 1950-2015 and regional distribution for China and India were conducted based on data of ethylene.
Polystyrene production	● Activity data: Polyethylene produced ● Data sources and treatments: ➢ China: National data in 2010 were obtained from Wei et al. (2011). The data were extrapolated to 1950 and distributed to each region using data of ethylene. ➢ India: National data in 2010 were derived from Sharma et al. (2015). The data were extrapolated to 1950 and distributed to each region using data of ethylene. ➢ Other countries and regions: National data before 1983 were taken from Industrial Commodity Statistical Yearbook and TOZAI BOEKI TSUSHINSHA (2014a). Missing data were interpolated and extrapolated based on data of ethylene.
Polyvinylchloride production	● Activity data: Polyvinylchloride produced ● Data sources and treatments: ➢ China: National data during 2008-2013 were obtained from TOZAI BOEKI TSUSHINSHA (2014b). The data were extrapolated to 1950 and distributed to each region using data of ethylene. ➢ India: National data in 2010 were derived from Sharma et al. (2015). The data were extrapolated to 1950 and distributed to each region using data of ethylene. ➢ Other countries and regions: National data before 1983 were taken from Industrial Commodity Statistical Yearbook and TOZAI BOEKI TSUSHINSHA (2014a). Missing data were interpolated and extrapolated based on data of ethylene.
Propylene production/ Polypropylene production	● Activity data: Propylene produced/Polypropylene produced ● Data sources and treatments: ➢ China: National data during 2008-2013 were obtained from TOZAI BOEKI TSUSHINSHA (2014b) and extrapolated to 1950 using data of ethylene.

	➢ Other countries and regions: National data before 1983 were taken from Industrial Commodity Statistical Yearbook and TOZAI BOEKI TSUSHINSHA (2014a). Missing data were interpolated and extrapolated based on data of ethylene. Regional distribution for China and India were conducted also based on data of ethylene.
Storage of organic chemicals	● Activity data: Total production of organic chemicals ● Data sources and treatments: See descriptions for organic chemicals in this table.
Polyvinylchloride processing	● Activity data: Polyvinylchloride produced ● Data sources and treatments: The same as for "Polyvinylchloride production"
Polystyrene processing	● Activity data: Polyethylene produced ● Data sources and treatments: The same as for "Polystyrene production"
Carbon black	● Activity data: Carbon black produced ● Data sources and treatments: See Sect. S4.1.7.

S5.1.6 Other industry

In this sub-section, activity data of NMVOC evaporative emissions from other industrial processes were described. Data sources and treatments for each sub-sector category used in REASv3 were summarized in Table 5.4. (See Sect. S4.1.7 for data sources of GDP used in this sub-section.)

Table 5.4. Data sources and treatments of activity data for sub-sectors of other industry.

Sub-sector categories	Data sources and treatments of activity data
Bread production	● Activity data: Bread produced ● Data sources and treatments: ➢ China: National total data in 2012 were taken from Wu et al. (2016). ➢ India: National data in 2010 were derived from Sharma et al. (2015). ➢ Other countries: National data were taken from Industrial Commodity Statistical Yearbook. ➢ All countries and regions: Extrapolation for missing data were based on population (see descriptions for domestic use of solvents in Sect. S5.1.2). For regional distribution of China and India, the default data were used as weighting factors.
Beer production	● Activity data: Beer produced

	● Data sources and treatments: ➢ China: Regional data during 1983-2015 were obtained from China Statistical Yearbook (National Bureau of Statistics of China, 1986–2016) and extrapolated to 1950 using Mitchell (1998). ➢ Other countries: National data after 2006 were taken from Brewers Association of Japan (http://www.brewers.or.jp/english/index.html) and before 1993 were obtained from Mitchell (1998). For regional distribution of India, the default data were used as weighting factors.
Coke production	● Activity data: Coke produced ● Data sources and treatments: See Sect. S4.1.8.
Asphalt production	● Activity data: Asphalt produced ● Data sources and treatments: See Sect. S5.1.2 (Asphalt blowing).
Crude steel production	● Activity data: Crude steel produced ● Data sources and treatments: See Sect. S4.1.1.
Hot rolled steel production	● Activity data: Hot rolled steel produced ● Data sources and treatments: See Sect. S4.1.1.
Pulp and paper production	● Activity data: Paper pulp produced ● Data sources and treatments: ➢ China: Regional data during 1983-2015 were obtained from China Statistical Yearbook (National Bureau of Statistics of China, 1986–2016) and extrapolated to 1950 using China Data Online. ➢ Other countries: National data were taken from FAOSTAT (http://www.fao.org/faostat/en/). For regional distribution of India, the default data were used as weighting factors.

S5.1.7 Waste disposal

In REASv3, evaporative NMVOC emissions from disposal of municipal wastes were considered and those of industrial wastes were not included due to lack of information. Activity data are amounts of municipal wastes. Data sources and treatments of activity data used in REASv3 were summarized in Table 5.5. (See Sect. S5.1.2 (Domestic use of solvents) for data sources of population used in this sub-section.)

Table 5.5. Data sources and treatments of activity data for waste disposal.

Countries and regions	Data sources and treatments of activity data
China	Regional amounts of municipal wastes after 2003 were derived from China Statistical Yearbook (National Bureau of Statistics of China, 1986–2016) and extrapolated to 1950 using number of population.
India	National total data in 2000, 2005, 2010, and 2015 were taken from Niyati (2015) and those in 2012 were obtained from UN Environment Programme (2017). The data were interpolated, extrapolated during 1950-2015, and distributed to each region based on number of population.
Rep. of Korea	National data during 1994-2004 were taken from Shragge and An (2014) and those in 2012 were obtained from UN Environment Programme (2017). The data were interpolated and extrapolated during 1950-2015 based on number of population.
Taiwan	National data during 2003-2015 were taken from Environmental Protection Administration (https://www.epa.gov.tw/eng/2C04F91E41A2000B/) and extrapolated during 1950-2015 using number of population
Thailand	National data during 1993-2002 were taken from Chiemchaisri et al., (2007) and extrapolated during 1950-2015 using number of population
Other countries	National data were obtained from UN Environment Programme (2017) and missing data were extrapolated during 1950-2015 based on number of population.

S5.2 Emission factors

In this section, emission factors for non-combustion sources of NMVOC for each sub-category are described. Note that emission controls were not considered for non-combustion emissions of NMVOC in REASv3.

S5.2.1 Extraction processes

Emission factors for following sub-sectors were taken from Klimont et al. (2002a) and the same settings were used for all countries and regions as well as for all target years of REASv3:

- Gas production
- Gas distribution
- Oil production

- Oil handling
- Petroleum refinery
- Service stations
- Transport and depots (gasoline/diesel)

S5.2.2 Solvent use

In this sub-section, emission factors for solvent use except for printing and paint use are described. Sources and settings of emission factors are summarized in Table 5.6.

Table 5.6. Sources and settings of emission factors for sub-sectors of solvent use.

Sub-sector categories	Sources and settings of emission factors
Dry cleaning	• Sources: Data for existing and new installations in Klimont et al. (2002a) • Settings: The value for existing installations was commonly used for all target countries and periods except for Rep. of Korea and Taiwan where the same value was used before 2000. For Rep of Korea and Taiwan, it was assumed that all installations in 2020 are new and ratios of existing and new installations were changed linearly between 2000 and 2020. Based on the assumption emission factors during 2001 and 2015 were calculated.
Degreasing operation	• Sources and settings are the same as those “Dry cleaning”.
Vehicle treatment	• Sources: Default data and settings until 2030 in Klimont et al. (2002a) • Settings: The Default value was used before 2000. After 2001, data in 2000 and those assumed in 2030 in Klimont et al. (2002a) were interpolated. These settings are commonly adopted for all countries.
Domestic use of solvents	• Sources: Default emission factors and settings until 2030 for rural and urban population in Klimont et al. (2002a) • Settings: Emission factors for rural and urban population were estimated by the same methodology for “Vehicle treatment” and adopted for all countries.
Asphalt blowing	• Sources: Klimont et al. (2002a) • Settings: The value was used for all target countries and periods.
Paint production	• Sources: Klimont et al. (2002a) • Settings: The value was used for all target countries and periods.

Ink production	● Sources: Klimont et al. (2002a) ● Settings: The value was used for all target countries and periods.
Tire production	● Sources: Klimont et al. (2002a) ● Settings: The value was used for all target countries and periods.
Synthetic rubber production	● Sources: Klimont et al. (2002a) ● Settings: The value was used for all target countries and periods.
Textile industry	● Sources: Klimont et al. (2002a) ● Settings: The value was used for all target countries and periods.
Preservation of wood	● Sources and settings are the same as those “Dry cleaning”.
Adhesive application	● Sources: EEA (2016) ● Settings: The value was used for all target countries and periods.

S5.2.3 Printing

Klimont et al. (2002a) provides emission factors of packaging, offset printing, publication, and screen printing for existing and new installations. The same assumption for sub-sectors such as dry cleaning described in Sect. S5.2.2 was used in RESv3.1. as follows:

- The values for existing installations were commonly used for all target countries and periods except for Rep. of Korea and Taiwan where the same value was used before 2000.
- For Rep of Korea and Taiwan, it was assumed that all installations in 2020 are new and ratios of existing and new installations were changed linearly between 2000 and 2020. Based on the assumption emission factors during 2001 and 2015 were calculated.

S5.2.4 Paint use

In this sub-section, emission factors for paint use for architecture, domestic usage, automobile manufacture, vehicle refinishing, and other industrial applications are described. Sources and settings of emission factors are summarized in Table 5.7.

Table 5.7. Sources and settings of emission factors for sub-sectors of paint use.

Sub-sector categories	Sources and settings of emission factors
Architecture	● Sources: Klimont et al. (2002a) ● Settings: The value was used for all target countries and periods.
Domestic use	● Sources: Klimont et al. (2002a)

	● Settings: The value was used for all target countries and periods.
Vehicle refinishing	● Sources: Data for existing and new installations in Klimont et al. (2002a) ● Settings: The value for existing installations was commonly used for all target countries and periods except for Rep. of Korea and Taiwan where the same value was used before 2000. For Rep of Korea and Taiwan, it was assumed that all installations in 2020 are new and ratios of existing and new installations were changed linearly between 2000 and 2020. Based on the assumption emission factors during 2001 and 2015 were calculated.
Automobile manufacturing	● Sources: Range of emission factors depending on the proportion of vehicle types in Klimont et al. (2002a) ● Settings: The lowest and highest values of the range were used for small and large vehicles, respectively. See Sect. S5.1.4 for the definitions of vehicle sizes here.
Other industrial application	● Sources: Klimont et al. (2002a) ● Settings: The value was used for all target countries and periods.

S5.2.5 Chemical industry

In this sub-section, emission factors for chemical industry are described. Sources and settings of emission factors are summarized in Table 5.8.

Table 5.8. Sources and settings of emission factors for sub-sectors of chemical industry.

Sub-sector categories	Sources and settings of emission factors
Ethylene production	● Sources: Klimont et al. (2002a) ● Settings: The value was used for all target countries and periods.
Polyethylene production	● Sources: Klimont et al. (2002a) ● Settings: Average of emission factors for low and high-density polyethylene production were used for all target countries and periods.
Styrene production	● Sources: EEA (2016) ● Settings: The value was used for all target countries and periods.
Polystyrene production	● Sources: EEA (2016) ● Settings: The value was used for all target countries and periods.
Polyvinylchloride production	● Sources: Klimont et al. (2002a) ● Settings: The value was used for all target countries and periods.

Propylene production	● Sources: Klimont et al. (2002a) ● Settings: The value was used for all target countries and periods.
Polypropylene production	● Sources: Klimont et al. (2002a) ● Settings: The value was used for all target countries and periods.
Storage of organic chemicals	● Sources: Klimont et al. (2002a) ● Settings: Emission factors of EEA (2016) include contribution from the storage. In REASv3, 10 percent of the value was used for all target countries and periods.
Polyvinylchloride processing	● Sources: Klimont et al. (2002a) ● Settings: The value was used for all target countries and periods.
Polystyrene processing	● Sources: EEA (2016) ● Settings: The value was used for all target countries and periods.
Carbon black	● Sources: Klimont et al. (2002a) ● Settings: The value was used for all target countries and periods.

S5.2.6 Other industry

In this sub-section, emission factors for non-combustion emissions from other industry are described. Sources and settings of emission factors are summarized in Table 5.9.

Table 5.9. Sources and settings of emission factors for sub-sectors of other industry.

Sub-sector categories	Data sources and treatments of activity data
Bread production	● Sources: Klimont et al. (2002a) ● Settings: The value was used for all target countries and periods.
Beer production	● Sources: Klimont et al. (2002a) ● Settings: The value was used for all target countries and periods.
Coke production	● Sources: Klimont et al. (2002a) ● Settings: The value was used for all target countries and periods.
Asphalt production	● Sources: Klimont et al. (2002a) ● Settings: The value was used for all target countries and periods.
Crude steel production	● Sources: Klimont et al. (2002a) ● Settings: The value for steel production was used for all target countries and periods.
Hot rolled steel production	● Sources: Klimont et al. (2002a) ● Settings: The value for rolling mills was used for all target countries and

	periods.
Pulp and paper production	● Sources: Klimont et al. (2002a) ● Settings: The value was used for all target countries and periods.

S5.2.7 Waste disposal

In REASv3, the emission factor for landfills for waste disposal in Klimont et al. (2002a) were adopted for all activity data (amounts of municipal wastes) described in S5.1.7.

S5.2.8 Speciation of NMVOC emissions

Emission factors described in Sect. S5.2 were for total NMVOC. In REASv3, total NMVOC emissions were allocated to 19 NMVOC species categories defined in Sect. S2.1. The speciation was conducted based on speciation profiles for each sub-sector provided by D. G. Streets (private communication) generally based on Klimont et al. (2002a) used for REASv1 and REASv2. The speciation profiles were commonly used for all countries and periods.

S5.3 Other emission inventories included in REASv3

S5.3.1 Japan

In REASv3, evaporative emissions of individual NMVOC species from sub-sectors in Japan during 2000-2015 were obtained from the Ministry of the Environment of Japan (MOEJ, 2017a). Information for regional distribution was also available in MOEJ (2017a). Emissions of the individual species were aggregated to 19 NMVOC species categories defined in Sect S2.1. Before 1999, data in 2000 were extrapolated based on trend factors related to each sub-sector as described in Table 5.10.

Table 5.10. Sources and treatments of trend factors for sub-sectors of NMVOC evaporative emissions in Japan

Sub-sector categories	Data sources and treatments of trend factors
Natural gas production	● Trend factors: Natural gas production ● Data sources and treatments: Data during 1960-2000 were derived from IEAWEB and extrapolated to 1950 using trends taken from the Historical Statistics of Japan (Japan Statistical Association, 2006).

Coke production	● Trend factors: Coke produced ● Data sources and treatments: See Sect. S4.1.8.
Petroleum refinery	● Trend factors: Consumption of crude oil in petroleum refineries ● Data sources and treatments: See Sect. S3.1.
Service stations	● Trend factors: Consumption of gasoline in road transport sector ● Data sources and treatments: See Sect. S3.1.
Transport and depots	● Trend factors: Consumption of gasoline and diesel in road transport sector ● Data sources and treatments: See Sect. S3.1.
Dry cleaning	● Trend factors: Number of facilities ● Data sources and treatments: Data during 1963-2000 were taken from Japan Cleaning Journal (http://www.nicli.co.jp/stat-sisetu.html) and extrapolated to 1950 using values of shipments for industrial organic chemicals obtained from the Historical Statistics of Japan (Japan Statistical Association, 2006) were used as trend factors.
Detergents usage in industry	● Trend factors: Values of shipments of detergents for industries ● Data sources and treatments: Data during 1960-2000 were obtained from Yearbook of Chemical Industry Statistics (Ministry of Economy, Trade and Industry, Japan, https://www.meti.go.jp/statistics/). Before 1960, values of shipments for industrial organic chemicals obtained from the Historical Statistics of Japan (Japan Statistical Association, 2006) were used as trend factors.
Adhesive application	● Trend factors: Adhesive produced ● Data sources and treatments: Data during 1960-2000 were obtained from Yearbook of Chemical Industry Statistics (Ministry of Economy, Trade and Industry, Japan, https://www.meti.go.jp/statistics/). Before 1960, values of shipments of industrial organic chemicals obtained from the Historical Statistics of Japan (Japan Statistical Association, 2006) were used as trend factors.
Asphalt blowing	● Trend factors: Asphalt produced ● Data sources and treatments: Data during 1950-2000 were derived from the Historical Statistics of Japan (Japan Statistical Association, 2006).
Rubber production	● Trend factors: Rubber produced ● Data sources and treatments: Production amounts and values of shipments for rubber products were taken from the Historical Statistics of Japan (Japan Statistical Association, 2006).

Synthetic leather production	● Trend factors: Synthetic leather produced ● Data sources and treatments: Data during 1985-2000 and those for all leather products before 1984 were obtained from the Historical Statistics of Japan (Japan Statistical Association, 2006).
Protection of fishing net	● Trend factors: Fishing net produced ● Data sources and treatments: Data were obtained from Yearbook of Current Production Statistics (Ministry of Economy, Trade and Industry, Japan, https://www.meti.go.jp/statistics/) and the Historical Statistics of Japan (Japan Statistical Association, 2006).
Ink application	● Trend factors: Values of shipments by publishing, printing and allied industries ● Data sources and treatments: Data were obtained from Yearbook of Chemical Industry Statistics (Ministry of Economy, Trade and Industry, Japan, https://www.meti.go.jp/statistics/) and the Historical Statistics of Japan (Japan Statistical Association, 2006).
Paint application	● Trend factors: Values of shipments by paint industries of manufacturing ● Data sources and treatments: Data during 1960-2000 were obtained from Yearbook of Chemical Industry Statistics (Ministry of Economy, Trade and Industry, Japan, https://www.meti.go.jp/statistics/). Before 1960, production of synthetic paints obtained from the Historical Statistics of Japan (Japan Statistical Association, 2006) were used.
Other solvent use	● Trend factors: Values of shipments of industrial organic chemicals ● Data sources and treatments: Data during 1950-2000 were obtained from the Historical Statistics of Japan (Japan Statistical Association, 2006)
Chemical industry	● Trend factors: Petrochemicals produced ● Data sources and treatments: Data during 1960-2000 were obtained from Yearbook of Chemical Industry Statistics (Ministry of Economy, Trade and Industry, Japan, https://www.meti.go.jp/statistics/) were extrapolated to 1950 using values of shipments of industrial organic chemicals obtained from the Historical Statistics of Japan (Japan Statistical Association, 2006) were used as trend factors.
Food production	● Trend factors: Values of shipments by food industries of manufacturing ● Data sources and treatments: Data during 1950-2000 were obtained from the Historical Statistics of Japan (Japan Statistical Association, 2006).
Pesticide application	● Trend factors: Pesticide produced ● Data sources and treatments: Data during 1950-2000 were taken from

	Japan Crop Production Association (https://www.jcpa.or.jp/qa/a5_12.html).
Others	● Trend factors: GDP ● Data sources and treatments: See Sect. S4.1.7

S5.3.2 Republic of Korea

For Republic of Korea, first, NMVOC (including 19 individual species) emissions from evaporative sources were tentatively estimated using activity data and emission factors described in Sects. S5.1 and S5.2, respectively. Then, emissions from extraction processes, solvent use including printing and paint application, and industrial processes in both chemical and other industries, and waste disposal were obtained from the National Institute of Environmental Research (http://airemiss.nier.go.kr/mbshome/mbs/airemiss/index.do) during 1999-2015. Finally, the tentatively estimated emissions for each sub-sector were adjusted by ratios between the aggregated emissions of the National Institute of Environmental Research and those of the tentative estimation. For example, tentative emissions from dry cleaning were adjusted by factors calculated for solvent use. Before 1999, the tentative emissions were adjusted using the factors for the year 1999. Note that emissions from combustion sources for Republic of Korea were originally estimated in REASv3.

S6. Road transport

S6.1 Activity data

S6.1.1 Annual mileage

In REASv3, exhaust emissions from road vehicles were estimated based on annual distances vehicles are driven (annual mileage) and corresponding emission factors (amounts of air pollutants per distance driven). The annual mileages were calculated by number of vehicles and annual distances traveled for each vehicle type. The number of vehicles was obtained from national and international statistics and related literatures. However, available vehicle categories in the data are different among countries and regions. In addition, information for categories of different fuel types such as gasoline and diesel and annual distances traveled for each vehicle type is limited. In Table 6.1, data sources and assumptions to estimate historical annual mileage data are provided.

Table 6.1. Data sources and settings of number of vehicles and annual distance travelled for each country and region in REASv3.

(a) China

Number of vehicles	● Data sources: ➢ Regional data of large/medium/small/mini passenger vehicles and heavy/medium/light/mini trucks during 1985-2015 were taken from China Statistical Yearbook and extrapolated to 1950 using number of civil motor vehicles in each region in China Data Online. ➢ For motorcycles, national total during 1991-2015 were taken from IRF (1990-2018) and distributed to each region and extrapolated to 1950 using the number of civil motor vehicles in each region. ● Vehicle categories: ➢ For data based on China Statistical Yearbook, large/medium and small/minicar passenger vehicles were treated as buses and cars, respectively. For trucks, heavy/medium and light/mini vehicles were treated as heavy and light trucks, respectively. For distribution of fuel types, data in He et al. (2005) were used for cars and those in Yan and Crookes (2009) were used for buses and trucks. ➢ No classification was done for motorcycles and it was assumed that only gasoline was used in motorcycles.
Annual distance travelled	● Settings of annual distance travelled for each vehicle type were based on Huo et al. (2012b).

(b) Hong Kong

Number of vehicles	● Data sources: ➢ Data of passenger cars, buses, trucks, and motorcycles during 1964-2015 were obtained from IRF (1976-2018) and extrapolated to 1950 using trends of number of vehicles for aggregated vehicle types in Mitchell (1998). ● Vehicle categories: ➢ Vehicle types include gasoline, diesel, and LPG passenger cars, taxis, buses, and light and heavy trucks, and motorcycles. For relative ratios of vehicles numbers of each fuel type, in addition to data of Streets et al. (2003) and REASv2 generally based on GAINS ASIA at that time, data in A clean air plan for Hong Kong (Environment Bureau, 2013) and consumption amounts of LPG in road transport sector in the International Energy Agency (IEA) World Energy Balances (IEAWEB) (IEA, 2017) were used.

Annual distance travelled	● Settings of Singapore were used in REASv3.

(c) Macau

Number of vehicles	● Data sources: ➢ Data of passenger cars, buses, trucks, and motorcycles during 1994-2015 were obtained from IRF (1976-2018) and extrapolated to 1950 using trends of fuel consumption in the United Nations (UN) Energy Statistics Database (UN, 2016). ● Vehicle categories: ➢ Vehicle types include gasoline and diesel passenger cars, buses, light and heavy trucks, and motorcycles. For relative ratios of gasoline and diesel vehicle numbers, data of Hong Kong in REASv2 generally based on GAINS ASIA at that time were used.
Annual distance travelled	● Settings of Singapore were used in REASv3.

(d) India

Number of vehicles	● Data sources: ➢ Regional data of passenger cars, taxis, jeeps, buses, light trucks, heavy trucks, trailers, light motor vehicles, and motorcycles during 2001-2015 were taken from TERI (2013, 2018) and extrapolated to 1950 using trends of national data for cars & jeeps & taxis, buses, trucks, and motorcycles obtained from Indiastat. ● Vehicle categories: ➢ In general, passenger cars, taxis, jeeps, light motor vehicles, and motorcycles assumed to consume gasoline and for buses, trucks, and trailers, the fuel type is assumed to be diesel. For Delhi and Mumbai (in Maharashtra), number of CNG cars, taxis, and buses in 2010 were assumed based on Sahu et al. (2014) and extrapolated using IEAWEB. ➢ According to Baidya and Borken-Kleefeld (2009), there are large differences between registered number of vehicles and those actually circulating on the road. Relative ratios of vehicle numbers in operation to registered ones were taken from Prakash and Habib (2018) and Baidya and Borken-Kleefeld (2009).

Annual distance travelled	● Settings of annual distance travelled for each vehicle type were based on Prakash and Habib (2018) and Pandey and Venkataraman (2014).

(e) Japan

Annual mileages	● Data sources: ➢ National annual mileages for each vehicle type (including different fuel types) among different vehicle speed categories were derived from reports of Pollutants Release and Transfer Register (METI, 2003-2017) during 2001-2015 and extrapolated to 1950 using trends of annual distances travelled for aggregated vehicle types in the Historical Statistics of Japan (Japan Statistical Association, 2006). Vehicle types were further divided into detailed categories using number of vehicles provided in the report of the Japan Auto-Oil Program (JATOP) Emission Inventory-Data Base (JEI-DB) (JPEC 2012a). ➢ For regional distribution of national data, weighting factors during 1960-2015 were calculated using annual distances travelled of aggregated vehicle types in annual reports of road transport statistics (MLIT, 1961-2016). Before 1960, data in 1960 were used. ● Vehicle categories: ➢ Vehicle types include passenger cars (gasoline and LPG), light, medium and heavy trucks (gasoline and diesel), buses (gasoline and diesel), special purpose vehicles (gasoline and diesel), and several sizes of motorcycles. Trucks, buses, and special purpose vehicles were further divided into different weight categories.

(f) Republic of Korea

Number of vehicles	● Data sources: ➢ National data of passenger cars, buses, trucks, and motorcycles during 1976-2015 were obtained from IRF (1976-2018) and extrapolated to 1950 using trends of number of vehicles for aggregated vehicle types in Mitchell (1998). ➢ Number of LPG and CNG vehicles in 2010 were taken from a report of European Commission (Alternative fuels and infrastructure in seven non-EU markets) and the Gas Vehicles Report, respectively and extrapolated using trends of fuel

	consumption in IEAWEB. ● Vehicle categories: ➢ Vehicle types include passenger cars (gasoline, diesel, and LPG), buses (gasoline, diesel, and CNG), light and heavy trucks (gasoline and diesel), rural vehicles, and several sizes of motorcycles. For relative ratios of number of gasoline and diesel vehicles, data of Streets et al. (2003) and REASv2 generally based on GAINS ASIA at that time were used.
Annual distance travelled	● Settings of Singapore were used in REASv3 except for motorcycles which were taken from Jang et al. (2010).

(g) Democratic People's Republic of Korea

Number of vehicles	● Data sources and vehicle categories: ➢ Number of gasoline and diesel vehicles for passenger cars, buses, light and heavy trucks, rural vehicles, and motorcycles in 2000 were taken from REASv1 generally based on Streets et al. (2003) and extrapolated using trends of gasoline and diesel oil consumption in road transport in IEAWEB.
Annual distance travelled	● Annual vehicle kilometer travelled per vehicle type averaged in Asia provided in Clean Air Asia (2012) were used.

(h) Mongolia

Number of vehicles	● Data sources: ➢ National data of passenger cars, buses, trucks, and motorcycles during 1950-2015 were obtained from National Statistics Office of Mongolia (https://www.en.nso.mn/). ● Vehicle categories: ➢ Vehicle types include gasoline and diesel passenger cars, buses, light and heavy trucks, and motorcycles. For relative ratios of gasoline and diesel vehicle numbers, data of Streets et al. (2003) and REASv2 generally based on GAINS ASIA at that time were used.
Annual distance travelled	● Annual vehicle kilometer travelled per vehicle type averaged in Asia provided in Clean Air Asia (2012) were used.

(i) Taiwan

Number of vehicles	● Data sources: ➢ National data of passenger cars, buses, trucks, and motorcycles during 1976-2015 were obtained from IRF (1976-2018) and extrapolated to 1950 using trends of number of vehicles in National Statistics of Taiwan (https://eng.stat.gov.tw/mp.asp?mp=5). ➢ Number of LPG vehicles in 2010 were estimated based on ratios of vehicle numbers and fuel consumption in Rep. of Korea and extrapolated using trends of fuel consumption in IEAWEB. ● Vehicle categories: ➢ Vehicle types include passenger cars (gasoline, diesel, and LPG), buses (gasoline and diesel), light and heavy trucks (gasoline and diesel), and motorcycles. For relative ratios of number of gasoline and diesel vehicles, data of Streets et al. (2003) and REASv2 generally based on GAINS ASIA at that time were used.
Annual distance travelled	● Settings of Singapore were used in REASv3.

(j) Brunei

Number of vehicles	● Data sources and vehicle categories: ➢ National data of passenger cars, buses, trucks, and motorcycles during 2010-2015 were obtained from IRF (1976-2018) and extrapolated to 1950 using trends of fuel consumption in IEAWEB and those of number of vehicles for aggregated vehicle types in Mitchell (1998). ● Vehicle categories: ➢ Vehicle types include gasoline and diesel passenger cars, buses, light and heavy trucks, and motorcycles. For relative ratios of gasoline and diesel vehicle numbers, data of Streets et al. (2003) and REASv2 generally based on GAINS ASIA at that time were used.
Annual distance travelled	● Annual vehicle kilometer travelled per vehicle type averaged in Asia provided in Clean Air Asia (2012) were used.

(k) Cambodia

Number of vehicles	● Data sources: ➢ National data of passenger cars, buses, trucks, and motorcycles during 1990-2015 were obtained from IRF (1976-2018) and extrapolated to 1950 using trends of fuel consumption in IEAWEB and those of number of vehicles for aggregated vehicle types in Mitchell (1998). ● Vehicle categories: ➢ Vehicle types include gasoline and diesel passenger cars, buses, light and heavy trucks, and motorcycles. For relative ratios of gasoline and diesel vehicle numbers, data of Streets et al. (2003) and REASv2 generally based on GAINS ASIA at that time were used.
Annual distance travelled	● Annual vehicle kilometer travelled per vehicle type averaged in Asia provided in Clean Air Asia (2012) were used.

(l) Indonesia

Number of vehicles	● Data sources: ➢ National data of passenger cars, buses, trucks, and motorcycles during 1950-2015 were obtained from Statistics Indonesia (https://www.bps.go.id/linkTableDinamis/view/id/1133/). ● Vehicle categories: ➢ Vehicle types include gasoline and diesel passenger cars, buses, light and heavy trucks, rural vehicles, and motorcycles. For relative ratios of gasoline and diesel vehicle numbers, data of Streets et al. (2003) and REASv2 generally based on GAINS ASIA at that time were used.
Annual distance travelled	● Annual vehicle kilometer travelled per vehicle type in Indonesia provided in Clean Air Asia (2012) were used.

(m) Laos

Number of vehicles	● Data sources: ➢ National data of passenger cars, buses, trucks, and motorcycles during 1987-2015 were obtained from IRF (1976-2018) and extrapolated to 1950 using trends of fuel consumption in IEAWEB and those of number of vehicles for aggregated vehicle types in

	Mitchell (1998). ● Vehicle categories: ➢ Vehicle types include gasoline and diesel passenger cars, buses, light and heavy trucks, and motorcycles. For relative ratios of gasoline and diesel vehicle numbers, data of Streets et al. (2003) and REASv2 generally based on GAINS ASIA at that time were used.
Annual distance travelled	● Annual vehicle kilometer travelled per vehicle type in Laos provided in Clean Air Asia (2012) were used.

(n) Malaysia

Number of vehicles	● Data sources: ➢ National data of passenger cars, buses, trucks, and motorcycles during 1963-2015 were obtained from IRF (1976-2018) and extrapolated to 1950 using trends of number of vehicles for aggregated vehicle types in Mitchell (1998). ● Vehicle categories: ➢ Vehicle types include gasoline and diesel passenger cars, buses, light and heavy trucks, rural vehicles, and motorcycles. For relative ratios of gasoline and diesel vehicle numbers, data of Streets et al. (2003) and REASv2 generally based on GAINS ASIA at that time were used.
Annual distance travelled	● Annual vehicle kilometer travelled per vehicle type in Malaysia provided in Clean Air Asia (2012) were used.

(o) Myanmar

Number of vehicles	● Data sources: ➢ National data of passenger cars, buses, trucks, and motorcycles during 1993-2015 were obtained from IRF (1976-2018) and extrapolated to 1950 using trends of fuel consumption in IEAWEB and those of number of vehicles for aggregated vehicle types in Mitchell (1998). ● Vehicle categories: ➢ Vehicle types include gasoline and diesel passenger cars, buses, light and heavy trucks, and motorcycles. For relative ratios of gasoline and diesel vehicle numbers, data of Streets et al. (2003)

	and REASv2 generally based on GAINS ASIA at that time were used.
Annual distance travelled	● Annual vehicle kilometer travelled per vehicle type averaged in Asia provided in Clean Air Asia (2012) were used.

(p) Philippines

Number of vehicles	● Data sources: ➢ National data of passenger cars, buses, trucks, and motorcycles during 1981-2015 were obtained from IRF (1976-2018) and extrapolated to 1950 using trends of number of vehicles for aggregated vehicle types in Mitchell (1998). ● Vehicle categories: ➢ Vehicle types include gasoline and diesel passenger cars, buses, light and heavy trucks, rural vehicles, and motorcycles. For relative ratios of gasoline and diesel vehicle numbers, data of Streets et al. (2003) and REASv2 generally based on GAINS ASIA at that time were used.
Annual distance travelled	● Annual vehicle kilometer travelled per vehicle type in Philippines provided in Clean Air Asia (2012) were used.

(q) Singapore

Number of vehicles	● Data sources: ➢ National data of passenger cars, buses, trucks, and motorcycles during 1981-2015 were obtained from IRF (1976-2018) and extrapolated to 1950 using trends of number of vehicles for aggregated vehicle types in Mitchell (1998). ● Vehicle categories: ➢ Vehicle types include gasoline and diesel passenger cars, buses, light and heavy trucks, and motorcycles. For relative ratios of gasoline and diesel vehicle numbers, data of Streets et al. (2003) and REASv2 generally based on GAINS ASIA at that time were used.
Annual distance travelled	● Annual vehicle kilometer travelled per vehicle type in Singapore provided in Clean Air Asia (2012) were used.

(r) Thailand

Number of vehicles	● Data sources: ➢ National data of passenger cars, buses, trucks, and motorcycles during 1967-2015 were obtained from IRF (1976-2018) and extrapolated to 1950 using trends of number of vehicles for aggregated vehicle types in Mitchell (1998). ● Vehicle categories: ➢ Vehicle types include gasoline, diesel, LPG, and CNG passenger cars, buses, and light and heavy trucks, rural vehicles, and motorcycles. For relative ratios of vehicles numbers of each fuel type, in addition to data of Streets et al. (2003) and REASv2 generally based on GAINS ASIA at that time, data in Chollacoop et al. (2011) and consumption amounts of LPG and CNG in road transport sector in IEAWEB were used.
Annual distance travelled	● Annual vehicle kilometer travelled per vehicle type in Thailand provided in Clean Air Asia (2012) were used.

(s) Vietnam

Number of vehicles	● Data sources: ➢ National data of passenger cars, buses, trucks, and motorcycles during 2007 were obtained from IRF (1976-2018) and extrapolated to 1950 using trends of fuel consumption in IEAWEB and those of number of vehicles for aggregated vehicle types in Mitchell (1998). ● Vehicle categories: ➢ Vehicle types include gasoline and diesel passenger cars, small and large buses, light and heavy trucks, rural vehicles, and motorcycles. For relative ratios of gasoline and diesel vehicle numbers, data of Streets et al. (2003) and REASv2 generally based on GAINS ASIA at that time were used.
Annual distance travelled	● Annual vehicle kilometer travelled per vehicle type in Vietnam provided in Clean Air Asia (2012) as well as Manh et al. (2011) were used.

(t) Afghanistan

Number of vehicles	● Data sources: ➢ National data of passenger cars, buses, trucks, and motorcycles during 1975-2015 were obtained from IRF (1976-2018) and extrapolated to 1950 using trends number of vehicles for aggregated vehicle types in Mitchell (1998). ● Vehicle categories: ➢ Vehicle types include gasoline and diesel passenger cars, buses, light and heavy trucks, and motorcycles. For relative ratios of gasoline and diesel vehicle numbers, data of India in REASv2 generally based on GAINS ASIA at that time were used.
Annual distance travelled	● Annual vehicle kilometer travelled per vehicle type averaged in Asia provided in Clean Air Asia (2012) were used.

(u) Bangladesh

Number of vehicles	● Data sources: ➢ National data of passenger cars, taxis, jeeps, buses, trucks, rural vehicles and motorcycles during 2000-2015 were obtained from Statistical Yearbook of Bangladesh (2013-2016) and extrapolated to 1950 using trends number of vehicles for aggregated vehicle types in Mitchell (1998). ● Vehicle categories: ➢ Vehicle types include gasoline, diesel, and CNG passenger cars, taxis, jeeps, small and large buses, light and heavy trucks, rural vehicles and motorcycles. For relative ratios of gasoline and diesel vehicle numbers, Wadud and Khan (2011) as well as data of Streets et al. (2003) and REASv2 generally based on GAINS ASIA at that time were used.
Annual distance travelled	● Annual vehicle kilometer travelled per vehicle type in Bangladesh provided in Clean Air Asia (2012) were used.

(v) Bhutan

Number of vehicles	● Data sources: ➢ National data of passenger cars, buses, trucks, and motorcycles during 1994-2015 were obtained from IRF (1976-2018) and extrapolated to 1950 using trends of number of vehicles taken from

	Statistical Yearbook of Bhutan (http://www.nsb.gov.bt/publication/publications.php?id=3) ● Vehicle categories: ➢ Vehicle types include gasoline and diesel passenger cars, buses, light and heavy trucks, and motorcycles. For relative ratios of gasoline and diesel vehicle numbers, data of Streets et al. (2003) and REASv2 generally based on GAINS ASIA at that time were used.
Annual distance travelled	● Annual vehicle kilometer travelled per vehicle type averaged in Asia provided in Clean Air Asia (2012) were used.

(w) Nepal

Number of vehicles	● Data sources and vehicle categories: ➢ National data of passenger cars/jeeps, 3 wheeler vehicle, taxis, micro, mini and medium buses, mini and medium trucks, pickup and motorcycles in 2013 and trends during 1990-2012 for aggregated vehicle types were derived from Malla (2014). ➢ Malla (2014) provided fuel types and ratios of operational to registered vehicle for each vehicle type. ➢ Before 1990, data during 1950-2015 were estimated based on trends of fuel consumption data in IEAWEB.
Annual distance travelled	● Settings of annual distance travelled for each vehicle type were based on Malla. (2014).

(x) Pakistan

Number of vehicles	● Data sources: ➢ National data of motor cars/jeeps, taxis, buses, trucks, motorcycles, 3 wheeler vehicles during 2001-2012 were taken from Pakistan Statistical Yearbook (http://www.pbs.gov.pk/publications/) and were extrapolated to 1963 and 2015 using trends of number of vehicles in IRF (1976-2018). ● Vehicle categories: ➢ Vehicle types include gasoline, diesel, and CNG passenger cars, taxis, mall and large buses, light and heavy trucks, rural vehicles and motorcycles. For relative ratios of gasoline, diesel, and CNG vehicle numbers, Khan and Yasmin (2014) as well as data of Streets

	et al. (2003) and REASv2 generally based on GAINS ASIA at that time were used.
Annual distance travelled	● Annual vehicle kilometer travelled per vehicle type in Pakistan provided in Clean Air Asia (2012) were used.

(y) Sri Lanka

Number of vehicles	● Data sources: ➢ National data of passenger cars, buses, trucks, and motorcycles during 1963-2015 were obtained from IRF (1976-2018) and extrapolated to 1950 using trends of number of vehicles for aggregated vehicle types in Mitchell (1998). ● Vehicle categories: ➢ Vehicle types include gasoline and diesel passenger cars, buses, light and heavy trucks, and motorcycles. For relative ratios of gasoline and diesel vehicle numbers, data of Streets et al. (2003) and REASv2 generally based on GAINS ASIA at that time were used.
Annual distance travelled	● Annual vehicle kilometer travelled per vehicle type in Sri Lanka provided in Clean Air Asia (2012) were used.

(z) Maldives

Number of vehicles	● Data sources: ➢ National data of passenger cars, buses, trucks, and motorcycles during 1991-2015 were obtained from IRF (1976-2018). ● Vehicle categories: ➢ Vehicle types include gasoline and diesel passenger cars, buses, light and heavy trucks, and motorcycles. For relative ratios of gasoline and diesel vehicle numbers, data of India in REASv2 generally based on GAINS ASIA at that time were used.
Annual distance travelled	● Annual vehicle kilometer travelled per vehicle type averaged in Asia provided in Clean Air Asia (2012) were used.

S6.1.2 Fuel consumption

In REASv3, emissions of SO_2 and CO_2 were calculated using fuel consumption amounts. In order to estimate emissions from each vehicle type, total fuel consumption in road transport sector (see Sect. S3.1.2) needs to be distributed to each type of vehicles. The distributions were performed in each country and region based on weighting factors which were products of annual mileages (see S6.1.1) and fuel efficiencies of each vehicle type. In this sub-section, the fuel efficiencies used in REASv3 are described.

The fuel efficiencies were taken from Clean Air Asia (2012) for following countries: Indonesia, Laos, Malaysia, Philippines, Singapore, Thailand, Vietnam, Bangladesh, Nepal, Pakistan, and Sri Lanka. For Republic of Korea, Taiwan, Hong Kong, and Macau, data of Singapore were used the same as for the annual distance travelled. For North Korea, Mongolia, Brunei, Cambodia, and Myanmar, averaged data of Southeast Asian countries in Clean Air Asia (2012) were used. Similarly, averaged values of South Asian countries in Clean Air Asia (2012) were used for Afghanistan, Bhutan, and Maldives. For China, the fuel efficiencies were derived from Yan and Crookes (2009). For Japan, fuel consumption in vehicle type are available in each region after 2009. Before 2008, the data in 2009 were extrapolated using trend of annual mileages for each vehicle type in each region and used as weighting factors to distribute regional fuel consumption in road transport to each vehicle type.

S6.2 Emission factors of exhaust emissions

S6.2.1 NO_x, CO, NMVOC, and PM species

In REASv3, emission factors of NO_x, CO, NMVOC, and PM species for exhaust emissions from road vehicles were estimated as follows:

1. Emission factors of each vehicle type in a base year (different from country to country) were estimated.
2. Trends of the emission factors for each vehicle type were estimated considering the timing of road vehicle regulations in each country and the regions and the ratios of vehicles production years.
3. Emission factors of each vehicle type during 1950-2015 were calculated using those of base years and the corresponding trends.

The information of road vehicle regulations in each country and regions were taken from Clean Air Asia (2014). For the ratios of vehicle production years, due to lack of information, data for Macau derived from Zhang et al. (2016) were used for Hong Kong, Republic of Korea, and Taiwan and those from Japan Environmental Sanitation Center and Suuri Keikaku (2011) for Vietnam were used for other countries and regions. Then, trends of emission factors were estimated using the above data and information with values of Europe and United States standards. Finally, emission factors used to estimate emissions were calculated for each vehicle type.

In this sub-section, ranges of emission factors during 1950-2015 used in REASv3 were presented in Tables 6.2-6.5 for following major vehicles types: CARG, CARD, LDTG, LDTD, HDTG, HDTD, BUSG, BUSD, and MC (CAR: Passenger cars, LDT: Light duty trucks, HDT: Heavy duty trucks, BUS: Buses, MC: Motorcycles, G: Gasoline vehicles, and D: Diesel vehicles). For PM species, referring Klimont et al. (2002b) and Bond et al. (2004), ratios of $PM_{2.5}$, BC, and OC to PM_{10} were assumed as follows:

- $PM_{2.5}/PM_{10}$: 0.95 for gasoline and light diesel vehicles, 1.0 for heavy diesel vehicles, and 0.9 for LPG and CNG vehicles.
- BC/PM_{10}: 0.34 for gasoline vehicles and 0.66 for diesel vehicles.
- OC/PM_{10}: 0.36 for gasoline vehicles and 0.21 for diesel vehicles.
- BC and OC emissions from LPG and CNV vehicles were neglected.

Note that emissions from road vehicles in Japan were estimated by different methodology as described in Sect. S.6.2.4.

Table 6.2. Emission factors of NO_x, CO, NMVOC (NMV), and PM_{10} for exhaust emissions from road vehicle in China. Unit is g/km (expressed as NO_2 for NO_x).

g/km	CARG[c]	LDTG	LDTD	HDTG	HDTD
NO_x	0.25-2.70 (0.53)[a]	0.23-3.00 (0.53)[a]	2.22-5.00 (2.85)[a]	0.78-2.18 (1.91)[a]	5.41-9.03 (7.65)[a]
CO	2.72-29.7 (5.93)[a]	3.17-40.0 (8.01)[a]	1.20-9.46 (1.89)[a]	5.26-81.6 (16.3)[a]	1.95-27.2 (5.44)[a]
NMV	0.33-1.89 (0.66)[a]	0.41-3.53 (0.88)[a]	0.37-2.50 (0.75)[a]	0.24-4.00 (1.47)[a]	0.32-1.47 (0.98)[a]
PM_{10}	0.013-0.019 (0.016)[a]	0.012-0.021 (0.016)[a]	0.075-0.37 (0.15)[a]	0.042-0.17 (0.081)[a]	0.13-0.63 (0.29)[a]
g/km	BUSG	BUSD	MC	BUS(LPG)[b]	BUS(CNG)[b]
NO_x	0.92-2.14 (1.91)[a]	5.75-8.79 (7.65)[a]	0.17-0.29 (0.22)[a]	2.60	5.70
CO	6.34-81.6 (16.3)[a]	2.43-27.2 (5.44)[a]	8.64-25.2 (12.9)[a]	1.00	12.0
NMV	0.40-4.00 (1.47)[a]	0.37-1.37 (0.98)[a]	2.41-5.45 (3.59)[a]	0.70	1.40

PM_{10}	0.050-0.15 (0.081)[a]	0.16-0.55 (0.29)[a]	0.060-0.16 (0.10)[a]	0.033	0.033

a. Emission factors in 2010 used as based data estimated referring Wu et al. (2011), Huo et al. (2012b; 2012c), Zhao et al. (2012), Zhang et al. (2013), and Xia et al. (2016). b. ABC Emission Inventory Manual (Shrestha et al., 2013). c. CARD was not categorized.

Table 6.3. Emission factors of NO_x, CO, NMVOC (NMV), and PM_{10} for exhaust emissions from road vehicle in India. Unit is g/km (expressed as NO_2 for NO_x).

g/km	CARG[c]	LDTG	LDTD	HDTD[c]	BUSD[c]
NO_x	0.98-2.70 (1.79)[a]	1.28-2.70 (2.24)[a]	5.22-9.00 (6.77)[a]	7.81-12.80 (11.3)[a]	5.70-9.08 (8.16)[a]
CO	1.62-9.01 (3.50)[a]	2.27-10.3 (4.00)[a]	2.80-8.12 (4.00)[a]	4.40-14.8 (11.9)[a]	5.24-14.3 (11.9)[a]
NMV	0.41-2.06 (0.80)[a]	0.58-2.91 (1.13)[a]	0.53-1.19 (1.13)[a]	0.47-1.96 (1.38)[a]	0.51-2.20 (1.09)[a]
PM_{10}	0.13-0.19 (0.18)[a]	0.43-0.68 (0.65)[a]	0.32-1.63 (0.65)[a]	0.55-2.79 (1.41)[a]	0.33-1.26 (072)[a]
g/km	MC	CAR_CNG[b]	BUS_CNG[b]		
NO_x	0.20-0.30 (0.24)[a]	2.10	5.70		
CO	1.98-15.7 (8.04)[a]	4.00	12.0		
NMV	1.63-4.60 (2.46)[a]	0.50	1.40		
PM_{10}	0.025-0.049 (0.030)[a]	0.067	0.067		

a. Emission factors in 2010 used as based data estimated referring Mishra et al. (2014), Sahu et al. (2014), and Pandey and Venkataraman. (2014). b. ABC Emission Inventory Manual (Shrestha et al., 2013). c. CARD, HDTG, and BUSG were not categorized.

Other East Asian countries

Emission factors of Republic of Korea and Taiwan were estimated with high uncertainties based on values of Europe and United States standards, respectively. For Democratic People's Republic of Korea and Mongolia, emission factors used in REASv1 and REASv2 were adopted. Ranges of emission factors are presented in Table 6.4.

Table 6.4. Emission factors of NO_x, CO, NMVOC (NMV), and PM_{10} for exhaust emissions from road vehicle in other East Asian countries. Unit is g/km (expressed as NO_2 for NO_x).

(a) Republic of Korea

g/km	CARG	CARD	LDTG	LDTD	HDTG
NO_x	0.10-2.70	0.34-0.67	0.10-2.14	0.50-0.90	3.01-5.37
CO	0.41-8.60	0.10-0.57	1.60-14.1	0.17-0.91	8.52-35.2
NMV	0.084-0.92	0.026-0.25	0.12-2.07	0.063-0.15	0.55-3.09
PM_{10}	0.0018-0.0030	0.018-0.20	0.0017-0.0030	0.014-0.28	0.0017-0.014

g/km	HDTD	BUSG	BUSD	MC
NO_x	3.04-12.0	5.17-8.42	5.59-9.09	0.05-0.43
CO	0.23-0.94	0.51-1.63	0.25-0.81	4.43-20.1
NMV	0.066-0.37	0.21-2.8	0.11-0.41	0.64-6.76
PM_{10}	0.021-0.62	0.012-0.060	0.11-1.01	0.010-0.14

g/km	CAR/LPG	BUS/CNG
NO_x	0.056	2.50
CO	0.62	1.00
NMV	0.10	0.052
PM_{10}	0.0012	0.0012

(b) Taiwan

g/km	CARG	CARD	LDTG	LDTD	HDTG
NO_x	0.30-2.70	0.55-1.11	0.28-3.10	1.02-1.66	3.62-6.81
CO	1.38-8.60	0.14-0.50	3.64-23.4	2.21-6.26	8.75-45.0
NMV	0.21-2.10	0.045-0.29	0.19-2.84	0.094-0.15	0.92-4.00
PM_{10}	0.0015-0.0020	0.053-0.27	0.0021-0.0030	0.029-0.28	0.0080-0.068

g/km	HDTD	BUSG	BUSD	MC	CAR/LPG
NO_x	3.99-7.50	5.72-9.66	8.74-14.8	0.19-0.39	0.056
CO	0.36-2.19	3.19-13.0	1.19-4.83	2.70-16.4	0.62
NMV	0.12-1.04	0.55-2.50	0.42-1.90	1.18-3.09	0.1
PM_{10}	0.11-0.93	0.023-0.12	0.20-1.05	0.086-0.32	0.0012

(c) Democratic People's Republic of Korea and Mongolia

g/km	CARG	CARD	LDTG	LDTD	HDTG
NO_x	1.79	2.39	3.51	2.58	9.56
CO	69.3	12.1	69.3	12.1	135.0
NMV	3.82	0.16	3.44	0.13	5.25
PM_{10}	0.033	0.34	0.033	0.34	0.066
g/km	HDTD	BUSG	BUSD	MC	
NO_x	24.1	9.56	24.1	0.12	
CO	17.7	135.0	17.7	21.1	
NMV	0.72	1.99	1.99	6.05	
PM_{10}	0.47	0.066	0.47	0.033	

Southeast Asian countries

For Southeast Asian countries, default emission factors were assumed based on Boken et al. (2007) and used as uncontrolled values. Then, emission factors during 1950-2015 were estimated considering effects of regulations. Ranges of emission factors of Southeast Asian countries are presented in the following tables.

Table 6.5. Emission factors of NO_x, CO, NMVOC (NMV), and PM_{10} for exhaust emissions from road vehicle in Southeast Asian countries. Unit is g/km (expressed as NO_2 for NO_x).

(a) Brunei, Cambodia, Laos, and Myanmar

g/km[a]	CARG	CARD	LDTG	LDTD	HDTG
NO_x	2.50	2.77	3.20	3.15	4.00
CO	15.4	1.07	28.0	2.00	45.0
NMV	1.70	0.99	2.40	1.28	4.00
PM_{10}	0.0030	0.23	0.0060	0.63	0.025
g/km[a]	HDTD	BUSG	BUSD	MC	
NO_x	11.7	4.00	14.8	0.15	
CO	3.30	45.0	6.00	15.9	
NMV	2.00	4.00	3.70	4.30	
PM_{10}	0.62	0.025	2.08	0.10	

a. Due to lack of information for regulations, default emission factors were used without changes during 1950-2015 for Brunei, Cambodia, Laos, and Myanmar.

(b) Indonesia

g/km	CARG	CARD	LDTG	LDTD	HDTG
NO_x	0.79-2.50	1.87-2.77	0.62-3.20	2.42-3.15	2.84-4.00
CO	5.53-15.4	0.61-1.07	9.25-28.0	1.01-2.00	22.6-45.0
NMV	0.61-1.70	0.41-0.99	0.49-2.40	1.28	1.64-4.00
PM_{10}	0.0030	0.099-0.23	0.0060	0.26-0.63	0.0080-0.025

g/km	HDTD	BUSG	BUSD	MC
NO_x	8.30-11.7	3.05-4.00	11.3-14.8	0.11-0.15
CO	1.66-3.30	26.8-45.0	3.57-6.00	7.49-15.9
NMV	0.82-2.00	2.03-4.00	1.88-3.70	2.87-4.30
PM_{10}	0.20-0.62	0.010-0.025	0.87-2.08	0.045-0.10

(c) Malaysia

g/km	CARG	CARD	LDTG	LDTD	HDTG
NO_x	0.17-2.50	2.23-2.77	0.17-3.20	2.32-3.15	3.74-4.00
CO	2.23-15.4	0.56-1.07	5.91-28.0	0.86-2.00	36.4-45.0
NMV	0.19-1.70	0.26-0.99	0.16-2.40	1.28	3.18-4.00
PM_{10}	0.0023-0.0030	0.074-0.23	0.0041-0.0060	0.21-0.63	0.015-0.025

g/km	HDTD	BUSG	BUSD	MC
NO_x	11.0-11.7	3.8-4.00	14.1-14.8	0.08-0.15
CO	2.67-3.30	37.5-45.0	5.00-6.00	3.28-15.9
NMV	1.59-2.00	3.33-4.00	3.08-3.70	1.92-4.30
PM_{10}	0.37-0.62	0.016-0.025	1.37-2.08	0.025-0.10

(d) Philippines

g/km	CARG	CARD	LDTG	LDTD	HDTG
NO_x	0.73-2.50	1.95-2.77	0.56-3.20	2.40-3.15	3.52-4.00
CO	5.24-15.4	0.60-1.07	8.85-28.0	0.97-2.00	36.9-45.0
NMV	0.58-1.70	0.38-0.99	0.45-2.40	1.28	2.73-4.00
PM_{10}	0.0030	0.096-0.23	0.0060	0.25-0.63	0.013-0.025

g/km	HDTD	BUSG	BUSD	MC
NO_x	10.3-11.7	3.58-4.00	13.3-14.8	0.12-0.15
CO	2.71-3.30	38.0-45.0	5.07-6.00	7.44-15.9
NMV	1.37-2.00	2.90-4.00	2.68-3.70	2.86-4.30
PM_{10}	0.31-0.62	0.014-0.025	1.19-2.08	0.050-0.10

(e) Singapore

g/km	CARG	CARD	LDTG	LDTD	HDTG
NO_x	0.24-2.50	1.39-2.77	0.22-3.20	1.69-3.15	1.92-4.00
CO	2.40-15.4	0.25-1.07	5.51-28.0	0.48-2.00	7.86-45.0
NMV	0.27-1.70	0.13-0.99	0.19-2.40	0.45-1.28	0.54-4.00
PM_{10}	0.0027-0.0030	0.039-0.23	0.0051-0.0060	0.073-0.63	0.0036-0.025
g/km	HDTD	BUSG	BUSD	MC	
NO_x	5.61-11.7	2.19-4.00	8.11-14.8	0.10-0.15	
CO	0.58-3.30	12.1-45.0	1.62-6.00	4.71-15.9	
NMV	0.27-2.00	0.92-4.00	0.85-3.70	2.30-4.30	
PM_{10}	0.088-0.62	0.0056-0.025	0.47-2.08	0.039-0.10	

(f) Thailand

g/km	CARG	CARD	LDTG	LDTD	HDTD[a]
NO_x	0.15-2.50	1.52-2.77	0.14-3.20	1.80-3.15	9.36-11.7
CO	2.01-15.4	0.25-1.07	4.16-28.0	0.65-2.00	2.59-3.30
NMV	0.18-1.70	0.14-0.99	0.14-2.40	0.60-1.28	1.21-2.00
PM_{10}	0.0018-0.0030	0.047-0.23	0.0032-0.0060	0.11-0.63	0.23-0.62
g/km	BUSG	BUSD	MC	CAR/LPG[b]	CAR/CNG[b]
NO_x	3.28-4.00	12.1-14.8	0.080-0.15	2.10	2.10
CO	36.0-45.0	4.80-6.00	3.25-15.9	6.05	4.00
NMV	2.56-4.00	2.37-3.70	1.75-4.30	1.84	0.50
PM_{10}	0.011-0.025	0.87-2.08	0.039-0.10	0.067	0.067
g/km	BUS/LPG[b]	BUS/CNG[b]	LDT/CNG[b]	HDT/CNG[b]	
NO_x	5.70	5.70	2.10	5.70	
CO	24.0	12.0	8.00	12.0	
NMV	8.00	1.40	3.50	1.40	
PM_{10}	0.067	0.067	0.067	0.067	

a. HDTG was not categorized. b. ABC Emission Inventory Manual (Shrestha et al., 2013).

(g) Vietnam

g/km	CARG	CARD	LDTG	LDTD	HDTG
NO_x	0.55-2.50	1.95-2.77	0.43-3.20	2.36-3.15	3.48-4.00
CO	4.31-15.4	0.57-1.07	7.94-28.0	0.92-2.00	35.4-45.0
NMV	0.48-1.70	0.32-0.99	0.35-2.40	1.28	2.60-4.00
PM_{10}	0.0030	0.083-0.23	0.0060	0.23-0.63	0.011-0.025
g/km	HDTD	BUSG	BUSD	MC	
NO_x	10.2-11.7	3.55-4.00	13.1-14.8	0.12-0.15	
CO	2.59-3.30	36.2-45.0	4.82-6.00	6.73-15.9	
NMV	1.30-2.00	2.76-4.00	2.56-3.70	2.74-4.30	
PM_{10}	0.27-0.62	0.012-0.025	1.03-2.08	0.050-0.10	

Other South Asian countries

For Southeast Asian countries except for India, default emission factors were assumed based on Boken et al. (2007) and used as uncontrolled values. Then, emission factors during 1950-2015 were estimated considering effects of regulations. Ranges of emission factors of Southeast Asian countries are presented in Table 6.6.

Table 6.6. Emission factors of NO_x, CO, NMVOC (NMV), and PM_{10} for exhaust emissions from road vehicle in other South Asian countries. Unit is g/km (expressed as NO_2 for NO_x).

(a) Afghanistan, Bhutan, and Maldives

g/km[a]	CARG	CARD	LDTG	LDTD	HDTG
NO_x	2.20	1.45	3.20	4.80	4.00
CO	12.2	1.45	28.0	1.50	45.0
NMV	2.10	1.18	2.40	1.41	4.00
PM_{10}	0.0030	0.26	0.0060	0.34	0.025
g/km[a]	HDTD	BUSG	BUSD	MC	
NO_x	13.6	4.00	15.3	0.20	
CO	3.60	45.0	6.10	15.7	
NMV	2.20	4.00	3.70	4.60	
PM_{10}	0.68	0.025	2.09	0.10	

a. Due to lack of information for regulations, default emission factors were used without changes during 1950-2015 for Afghanistan, Bhutan, and Maldives.

(b) Bangladesh

g/km	CARG[a]	LDTG	LDTD	HDTD[a]	BUSD[a]
NO_x	0.21-2.20	0.21-2.20	3.53-4.80	13.0-13.6	14.8-15.3
CO	1.86-12.2	1.86-12.2	0.65-1.50	2.86-3.60	4.86-6.10
NMV	0.31-2.10	0.31-2.10	1.41	1.83-2.20	3.16-3.70
PM_{10}	0.0030	0.003	0.11-0.34	0.42-0.68	1.33-2.09
g/km	**MC**	**CAR/CNG[a]**	**LDT/CNG[a]**	**BUS/CNG[a]**	
NO_x	0.13-0.20	2.10	2.10	5.70	
CO	4.38-15.7	4.00	4.00	12.0	
NMV	2.51-4.60	0.50	0.50	1.40	
PM_{10}	0.025-0.10	0.067	0.067	0.067	

a. CARD, HDTG, and BUSG were not categorized.

(c) Nepal

g/km	CARG[a]	LDTG	LDTD	HDTD[a]	BUSG
NO_x	0.56-2.20	0.56-2.20	3.33-4.80	12.3-13.6	0.99-4.00
CO	4.18-12.2	4.18-12.2	0.64-1.50	2.89-3.60	17.2-45.0
NMV	0.69-2.10	0.69-2.10	1.14-1.41	1.72-2.20	1.01-4.00
PM_{10}	0.0024-0.0030	0.0024-0.0030	0.11-0.34	0.38-0.68	0.019-0.025
	BUSD	**MC**	**BUS/LPG[b]**		
NO_x	14.2-15.3	0.16-0.20	0.20		
CO	5.00-6.10	7.21-15.7	3.90		
NMV	3.04-3.70	2.83-4.60	0.77		
PM_{10}	1.30-2.09	0.072-0.10	0.00		

a. CARD and HDTG were not categorized. b. Malla (2014).

(d) Pakistan

g/km	CARG[a]	LDTG[a]	HDTD[a]	BUSG	BUSD
NO_x	1.47-2.20	1.65-3.20	9.75-13.6	2.42-4.00	11.7-15.3
CO	8.38-12.2	16.8-28.0	1.83-3.60	30.2-45.0	3.66-6.10
NMV	1.44-2.10	1.26-2.40	1.02-2.20	2.44-4.00	2.05-3.70
PM_{10}	0.0030	0.0060	0.25-0.68	0.025	0.96-2.09
g/km	MC	CAR/CNG[b]			
NO_x	0.18-0.20	2.10			
CO	11.5-15.7	4.00			
NMV	3.83-4.60	0.50			
PM_{10}	0.072-0.10	0.067			

a. CARD, LDTD, and HDTG were not categorized. b. ABC Emission Inventory Manual (Shrestha et al., 2013).

(e) Sri Lanka

g/km	CARG	CARD	LDTG	LDTD	HDTG
NO_x	0.65-2.20	1.05-1.45	0.57-3.20	3.65-4.80	4.00
CO	4.23-12.2	0.83-1.45	8.97-28.0	0.73-1.50	45.0
NMV	0.73-2.10	0.46-1.18	0.45-2.40	1.41	4.00
PM_{10}	0.0030	0.11-0.26	0.0060	0.13-0.34	0.025
g/km	HDTD	BUSG	BUSD	MC	
NO_x	13.6	4.00	15.3	0.16-0.20	
CO	3.60	45.0	6.10	7.52-15.7	
NMV	2.20	4.00	3.70	3.09-4.60	
PM_{10}	0.68	0.025	2.09	0.053-0.10	

Cold start emissions

In REASv3, cold start emissions were roughly estimated for NO_x, CO, NMVOC, and PM species using the following equation:

$$E_{COLD} = \sum_i \{NV_i \times ADT_i \times EF_{HOTi} \times \beta_i(T) \times F_i(T)\}$$

where, E_{COLD} is the cold start emission, i is the vehicle type, NV is the number of vehicles in operation, ADT is the annual distance traveled, EF_{HOT} is the emission factor for the hot emission, β is the fraction of distance traveled driven with a cold engine or with the catalyst operating below the light-off temperature, and F is the correction factor of EF_{HOT} for cold start emission. β and F are functions of temperature T and assumed based on EEA (2016) as follows:

- $\beta = 0.33182 - 0.004966 \times T$
- F for gasoline vehicles
  - $1.14 - 0.006 \times T$ for NO_x
  - $3.7 - 0.09 \times T$ for CO
  - $2.8 - 0.06 \times T$ for NMVOC
- F for diesel vehicles
  - $1.3 - 0.013 \times T$ for NO_x
  - $1.9 - 0.03 \times T$ for CO
  - $3.1 - 0.09 \times T$ for NMVOC
  - $3.1 - 0.1 \times T$ for PM species
- F for LPG vehicles
  - $0.98 - 0.006 \times T$ for NO_x
  - $3.66 - 0.09 \times T$ for CO
  - $2.24 - 0.06 \times T$ for NMVOC

For T, monthly averaged temperature at surface were calculated using NCEP reanalysis data provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA (https://psl.noaa.gov/data/gridded/data.ncep.reanalysis.html). Therefore, cold start emissions were estimated in each month assuming daily traffic volumes were unchanged during the target year. In addition, effects of regulations on cold start emission were not considered in REASv3.

S6.2.2 NH_3

Exhaust emissions of NH_3 only from gasoline vehicles were roughly estimated in REASv3. Emission factors were obtained from Kannari et al. (2001) as follows:

- 0.0221 g/km for passenger cars
- 0.0211 g/km for buses
- 0.0108 g/km for light trucks
- 0.0146 g/km for heavy trucks
- 0.0068 g/km for motorcycles

S6.2.3 SO_2 and CO_2

For SO_2 and CO_2, emissions were estimated based on fuel consumption in REASv3 except for Japan (see Sect. S6.2.4). SO_2 emissions were calculated using sulfur contents in fuels in gasoline and diesel consumed in road transport sector, assuming sulfur retention in ash is zero. Default settings of sulfur contents were taken from REASv1 and REASv2 described in Sect S3.2.1 and update with information obtained from Clean Air Asia (2011), Wang and Hao (2012), etc. The data for gasoline and diesel oil used in REASv3 are summarized in Table 6.7.

Table 6.7. Sulfur contents in gasoline and diesel oil for road vehicles used in REASv3.

Countries	Settings and data sources
China	● Gasoline referring Wang and Hao (2012): ➢ Beijing: 0.15/0.1/0.08/0.05/0.015/0.005 in 1950-1999/2000/2001-2003/2004/2005-2007/2008-2015 ➢ Shanghai 0.15/0.1/0.08/0.05/0.005 in 1950-1999/2000/2001-2004/2005-2008/2009-2015 ➢ Guangdong 0.15/0.08/0.05/0.015 in 1950-1999/2000-2003/2004/2005-2015 ➢ Others: 0.15/0.1/0.08/0.05 in 1950-1999/2000-2002/2003-2005/2006-2015 ● Diesel referring Clean Air Asia (2011)[b]: ➢ Beijing, Shanghai, and Guangdong 0.5/0.2/0.05/0.35/0.05 in 1950-2001/2002-2003/2004/2005-2007/2008-2015 ➢ Hong Kong 0.5/0.5-0.05/0.05/0.005/0.001 in 1950-1989/1990-1996/1997-2001/2002-2006/2007-2015 ➢ Others 0.5/0.2/0.125/0.35/ in 1950-2001/2002-2004/2005-2009/2010-2015
India	● Gasoline: REASv1 and REASv2[a] ● Diesel: referring Clean Air Asia (2011)[b]: ➢ Delhi 1.0/0.5/0.25/0.05/0.035/0.005 in 1950-1995/1996-1999/2000/2001-2004/2005-2009/2010-2015 ➢ Others 1.0/0.5/0.25/0.05/0.035 in 1950-1995/1996-1999/2000/2001-2009/2010-2015

Republic of Korea	● Gasoline: REASv1 and REASv2[a] ● Diesel referring Clean Air Asia (2011)[b]: ➢ 0.4/0.25/0.05/0.043/0.01/0.003/0.0015 in 1950-1989/1990-1994/1995-2002/2003/2004-2005/2006/2007-2015
Taiwan	● Gasoline: REASv1 and REASv2[a] ● Diesel referring Clean Air Asia (2011)[b]: ➢ 0.8/0.8-0.3/0.3/0.05/0.035/0.01/0.005 in 1950-1988/1989-1996/1997-1998/1999-2001/2002-2003/2004-2007/ 2008-2015
Cambodia	● Gasoline: REASv1 and REASv2[a] ● Diesel: referring Clean Air Asia (2011)[b]: ➢ 0.8/0.8-0.2/0.2/0.15 in 1950-1989/1990-1996/1997-2003/2004-2015
Indonesia	● Gasoline: REASv1 and REASv2[a] ● Diesel: referring Clean Air Asia (2011)[b]: ➢ 1.0/1.0-0.5/0.5/0.35/0.035 in 1950-1988/1989-1996/1997-2004/2005-2015
Malaysia	● Gasoline: REASv1 and REASv2[a] ● Diesel: referring Clean Air Asia (2011)[b]: ➢ 0.5/0.3/0.05 in 1950-1997/1998-2001/2002-2015
Philippines	● Gasoline: REASv1 and REASv2[a] ● Diesel: referring Clean Air Asia (2011)[b]: ➢ 0.5/0.2/0.05 in 1950-2000/2001-2003/2004-2015
Singapore	● Gasoline: REASv1 and REASv2[a] ● Diesel: referring Clean Air Asia (2011)[b]: ➢ 0.5/0.5-0.3/0.3/0.05/0.005 in 1950-1989/1990-1996/1997/1998-2005/2006-2015
Thailand	● Gasoline: REASv1 and REASv2[a] ● Diesel: referring Clean Air Asia (2011)[b]: ➢ 1.0/1.0-0.25/0.25/0.05/0.035/0.005 in 1950-1989/1990-1996/1997-1998/1999-2003/2004-2011/2012-2015
Vietnam	● Gasoline: REASv1 and REASv2[a] ● Diesel: referring Clean Air Asia (2011)[b]: ➢ 1.0/0.05 in 1950-2006/2007-2015
Bangladesh	● Gasoline: REASv1 and REASv2[a] ● Diesel: referring Clean Air Asia (2011)[b]: ➢ 1.0/1.0-0.5/0.5 in 1950-1989/1990-1996/1997-2015

Pakistan	• Gasoline: REASv1 and REASv2[a] • Diesel: referring Clean Air Asia (2011)[b]: ➢ 1.2/1.2-1.0/1.0/0.7 in 1950-1989/1990-1996/1997-2001/2002-2015
Sri Lanka	• Gasoline: REASv1 and REASv2[a] • Diesel: referring Clean Air Asia (2011)[b]: ➢ 1.0/0.5/0.175/0.05/0.005 in 1950-2002/2003/2004-2006/2007-2011/2012-2015
Others	• Gasoline and: diesel: REASv1 and REASv2[a]

a. Settings of "REASv1 and REASv2" are as follows:

- Data of REASv1 and REASv2 were used in 1980-1999 and 2000-2008, respectively.
- Data in 1980 and 2008 were used before 1979 and after 2009, respectively.

b. Settings before 1995 were taken from REASv1 and after 1996 were based on Clean Air Asia (2011).

For CO_2, emissions were simply calculated by consumption amounts of fuels (gasoline, diesel, liquefied petroleum gas, and natural gas) and the corresponding emission factors taken from IPCC (2006).

S6.2.4 Japan

Emissions of NO_x, CO, NMVOC, NH_3, CO_2, and PM species in Japan were estimated using following data and information:

- Emission factors for different speed ranges and production years
- Regulations for vehicle emissions and their phase-in periods
- Ratios of number of vehicles of different ages
- Traffic volumes by the speed ranges

Emission factors and information of regulations were obtained from JPEC (2012a). Data of vehicle ages were taken from NILIM (2012). See Sect. 6.1.1 for other data. For SO_2, emission factors after 2005 were estimated by the same methodologies for the other species and those before 2004 were adjusted based on regulation of sulfur contents in gasoline and diesel oil.

Ranges of net emission factors during 1950-2015 used in REASv3 were presented in Table 6.8 for following vehicle categories: CARG, CARD, LDTG, LDTD, MDTG, MDTD, HDTG, HDTD, BUSG, LBUSD, MBUSD, HBUSD, LSPCG, HSPCG, LSPCD, HSPCD, SMC, and MC (CAR: Passenger cars, LDT: Light duty trucks, MDT: Middle duty trucks, HDT: Heavy duty trucks, LBUS: Light buses, MBUS: Middle buses, HBUS: Heavy Buses, LSPC: Light special purpose vehicles, HSPC: Heavy special purpose vehicles, SMC: Small motorcycles, MC: Motorcycles, G: Gasoline vehicles, and D: Diesel vehicles). Note that each vehicle category includes several seizes of vehicles especially trucks and buses. Therefore, ranges of net emission factors in Table 6.8 were caused not only by regulations, but also differences of vehicle types in each category.

Table 6.8. Ranges of net emission factors for Japan used in REASv3. Unit is g/km (expressed as NO_2 for NO_x).

g/km	CARG	CARD	LDTG	LDTD	MDTG
SO_2	0.00085-0.012	0.0015-1.48	0.00097-0.032	0.0011-3.20	0.0091-0.014
NO_x	0.062-3.49	0.18-3.77	0.21-19.3	0.24-9.04	0.052-6.12
CO	1.13-21.3	0.23-1.00	3.09-60.5	0.30-3.01	1.13-24.9
NMV	0.033-2.90	0.017-0.19	0.020-6.07	0.020-1.47	0.015-2.79
NH_3	0.015-0.033	-	0.018-0.090	-	0.016-0.049
CO_2	130-190	159-249	128-535	163-411	140-240
PM_{10}[a]	-	0.037-0.13	-	0.0094-0.65	-
$PM_{2.5}$[a]	-	0.037-0.13	-	0.0094-0.65	-
BC	-	0.015-0.053	-	0.0050-0.34	-
OC	-	0.012-0.041	-	0.0023-0.16	-
g/km	**MDTD**	**HDTG**	**HDTD**	**BUSG**	**LBUSD**
SO_2	0.0013-3.42	0.0022-0.03	0.0040-16.6	0.0013-0.03	0.0014-2.01
NO_x	0.72-9.68	0.10-20.1	4.17-46.9	0.071-19.8	0.82-6.30
CO	0.23-3.11	3.92-52.8	0.48-15.1	2.98-54.6	0.29-1.85
NMV	0.021-1.47	0.028-5.23	0.11-7.14	0.039-5.45	0.035-1.03
NH_3	-	0.028-0.090	-	0.022-0.087	-
CO_2	184-446	339-511	612-2127	197-500	192-266
PM_{10}[a]	0.014-0.69	-	0.055-3.35	-	0.022-0.44
$PM_{2.5}$[a]	0.014-0.69	-	0.055-3.35	-	0.022-0.44
BC	0.0081-0.39	-	0.031-1.89	-	0.010-0.20
OC	0.0030-0.15	-	0.011-0.70	-	0.0062-0.12
g/km	**MBUSD**	**HBUSD**	**LSPCG**	**LSPCD**	**HSPCG**
SO_2	0.0023-3.56	0.0040-7.66	0.00091-0.014	0.0014-1.34	0.0022-0.030
NO_x	2.02-10.1	4.83-21.7	0.042-6.07	0.23-2.36	0.10-20.0
CO	0.48-3.29	0.75-7.09	0.70-25.1	0.050-0.83	4.04-53.5
NMV	0.12-1.59	0.17-3.43	0.015-2.81	0.010-0.18	0.029-5.30
NH_3	-	-	0.012-0.049	-	0.028-0.091
CO_2	352-456	619-982	140-241	159-246	339-512

PM_{10}[a]	0.056-0.72	0.094-1.55	-	0.026-0.13	-
$PM_{2/5}$[a]	0.056-0.72	0.094-1.55	-	0.026-0.13	-
BC	0.025-0.32	0.041-0.68	-	0.015-0.071	-
OC	0.015-0.20	0.026-0.42	-	0.0020-0.010	-

g/km	HSPCD	SMC	MC
SO_2	0.0014-7.42	0.00027-0.0025	0.00036-0.0056
NO_x	0.72-21.0	0.13-0.511	0.048-0.59
CO	0.24-6.77	7.01-14.9	17.5-24.2
NMV	0.022-3.22	0.16-2.76	0.13-5.85
NH_3	-	-	-
CO_2	189-951	19.7-50.3	49.3-97.8
PM_{10}[a]	0.015-1.50	-	-
$PM_{2/5}$[a]	0.015-1.50	-	-
BC	0.0083-0.85	-	-
OC	0.0011-0.11	-	-

a. It was assumed that emissions of PM species were only from diesel vehicles and ratios of $PM_{2.5}/PM_{10}$ were 1.0 for all vehicle categories.

For cold start emissions, ratios of cold start and hot emissions for each vehicle type for SO_2, NO_x, CO, NMVOC, and PM species were estimated based on the JEI-DB (JPEC 2012a, b, c; 2014). Then, cold start emissions for each vehicle type were calculated by the hot emissions and the corresponding ratios. Note that the ratios were adopted for all target years without changes which means that effects of regulations on cold start emissions were not considered in REAS3.

S6.3 Evaporative emissions

In REASv3, evaporative emissions from gasoline vehicles except for Japan were estimated using the following equation:

$$E_{EVP} = \sum_i \{NV_i \times EF_{EVPi}(T) \times 365\}$$

where, E_{EVP} is the evaporative emission, i is the vehicle type, NV is the number of vehicles in operation, and EF_{EVP} is the emission factor as a function of surface temperature T. Settings of EF_{EVP} g/vehicle/day were taken from EEA (2016) as follow:

- T: around 20 to 30 °C
  - 14.6 for Passenger cars
  - 22.2 for Light duty vehicles

    - 7.50 for Motorcycles
- T: around 10 to 20 ℃
    - 7.80 for Passenger cars
    - 12.7 for Light duty vehicles
    - 4.60 for Motorcycles
- T: around 0 to 10 ℃
    - 5.7 for Passenger cars
    - 9.3 for Light duty vehicles
    - 3.4 for Motorcycles
- T: less than 0 ℃
    - 4.0 for Passenger cars
    - 6.5 for Light duty vehicles
    - 2.6 for Motorcycles

The same as for the cold start emissions, evaporative emissions were estimated each month based on monthly averaged temperature at surface calculated using NCEP reanalysis data provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA (https://psl.noaa.gov/data/gridded/data.ncep.reanalysis.html).

For Japan, evaporative emissions from running loss, hot soak loss and diurnal breaking loss in 2000, 2005, and 2010 were obtained for 6 sub-regions in Japan defined in Sect. S2.3 from the JEI-DB (JPEC 2012a, b, c; 2014). Data between 2000 (2005) and 2005 (2010) were interpolated and those before 2000 and after 2000 were extrapolated using the following trend factors:

- Running loss: Trends of traffic volumes of gasoline vehicles
- Diurnal breaking loss: Trends of number of gasoline vehicles
- Hot soak loss: Trends of emissions from gasoline vehicles roughly estimated by number of gasoline vehicles and corresponding emission factors obtained from JPEC (2012a).

S6.4 Speciation of NMVOC emissions

Emission factors of NMVOC described in Sects. S6.2 and S6.3 were for total NMVOC. In REASv3, total NMVOC emissions were allocated to 19 NMVOC species categories defined in Sect. S2.1. The speciation was conducted based on speciation profiles for exhaust emissions from each vehicle type and evaporative emissions provided by D. G. Streets (private communication) based on Klimont et al. (2002a) used for REASv1 and REASv2. The speciation profiles were commonly used for all countries and periods.

S7. Other transport

S7.1 Sub-sectors included in REASv3

In REASv3, emissions from railway, pipeline transport and non-specified sectors defined in the International Energy Agency (IEA) World Energy Balances (IEA, 2017) were included in transport sector except for road transport. Aviation and navigation are out of scope of REASv3.

S7.2 Activity data

Activity data in other transport sectors are fuel consumption which was described in Sect. S3.1.

S7.3 Emission factors

Table 7.1 summarized emission factors for diesel oil and heavy fuel oil combustion in railway sector. For emission factors of other sources and speciation of NMVOC species, settings for fuel combustion in industry sector were used as default. Note that emission controls were not considered emissions from other transport sectors in REASv3.

Table 7.1. Emission factors for diesel oil and heavy fuel oil combustion in railway. Unit is t/PJ (expressed as NO_2 for NO_x).

	Diesel oil	Heavy fuel oil
NO_x[a]	900	1249
CO[a]	250	1000
NMVOC[a]	200	110
NH_3[a]	0.16	0.01
CO_2[b]	74100	77400
PM_{10}[c]	102	143
$PM_{2.5}$[c]	96.4	135
BC[c]	44.0	58.5
OC[c]	25.0	39.0

a. ABC Emission Inventory Manual (Shrestha et al., 2013). b. IPCC (2006). c. Klimont et al. (2002b) and Kupiainen and Klimont (2004) for PM species.

S7.4 Speciation of NMVOC emissions

Emission factors of NMVOC described in Sect. S7.3 were for total NMVOC. In REASv3, total NMVOC emissions were allocated to 19 NMVOC species categories defined in Sect. S2.1. The speciation was conducted based on speciation profiles for exhaust emissions from each vehicle type and evaporative emissions provided by D. G. Streets (private communication) based on Klimont et al. (2002a) used for REASv1 and REASv2. The speciation profiles were commonly used for all countries and periods.

S8. Non-combustion sources of NH_3

S8.1 Manure management

S8.1.1 Methodology

In REASv3, gridded emissions from manure management were developed based on following procedures except for Japan (see Sect. S8.1.5 for Japan):

1. Gridded emissions of REASv1 (Yamaji et al., 2004) in 2000 were used for based data.
2. Emissions in each country and region during 1950-2015 were estimated using numbers of livestock as activity data (see Sect. S8.1.2) and emission factors for each livestock (see Sect. S8.1.3).
3. Spatial allocation factors of emissions in target years were created using the base data and ratios of emission amounts in each grid between target years and 2000 obtained from the Emission Database for Global Atmospheric Research (EDGAR) version 4.3.2 during 1970-2012 (Crippa et al., 2016). Before 1970 and 2012, data in 1970 and 2012 were used, respectively.
4. Annual gridded emissions data in each country and region during 1950-2015 were developed using the base data described in No.1, ratios of emissions between target years and the base year based on the trends of emissions estimated in No.2, and the spatial allocation factors for each country and region in target years developed in No.3. Note that emission values estimated in No.2 were not directly used in REASv3.
5. Monthly gridded data during 1950-2015 were created using the annual gridded emission data developed in No.4 and monthly allocation factors for each country and region (see Sect. S8.1.4).

Note that in REASv3, emissions from animal manures utilized for fertilizers are not included in manure management, but in fertilizer application (see Sect. S8.2).

S8.1.2 Activity data

As described in Sect. S8.1.1, activity data to estimate NH_3 emissions from manure management of livestock are number of livestock. In REASv3, contributions from following livestock were included: buffalo, dairy cows, other cattle, swine, goats, sheep, horses, camels, mules and asses, broilers, ducks, geese, laying hens, and turkeys. National data were derived from FAOSTAT (http://www.fao.org/faostat/en/) during 1961-2015 and extrapolated to 1950 using Mitchell (1998). For China, weighting factors for regional distribution were calculated during 1987-2015 based on China Statistical Yearbook (National Bureau of Statistics of China, 1986–2016). The weighting factors in 1987 were used for the data before 1986. For regional weighting factors for India, data during 1997-2012 were estimated based on Livestock Census (http://www.dahd.nic.in/about-us/divisions/statistics/) and the weighting factors in 1997 and 2012 were used before 1997 and 2012, respectively.

S8.1.3 Emission factors

Annual emission factors of manure management were taken from EEA (2016) for emissions from housing, storage and yards for all countries and regions except for China. For China, regional monthly emission factors were estimated based on those for manure spreading from Xu et al. (2016) and ratios of emission factors between manure management and manure applied to soils from EEA (2016). The emission factors were commonly used for all target years.

S8.1.4 Monthly allocation factors

For China, as descried in Sect. S8.1.3, monthly emission factors were estimated. For other countries and regions, monthly allocation factors were calculated based on relationships between monthly weighting factors of Japan from the Japan Auto-Oil Program (JATOP) Emission Inventory-Data Base (JEI-DB) (JPEC, 2012b; 2014) and monthly averaged temperature.

S8.1.5 Japan

In REASv3, gridded emissions from manure management were developed based on following procedures:

1. Monthly gridded emissions of JEI-DB (JPEC, 2012b; 2014) in 2000 were used as based data before 2002 and those in 2005 were used after 2003.
2. Emissions in 47 prefectures during 1950-2015 were estimated using numbers of livestock as activity data and corresponding emission factors for each livestock.
3. Monthly gridded emissions data in each prefecture during 1950-2015 were developed using the base data described in No.1, ratios of emissions between target years and the base year based on the trends of emissions estimated in No.2. Note that emission values estimated in No.2 were not directly used in REASv3.
4. Monthly gridded data during 1950-2015 were created by adding data of each prefecture developed in No.3.

For Japan, contributions from following livestock were included: dairy cows, other cattle, fattening pigs, other hogs, sheep, goats, broilers, and layers. Data of each prefecture during

1960-2015 were obtained from the statistics of Ministry of Agriculture, Forestry and Fisheries (https://www.maff.go.jp/j/tokei/kouhyou/tikusan/) and extrapolated using Historical Statistics of Japan (Japan Statistical Association, 2006). Emission factors were taken from EEA (2016) for housing, storage and yards the same as for other countries and regions.

S8.2 Fertilizer application

S8.2.1 Methodology

In REASv3, gridded emissions from fertilizer were developed based on following procedures except for Japan (see Sect. S8.2.5 for Japan):

1. Gridded emissions of REASv1 (Yan et al., 2003) in 2000 were used for based data.
2. Emissions from both synthetic fertilizer and animal manure used as fertilizer in each country and region during 1950-2015 were estimated. Those from synthetic fertilizer were calculated using amounts of applied synthetic fertilizer (see Sect. S8.2.2) and emission factors for each fertilizer type (see Sect. S8.2.3) and those from animal manure were estimated based on number of livestock (see Sect. S8.1.2) and emission factors for each livestock (see S8.2.3).
3. Spatial allocation factors of emissions in target years were created using the base data and ratios of amounts of synthetic nitrogen fertilizer applied to each grid between target years and 2000 obtained from Nishina et al. (2017) during 1961-2010. Before 1961 and 2010, data in 1961 and 2010 were used, respectively.
4. Annual gridded emissions data in each country and region during 1950-2015 were developed using the base data described in No.1, ratios of emissions between target years and the base year based on the trends of emissions estimated in No.2, and the spatial allocation factors for each country and region in target years developed in No.3. Note that emission values estimated in No.2 were not directly used in REASv3.
5. Monthly gridded data during 1950-2015 were created using the annual gridded emission data developed in No.4 and monthly allocation factors for each country and region (see Sect. S8.2.4).

S8.2.2 Activity data

Synthetic fertilizer

As described in Sect. S8.2.1, activity data to estimate NH_3 emissions from synthetic fertilizer are applied amounts of synthetic fertilizer. In REASv3, contributions from following synthetic fertilizer were included: ammonium nitrate, ammonium phosphate, ammonium sulphate, ammonium sulphate nitrate, ammonium bicarbonate, calcium ammonium nitrate, calcium nitrate, sodium nitrate, urea, other nitrogen fertilizer, and other complex fertilizer.

For China, national data of different fertilizers were taken from FAOSTAT (http://www.fao.org/faostat/en/) and Fu et al. (2017) during 1982-2015. The data were extrapolated to 1950 and regionally distributed based on total consumption of chemical fertilizer obtained from China Data Online. For India, national data for each fertilizer type were taken from FAOSTAT during 1982-2015 and regionally distributed using state-wise consumption of nitrogen fertilizers obtained from Indiastat. The data were extrapolated to 1961 using national consumption data of total nitrogen fertilizer in India from FAOSTAT and to 1950 based on global nitrogen fertilizer consumption from Hammond and Matthews (1999). Using the same procedures for India, national data of other countries and regions for each fertilizer type were derived from FAOSTAT and were extrapolated based on national and global nitrogen fertilizer consumption data.

Animal manure

Activity data for emissions from animal manure used as fertilizer are numbers of livestock and the same data for manure management described in Sect. S8.1.2 were used.

S8.2.3 Emission factors

Synthetic fertilizer

Annual emission factors of ammonium nitrate, ammonium phosphate, ammonium sulphate, calcium ammonium nitrate, and urea were based on EEA (2016). In REASv3, data for normal pH and temperate climate were adopted. For ammonium bicarbonate, emission factor was obtained from Yan et al. (2003). For other fertilizers including ammonium sulphate nitrate, calcium nitrate, sodium nitrate, other nitrogen fertilizer, and other complex fertilizer, data of other straight N compounds in EEA (2016) were used. The emission factors were commonly used for all target years.

Animal manure

Annual emission factors of from animal manure used as fertilizer were taken from EEA (2016) for emissions from following manure application for all countries and regions except for China. For China, regional monthly emission factors were taken from Xu et al. (2016). The emission factors were commonly used for all target years.

S8.2.4 Monthly allocation factors

Synthetic fertilizer

For China, monthly allocation factors in REASv3 were estimated based on monthly application nitrogen ratio taken from Xu et al. (2015). The data were used commonly for each grid in China during 1950-2015. For other countries and regions, first, monthly allocation factors were calculated using N fertilizer application amounts for each country and region obtained from Nishina et al. (2017) during 1961-2010. In the calculated monthly factors, there are cases that some months have high factors, whereas the others have almost zero. In REASv3, the highest monthly factor was set at 0.2 and the factors of all months were adjusted accordingly referring to Janssens-Maenhout et al. (2015). The modified monthly factors during 1961-2010 were commonly used for each country and region and data in 1961 and 2010 were used before 1960 and 2011, respectively.

Animal manure

For China, as descried in Sect. S8.2.3, monthly emission factors were estimated. For other countries and regions, monthly allocation factors were calculated based on relationships between monthly weighting factors of Japan from JEI-DB (JPEC, 2012b; 2014) and monthly averaged temperature.

S8.2.5 Japan

In REASv3, gridded emissions from fertilizer application were developed based on following procedures:

1. Monthly gridded emissions of JEI-DB (JPEC, 2012b; 2014) in 2000 were used as based data before 2002 and those in 2005 were used after 2003.
2. Emissions from both synthetic fertilizer and animal manure used as fertilizer in 47 prefectures during 1950-2015 were estimated. Those from synthetic fertilizer were calculated using amounts of applied synthetic fertilizer and emission factors for each fertilizer type and those from animal manure were estimated based on number of livestock and emission factors for each livestock.
3. Monthly gridded emissions data in each prefecture during 1950-2015 were developed using the base data described in No.1, ratios of emissions between target years and the base year based on the trends of emissions estimated in No.2. Note that emission values estimated in No.2 were not directly used in REASv3.

4. Monthly gridded data during 1950-2015 were created by adding data of each prefecture developed in No.3.

Synthetic fertilizer

Activity data for emissions from synthetic fertilizer were applied amounts of synthetic fertilizers. National data of different fertilizers were derived from FAOSTAT during 1971-2002 and extrapolated during 1960-2015 and distributed to 47 prefectures based on data in Fertilizer Statistics Yearbook (Newspaper department of Japan Fertilizer Association), Handbook of Fertilizer (Association of Agriculture and Forestry Statistics) and statistics provided by Japan Fertilizer & Ammonia Producers Association (http://www.jaf.gr.jp/en.html). The data were extrapolated to 1950 based on global nitrogen fertilizer consumption from Hammond and Matthews (1999).

Animal manure

Activity data for emissions from animal manure used as fertilizer are numbers of livestock and the same data for manure management described in Sect. S8.1.5 were used. Emission factors were taken from EEA (2016) for manure applied to soils the same as for other countries and regions. The emission factors were commonly used for all target years.

S8.3 Industrial production

In REASv3, NH_3 emissions from industrial processes for production of ammonia, ammonium nitrate, and urea (fertilizers) are considered. National production amounts of ammonia during 1990-2015 were obtained from Minerals Yearbook (USGS). For China, data before 1990 were taken from Vroomen (2013). Data of Japan before 1990 were derived from the Historical Statistics of Japan (Japan Statistical Association, 2006). For other countries, data were extrapolated based on trends of production capacity obtained from World Nitrogen Survey (Constant and Sheldrick, 1992). For urea and ammonium nitrate, data of Japan were derived from Handbook of Fertilizer (Association of Agriculture and Forestry Statistics). For China, national production amounts of urea obtained taken from Vroomen (2013). Other national data of urea and ammonium nitrate were estimated from IFASTAT (https://www.ifastat.org/) and World Nitrogen Survey (Constant and Sheldrick, 1992). For regional distribution of Japan, weighting factors were developed using reginal shipment data for chemical industrial products obtained from Ministry of Economy, Trade and Industry (https://www.meti.go.jp/statistics/tyo/kougyo/index.html). For China, regional production ratios of urea in 2015 were used as weighting factors. For India, national data were distributed to each region using total energy consumption in chemical industry developed based on methodologies described in Sect. S3.1.

Emission factors for industrial process emissions from production of ammonia, and urea were derived from Shrestha et al. (2013). For ammonium nitrate, median of the range provided in Shrestha et al. (2013) were used. The emission factors were adopted for all target countries and periods.

S8.4 Human

NH_3 emissions from human perspiration and respiration were included in REASv3. Activity data are number of total population in each country and region. See descriptions for domestic use of solvents in Sect. S5.1.2 for data sources of total population. Emission factors were taken from Kannari et al. (2001) and adopted for all target countries and periods.

S8.5 Latrines

In REASv3, emissions from latrines were estimated based on number of population in no sewage service areas. For Japan, data were obtained from Mizuochi (2012) and MOEJ (Ministry of Environment of Japan) (2017b). Due to lack of information, corresponding data in other countries and regions were roughly estimated based on the following assumptions referring Kanamori and Hijioka (2013):

- Rep. of Korea, Taiwan, Singapore, Hong Kong, and Macau: ratios of population in sewage service areas were 95 percent of Japan
- Beijing and Shanghai: ratios of population in sewage service areas were 60 percent of Japan
- Other countries and regions: ratios of population in sewage service areas were one-third of Japan

Emission factor for latrines was taken from Vallack and Rypdal (2012) which was half value provided in EEA (2016) and adopted for all target countries and periods.

S9. Spatial and temporal distribution

S9.1 Grid allocation factors

S9.1.1 Population distribution

In REASv3, spatial distributions of total population were used as default grid allocation factors. In addition, urban and rural population distributions were also used for spatial allocation factors for several sectors (see Sects. S9.1.2, S9.1.3, S9.1.4, and S9.1.6). HYDE 3.2.1 (Klein Goldwijk et al. 2017) provides total, urban, and rural population data with $5' \times 5'$ in 1950, 1960, 1970, 1980, 1990, 2000, 2005, 2010, and 2015. REASv3 used the total, urban, and rural population data of HYDE 3.2.1 as weighting factors to create grid allocation factors for .$0.25° \times 0.25°$ data. The data of missing years were created by interpolation.

S9.1.2 Power plants

As described in Sects. S2.5 and S3.1.6, REASv3 treats large power plants as point sources and information of longitude and latitude were provided with emissions from each power plant. The locations of power plants were surveyed using internet services such as Industry About (https://www.industryabout.com/), Global Energy Observatory (http://globalenergyobservatory.org/), and search engines based on names of units, plants, and companies derived from the World Electric Power Plants Database (WEPP) (Platts, 2018). Emissions form area sources were distributed to grid cells using based on total population distribution. For Japan, emissions from area sources were gridded using grid allocation factors for other industries (see Sect. S9.1.7).

S9.1.3 Iron and steel industry

In REASv3, iron and steel plants were not treated as point sources, but grid allocation factors for iron and steel industry were developed as follows:

1. Major iron and steel plants including names, production capacities, and start years of operations were surveyed using Minerals Yearbook (USGS), websites of iron and steel plants, and internet search engines. For plants without information of production capacity and start years of operations, small values were assumed for production capacities by referring to other plants in each country and region and the data were used for all target years to estimate grid allocation factors.
2. Locations of the surveyed plants were searched using internet services such as Industry About

(https://www.industryabout.com/), websites of iron and steel plants, and Google Map.

3. Grid allocation factors were created for each target year based on longitude and latitude and production capacity of each plant in operation used as weighting factors.

One problem of these grid allocation factors is that not all emissions in iron and steel industry sector were from plants considered in above procedures. In REASv3, 80% of both combustion and non-combustion emissions from iron and steel industry were allocated to grid cells using the grid allocation factors developed here. For the other 20%, emissions were distributed to grid cells based on total population distribution except for Japan where grid allocation factors for other industries (see Sect. S9.1.7) were used.

S9.1.4 Cement industry

The same as for iron and steel plants, in REASv3, cement plants were not treated as point sources, but grid allocation factors for iron and steel industry were developed as follows:

4. Major cement plants including names, production capacities, and start years of operations were surveyed using Minerals Yearbook (USGS), websites of cement plants, and internet search engines. For plants without information of production capacity and start years of operations, small values were assumed for production capacities by referring to other plants in each country and region and the data were used for all target years to estimate grid allocation factors.
5. Locations of the surveyed plants were searched using internet services such as Industry About (https://www.industryabout.com/), websites of cement plants and Google Map.
6. Grid allocation factors were created for each target year based on longitude and latitude and production capacity of each plant in operation used as weighting factors.

Also, the same as for the case of iron and steel plants, one problem of these grid allocation factors is that not all emissions in cement industry sector were from plants considered in above procedures. In REASv3, 80% of both combustion and non-combustion emissions from cement industry were allocated to grid cells using the grid allocation factors developed here. For the other 10%, emissions were distributed to grid cells based on total population distribution except for Japan where grid allocation factors for other industries (see Sect. S9.1.7) were used.

S9.1.5 Road transport

Grid allocation factors for road transport sector were created from other emission inventory datasets. For Japan, gridded emission data of the Japan Auto-Oil Program (JATOP) Emission Inventory-Data Base (JEI-DB) (JPEC 2012a, c; 2014) 2000, 2005, and 2010 were used to create grid allocation factors for each target species. For the year between 2000 and 2005/2005 and 2010, the

JEI-DB data were interpolated. Before 2000 and after 2010, the JEI-DB data for 2000 and 2010 were used, respectively. For other countries and regions, grid allocation factors for each species were created using gridded emission data of road transport sector of the Emission Database for Global Atmospheric Research (EDGAR) version 4.3.2 (Crippa et al., 2016) during 1970-2012. Before 1970 and after 2012, data for 1970 and 2012 were used, respectively.

S9.1.6 Domestic sectors

Residential fuel combustion

For China, emissions from residential fuel combustion were estimated in urban and rural areas separately. They were distributed to grid cells based on rural and total population distribution, respectively. For other countries and regions, emissions from fuel combustion were estimated for total residential sector. For emissions from coal fuels, kerosene, and biofuels combustion, grid allocation factors developed using rural population distribution were used. For other fuels, emissions were distributed to grid cells based on total population distribution.

Commercial and public services (fuel combustion)

Emissions were distributed to grid cells based on urban population distribution.

Agriculture and forestry (fuel combustion)

Emissions were distributed to grid cells based on rural population distribution.

NMVOC non-combustion emissions related to residential activities

Emissions from dry cleaning and waste disposal were distributed to grid cells based on urban and rural population distributions, respectively. For those from domestic use of solvents and paint, grid allocation factors developed using total population distribution were used.

NH_3 emissions related to human biological phenomenon

Emissions from human perspiration and respiration were distributed to grid cells based on total population distribution and those from latrines were gridded using grid allocation factors developed using rural population distribution.

S9.1.7 Others

For all other sources which were not included in descriptions in Sects. S9.1.2-6, emissions were allocated to grid cells based on total population distribution except for Japan. Grid allocation factors for the other sources of Japan were summarized in Table 9.1.

Table 9.1. Data sources and treatments for grid allocation factors for Japan for sources not described in Sects. S9.1.2-S9.1.6.

Sector categories	Data sources and treatment
Non-ferrous metal industry	● Longitude and latitude, start years of operations, and production capacities of copper, zinc, lead, and aluminium plants surveyed using Minerals Yearbook (USGS), websites of non-ferrous metal plants, and internet search engines. ● Using the same methodology for iron and steel industry described in Sect. S9.1.3, grid allocation factors were developed for copper, zinc, lead, aluminium, and total non-ferrous metal sectors independently. Data for total non-ferrous metal sector include points of all non-ferrous metal plants. ● Emissions from non-combustion sources were estimated for each metal sector and corresponding grid allocation factors were used. For combustion sources, grid allocation factors for total non-ferrous metal sector were used. ● Similar to the methodology for iron and steel, 80% of emissions from non-ferrous metal industry sectors were allocated to grid cells using the grid allocation factors developed here. For the other 20%, emissions were distributed to grid cells based on grid allocation factors for other industries (see “Other industry” of this table).
Other industry	● Grid allocation factors for each target species were created based on gridded emission data of JEI-DB (JPEC 2012b, c; 2014) in 2000, 2005 and 2010 for industry sector where contributions from grids including point sources of iron and steel, cement, and non-ferrous metals were excluded. For the year between 2000 and 2005/2005 and 2010, the data were interpolated. Before 1999 and after 2011, the data for 2000 and 2010 were used, respectively.
NMVOC evaporative sources	● Grid allocation factors were created based on gridded emission data of JEI-DB (JPEC 2012b, c; 2014) for NMVOC evaporative sources

	using the same methodology for road transport sector described in Sect. S9.1.5.

S9.2 Monthly variation factors

S9.2.1 Power plants

Data sources and treatment for monthly variation factors used in REASv3 were summarized in Table 9.2.

Table 9.2. Data sources and treatments for monthly variation factors for emissions from power plants used in REASv3.

Countries and regions	Data sources and treatment
China	● Weighting factors: Monthly generated electricity ● Data sources and treatment: ➢ Regional data during 2002-2010 were obtained from China Data Online. Before 2001 and after 2011, the data in 2002 and 2011 were used, respectively. ➢ Estimated monthly variation factors were used for all fuel types.
India	● Weighting factors: Monthly thermal generation of electricity ● Data sources and treatment: ➢ National data during in 2000, 2005, 2010 were taken from Monthly Abstract of Statistics (Ministry of Statistics and Programme Implementation, http://mospi.gov.in/). Data during 2001-2004/2006-2009 were interpolated. Before 1999 and after 2011, the data in 2000 and 2010 were used, respectively. ➢ Estimated monthly variation factors were used for all fuel types and regions.
Japan	● Monthly variation factors were derived from a report of JEI-DB (2014) and used for all fuel types, regions, and periods.
Taiwan	● Weighting factors: Monthly generated electricity ● Data sources and treatment: ➢ National data in 2011 were taken from Monthly Bulletin of Statistics (National Statistics, https://eng.stat.gov.tw/). ➢ Estimated monthly variation factors were used for all fuel types and periods.

Thailand	● Monthly variation factors were derived from Thao Pham et al. (2008) and used for all fuel types, regions, and periods.
Vietnam	● Weighting factors: Monthly generated electricity ● Data sources and treatment: ➢ National data during 2005-2010 were taken from monthly statistics provided by General Statistics Office of Vietnam (https://www.gso.gov.vn/). Before 2004 and after 2011, the data in 2005 and 2010 were used, respectively. ➢ Estimated monthly variation factors were used for all fuel types.

S9.2.2 Industry

Data sources and treatment for monthly variation factors used in REASv3 were summarized in Table 9.3. Note that emissions from industry sub-categories not described in Table 9.3 were distributed to each month using number of dates as weighting factors.

Table 9.3. Data sources and treatments for monthly variation factors for emissions from power plants used in REASv3.

Countries and regions	Data sources and treatment
China	● Weighting factors: Monthly production ● Data sources and treatment: ➢ Regional data of steel and cement during 2002-2010 were derived from China Data Online. Before 2001 and after 2011, the data in 2002 and 2011 were used, respectively. Monthly variations based on steel (cement) production were adopted to both combustion and non-combustion emissions from iron and steel (cement) industry. ➢ National data of coke and sulphuric acid production during 2006-2010 were derived from China Data Online. Before 2005 and after 2011, the data in 2006 and 2010 were used, respectively. The monthly variations based on coke production were adopted to both combustion and non-combustion emissions from coke industry and those for sulphuric acid were used only for non-combustion emissions. ➢ National data of copper, zinc, lead, and aluminum in 2001 and 2002 were obtained from JOGMEC (2002-2003). Before 2000 and after 2003, data in 2001 and 2002 were used. The monthly variations

	based on production of each metal type were adopted to non-combustion emissions from each metal industry. Those for combustion in non-ferrous metal industry were estimated using production amounts of total non-ferrous metals. ➢ For petroleum refinery, monthly variations were calculated based on national monthly processed volume of crude oil derived from China Data Online during 2006-2010. Before 2005 and after 2011, the data in 2006 and 2010 were used, respectively. The monthly variations were adopted to both combustion and non-combustion emissions from petroleum refinery industry including energy sector. ➢ For other industries, monthly variations were calculated using numbers of each month as weighting factors. ➢ Estimated monthly variation factors were used for all fuel types
India	● Weighting factors: Monthly production ● Data sources and treatment: ➢ National data during in 2000, 2005, 2010 were taken from Monthly Abstract of Statistics (Ministry of Statistics and Programme Implementation, http://mospi.gov.in/). Data during 2001-2004/2006-2009 were interpolated. Before 1999 and after 2011, the data in 2000 and 2010 were used, respectively. Following monthly variations were estimated. ✧ Pig iron: Non-combustion emissions from pig iron production ✧ Steel products: Non-combustion emissions from steel production ✧ Total production amounts of iron and steel: Combustion emissions from iron and steel industry ✧ Total production amounts of non-ferrous metals: Combustion and non-combustion emissions from non-ferrous metal industry ✧ Cement: Combustion and non-combustion emissions from cement industry ✧ Non-metallic mineral products (index numbers of industrial production): Combustion and non-combustion emissions from non-metallic minerals industry except for cement and brick. ✧ Sulphuric acid: Non-combustion emissions from sulphuric acid production ✧ Coke: Combustion and non-combustion emissions from coke industry

<table>
<tr><td></td><td>
✧ Total production amounts of refined petroleum: Combustion and non-combustion emissions from petroleum refinery including energy sector.
➢ Emissions from brick production were allocated to November to June referring Maithel (2013).
➢ Estimated monthly variation factors were used for all fuel types.
</td></tr>
<tr><td>Japan</td><td>
● Monthly variation factors were derived from a report of JEI-DB (JPEC, 2014) and adopted as follows:
➢ Iron and steel industry: Combustion and non-combustion emissions from iron and steel industry
➢ Construction: Combustion emissions from construction industry.
➢ Petroleum refinery: Combustion and non-combustion emissions from petroleum refinery including energy sector.
➢ Gas works: Combustion emissions from manufacture of gaseous fuels including energy sector
➢ Other industry sectors: Settings of monthly variations for other industries in JPEC (2014) are relatively close and in REASv3, their averaged values were adopted to combustion and non-combustion emissions from other industries not included above.
● Estimated monthly variation factors were used for all fuel types and periods.
</td></tr>
<tr><td>Republic of Korea</td><td>
● Weighting factors: Monthly production
● Data sources and treatment:
➢ Pig iron: and crude steel: National data during 2000-2010 were taken from Steel Statistical Yearbook (https://www.worldsteel.org/steel-by-topic/statistics/steel-statistical-yearbook.html). Monthly production amounts of pig iron (crude steel) were used to calculate monthly variations for non-combustion emissions from pig iron (crude steel) production. Monthly variations for combustion emissions from iron and steel industry were estimated based on total production amounts of pig iron and crude steel. Before 1999 and 2011, monthly variations in 2000 and 2010 were used, respectively.
➢ Estimated monthly variation factors were used for all fuel types.
</td></tr>
<tr><td>Taiwan</td><td>
● Weighting factors: Monthly production
● Data sources and treatment:
</td></tr>
</table>

	➢ Cement: National data in 2011 were taken from Monthly Bulletin of Statistics (National Statistics, https://eng.stat.gov.tw/). Estimated monthly variation factors were used for all fuel types and periods. ➢ Pig iron: and crude steel: National data during 2000-2010 were taken from Steel Statistical Yearbook (https://www.worldsteel.org/steel-by-topic/statistics/steel-statistical-yearbook.html). Monthly production amounts of pig iron (crude steel) were used to calculate monthly variations for non-combustion emissions from pig iron (crude steel) production. Monthly variations for combustion emissions from iron and steel industry were estimated based on total production amounts of pig iron and crude steel. Before 1999 and 2011, monthly variations in 2000 and 2010 were used, respectively. Estimated monthly variation factors were used for all fuel types.
Brunei	● Monthly variations for NMVOC emissions from crude oil production were estimated based on monthly crude oil production during 2000 and 2005 taken from Brunei Economic Bulletin. Before 1999 and 2006, monthly variations in 2000 and 2005 were used.
Indonesia	● Combustion and non-combustion emissions from brick production were mainly allocated to dry seasons during June to September.
Malaysia	● Monthly production amounts during 2008-2010 were taken from Monthly Statistics Bulletin Malaysia and adopted as follows: ➢ Iron and steel: Combustion and non-combustion emissions from iron and steel industry. ➢ Cement: Combustion and non-combustion emissions from cement industry. ➢ Crude oil: NMVOC emissions from crude oil production ➢ Natural gas: NMVOC emissions from natural gas production ➢ Before 2007 and after 2011, monthly variations in 2008 and 2010 were used, respectively. ● Combustion and non-combustion emissions from brick production were mainly allocated to dry seasons during June to September. ● Estimated monthly variation factors were used for all fuel types.
Myanmar	● Combustion and non-combustion emissions from brick production were mainly allocated to dry seasons during December to April.
Philippines	● Monthly variations of emissions were estimated during 2001-2010 based

	on value of production index taken from Philippine Statistics Authority and adopted as follows: ➢ Iron and steel: Combustion and non-combustion emissions from iron and steel industry. ➢ Non-ferrous metal: Combustion and non-combustion emissions from non-ferrous metal industry. ➢ Cement: Combustion and non-combustion emissions from cement industry. ➢ Non-metallic minerals: Combustion and non-combustion emissions from non-metallic minerals industry except for cement. ➢ Refined petroleum products: Combustion and non-combustion emissions from petroleum refinery. ➢ Before 2000 and after 2011, monthly variations in 2001 and 2010 were used, respectively. ● Estimated monthly variation factors were used for all fuel types.
Singapore	● Relative ratios of monthly production in 2006, 2008, and 2009 were estimated based on Monthly digest statistics Singapore and adopted as follows: ➢ Refinery petroleum products: Combustion and non-combustion emissions from petroleum refinery including energy sector. ➢ Non-metallic minerals products: Combustion and non-combustion emissions from cement industry. ➢ Before 2007 and after 2010, data in 2006 and 2009 were used, respectively. Estimated monthly variation factors were used for all fuel types.
Thailand	● Monthly variation factors were derived from Thao Pham et al. (2008) and adopted as follows: ➢ Basic Metal: Iron and steel and non-ferrous metal ➢ Chemicals: Chemical and petrochemical ➢ Non-Metal: Cement, lime, and non-specified non-metallic minerals except for brick ➢ Food & Beverage: Food and tobacco ➢ Paper: Paper, pulp and printing ➢ Wood & Furniture: Wood and wood products ➢ Textile: Textile and leather ➢ Other: Other industry sectors not included above except for brick

	industry whose emissions were mainly allocated to dry seasons during November to May. ● Estimated monthly variation factors were used for all fuel types and periods.
Vietnam	● Monthly variations of emissions were estimated during 2005-2010 based on production amounts taken from General Statistics Office of Viet Nam and adopted as follows: ➢ Cement: Cement: Combustion and non-combustion emissions from cement industry. ➢ Crude oil: NMVOC emissions from crude oil production ➢ Natural gas: NMVOC emissions from natural gas production ➢ Before 2004 and after 2011, monthly variations in 2005 and 2010 were used, respectively. ● Combustion and non-combustion emissions from brick production were mainly allocated to dry seasons during December to March. ● Estimated monthly variation factors were used for all fuel types.
Pakistan	● Weighting factors: Monthly production ● Data sources and treatment: ➢ Pig iron: and crude steel: National data during 2000-2010 were taken from Steel Statistical Yearbook (https://www.worldsteel.org/steel-by-topic/statistics/steel-statistical-yearbook.html). Monthly production amounts of pig iron (crude steel) were used to calculate monthly variations for non-combustion emissions from pig iron (crude steel) production. Monthly variations for combustion emissions from iron and steel industry were estimated based on total production amounts of pig iron and crude steel. Before 1999 and 2011, monthly variations in 2000 and 2010 were used, respectively. ➢ Estimated monthly variation factors were used for all fuel types.
Bangladesh Nepal Sri Lanka	● Monthly variations of India were used for combustion and non-combustion emissions from brick production.

S9.2.3 Road transport

Japan

Monthly variation factors for total emissions from road transport including hot, cold start and NMVOC evaporative emissions were calculated for each region using gridded emission data of JEI-DB (JPEC 2012a, c; 2014) in 2000, 2005, and 2010 for each species. For the year between 2000 and 2005/2005 and 2010, the data were interpolated. Before 1999 and after 2011, the data for 2000 and 2010 were used, respectively.

Other countries and regions

In REASv3, cold start emissions were estimated on a monthly basis using monthly average surface temperature. For hot emissions and NMVOC evaporative emissions, monthly variations were not considered. Annual emissions were distributed to each month using number of date as weighting factors. Data of surface temperature were obtained from NCEP reanalysis data provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA (https://psl.noaa.gov/data/gridded/data.ncep.reanalysis.html).

S9.2.4 Residential combustion

Japan

Monthly variation factors for gas fuels, kerosene, and liquefied petroleum gas (LPG) were taken from a report of JEI-DB (2014) and used for all regions and periods. For other fuel types, data for LPG were adopted.

Other countries and regions

In REASv3, monthly variation of emissions from residential combustion was assumed to be correlated to monthly average surface temperature. Based on monthly proportions of coal consumption in Beijing, Tianjin, and Hebei taken from Zhu et al. (2018), indices of residential emissions as functions of monthly average temperature were created. Using the indices, monthly variations of emissions from residential combustion were estimated for each country and region based on monthly average surface temperature.

S9.2.5 Others

NH_3 emissions from human and latrines

Monthly variations for Japan were obtained from JPEC (2014). For other countries and regions, similar to residential combustion described in Sect. S9.2.4, indices of emissions as function of monthly average surface temperature were created using data of JPEC (2014), assuming that NH_3 emissions from human and latrines are correlated to surface temperature. Then, using the indices, monthly variations of emissions from residential combustion were estimated for each country and region based on monthly average surface temperature.

NMVOC emissions from solvent and paint use

Monthly variation of evaporative emissions from solvent and paint use for reach region of Japan were calculated using gridded emission data of JEI-DB (JPEC 2012b, c; 2014) in 2000, 2005 and 2010 for total solvent use. For the year between 2000 and 2005/2005 and 2010, the data were interpolated. Before 1999 and after 2011, the data for 2000 and 2010 were used, respectively. For other countries and regions, annual emissions were distributed to each month using number of date as weighting factors.

Other sources

For other sources not described above, annual emissions were distributed to each month using number of date as weighting factors.

S10. Uncertainties

S10.1 Methodology

In REASv3, uncertainties of emissions were estimated after Streets et al. (2003) and Huang et al. (2011) using the following equation:

$$U_{i,j} = 1.96 \times \sqrt{(1 + U_A^2)(1 + U_F^2) - 1} \times E_{i,j} \quad (1)$$

where $E_{i,j}$ and $U_{i,j}$ represents respectively emission and its uncertainty for sub-sector category j and its activity i, U_A is uncertainty of i and U_F is uncertainty of emission factor for i and j. U_F were generally estimated based on uncertainties of emission factors (U_{EF}) and those of removal ratios (U_R) as follows:

$$U_F = \sqrt{U_{EF}^2 + U_R^2} \quad (2)$$

U_F for SO_2 emissions based on sulfur contents of fuels and ratio of sulfur retention in ash were estimated using the following equation:

$$U_F = \sqrt{U_S^2 + U_{ERS}^2 + U_R^2} \quad (3)$$

where U_S, U_{ERS}, and U_R represent uncertainties of sulfur contents in fuels, ratios of sulfur retention in ash, and removal ratios, respectively. For road transport sectors, activity data is annual mileage which were calculated by number of vehicles and annual distances traveled for each vehicle type. U_A for road transport sector were estimated using following equation:

$$U_F = \sqrt{U_{NV}^2 + U_{ADT}^2} \quad (4)$$

where U_{NV}, and U_{ADT} represent uncertainties of number of vehicles and those of annual distances traveled, respectively.

The uncertainties in emissions from power plants, industries, road transport, other transport, domestic and other sectors, as well as uncertainties in total emissions were calculated for all target species. The uncertainties of different sub-sectors and activities were combined in quadrature and estimated for each country and region. For uncertainties of national emissions in China, India, and Japan, those in their sub-regions were added linearly.

S10.2 Settings of uncertainties of each component

In REASv3, uncertainties in emissions were estimated in 1955, 1985, and 2015 for all species and most sources. In this sub-section, settings of uncertainties of activity data, emission factors, and emission controls and their assumption are described. Note that uncertainties of emissions that were not originally developed in REASv3 (NH_3 emissions from manure management and fertilizer application, and NMVOC evaporative emissions from Japan and the Republic of Korea) were not evaluated.

S10.2.1 Stationary combustion sources

Activity data

Activity data of stationary combustion sources are amounts of fuel consumption in each sub-sector. The data were derived from variety of sources and a lot of treatments were done for missing data as described in Sect. S3.1. Settings of uncertainties of the data were based on the differences of the data sources and following assumption were taken into considered:

- Values of uncertainties were estimated referring EEA (2016) assuming uncertainties of data for Asian countries are generally higher than those of European countries.
- Uncertainties of fossil fuel consumption data are lower for Japan, Republic of Korea, and Taiwan in 2015 and Japan in 1985 compare to other countries and regions. Those for China using the China Energy Statistical Yearbook (CESY) (National Bureau of Statistics of China, 1986, 2001-2017) and those for other countries using the International Energy Agency (IEA) World Energy Balances (IEAWEB) (IEA, 2017) are assumed to be the same.
- Uncertainties of primary biofuels (fuelwood, crop residue, and animal waste) are higher than those of fossil fuels.
- Uncertainties of other fuels such as charcoal and municipal wastes are higher than those of fossil fuels but lower than those of biofuels.
- Uncertainties of data in the United Nations (UN) Energy Statistics Database (UN, 2016) and the UN data, which is a web-based data service of the UN (http://data.un.org/) are higher than those in CESY and IEAWEB. (The data were used for Macau, Laos, Bhutan, Afghanistan, and Maldives in 1955, 1985, and 2015 and Cambodia in 1955 and 1985).
- Uncertainties of data in 2015 are lower than in 1985.
- Uncertainties of fuel consumption in power plants, iron and steel, and cement industries are lower than those in other industries.
- Uncertainties of fuel consumption in residential and other domestic sectors were higher than those in the other industries.
- All fuel consumption data in 1955 were extrapolated using trend factors (see Sect. S3.1). Therefore, the same settings of uncertainties much higher than 1985 are assumed.

Uncertainties of fuel consumption data adopted in REASv3 are summarized in Table 10.1.

Table 10.1. Uncertainties [%] of fuel consumption amounts in 1995, 1985, and 2015 assumed in REASv3. Values in the table (X/Y/Z) are for power plants and iron and steel, and cement industries/other industries/residential and other domestic sectors, respectively.

	Fossil fuels	Primary biofuels	Other fuels
2015			
Japan	±2/±2/±5	±30/±30/±30	±5/±5/±10
Group A	±2/±2/±5	±30/±30/±30	±5/±5/±10
Group B	±10/±15/±20	±30/±30/±30	±15/±20/±25
Group C	±30/±30/±30	±50/±50/±50	±35/±35/±35
1985			
Japan	±5/±10/±15	±40/±40/±40	±10/±15/±20
Group A	±10/±15/±20	±40/±40/±40	±15/±20/±25
Group D	±15/±20/±25	±40/±40/±40	±20/±25/±30
Group E	±40/±40/±40	±60/±60/±60	±45/±45/±45
1955			
All countries and regions	±50/±50/±50	±70/±70/±70	±55/±55/±55

Group A: Republic of Korea and Taiwan. Group B: Countries and regions except for Japan and those in Group A and C using IEAWEB in 2015. Group C: Macau, Laos, Bhutan, Afghanistan, and Maldives using UNESD in 2015. Group D: Group B – Cambodia. Group E: Group C + Cambodia.

Emission factors

For emission factors, two causes need to be considered for their uncertainties. One is uncertainties in the data themselves. Another is those caused by selections of the data including technologies. Values of uncertainties of emission factors were not available in most literature used in REASv3. In addition, there is no specific way to quantify the uncertainties of emission factors caused by the second reason. In REASv3, uncertainties of emission factors were roughly estimated as summarized in Table 10.2 based on the following assumption:

- Uncertainties of CO_2 and SO_2 for gas and oil combustion are smaller than those of others. (Note that uncertainties of SO_2 estimated here were both for ratios of sulfur in fuels emitted as SO_2 (U_{ERS} in equation (3) in Sect. 10.1) and for emission factors in the case of not using sulfur contents in fuels (see Sect. 3.2.1).)
- Uncertainties of NO_x for fossil fuel combustion are larger than those of CO_2 and SO_2, but smaller than those of other species.
- The same settings were adopted for CO, NMVOC, and PM species for fossil fuel combustion

except for those of PM species for coal combustion in residential sector where their uncertainties are assumed to be larger than those of other species.

- In general, uncertainties for coal combustion are larger than those for gas and oil combustion.
- Uncertainties for biofuel combustion are much larger than those for fossil fuel combustion. Due to lack of information, the same settings were used for uncertainties of emission factors for other fuels including charcoal and municipal wastes.
- The smallest uncertainties were assumed for power plants, the largest ones were assumed for residential and other domestic sectors, and uncertainties for industry sectors were generally between them.
- For industry sectors, uncertainties for iron and steel, and cement industries were smaller than those for other industry sectors.
- The largest uncertainties were assumed for NH_3 due to lack of limited information.
- The common settings of uncertainties were adopted for all countries and regions. Exceptions were uncertainties of emission factors of NO_x for coal combustion in power plants and those of PM species for coal combustion in China based on Zhang et al. (2007) and Lei et al. (2011b) where 10% smaller values than those of other countries and regions were adopted.
- It was assumed that estimated uncertainties for emission factors include effects from limited information of technologies.

Note that except for SO_2 and CO_2, uncertainties for the year 1985 and 1955 were assumed to be 10% and 20% larger than those in 2015, respectively. For SO_2 and CO_2, settings of uncertainties were not changed between 2015, 1985, and 1955.

For SO_2, uncertainties for sulfur contents in fuels including effects of regulation (i.e. usage of low sulfur fuels) need to be taken into considered. The uncertainties were assumed based on data sources as follows:

- China:
  - 15%/15%, 15%/20%, and 20%/25% for coal, light and diesel oil, and heavy oil in 2015/1985, respectively.
  - 30% for all fossil fuels in 1955.
- India:
  - 20%/15%, 30%/25%, 20%/20%, and 25%/25% for hard coal, brown coal, light and diesel oil, and heavy oil in 2015/1985, respectively.
  - 30% for all fossil fuels in 1955.
- Japan:
  - 10%/10%, 20%/20%, 15%/15%, and 20%/20% for hard coal, brown coal, light and diesel oil, and heavy oil in 2015/1985, respectively.

- 30% for all fossil fuels in 1955.

- Republic of Korea and Taiwan
  - 20%/15%, 30%/25%, 20%/15%, and 25%/20% for hard coal, brown coal, light and diesel oil, and heavy oil in 2015/1985, respectively.
  - 30% for all fossil fuels in 1955.
- Others:
  - 20%/15%, 30%/25%, 20%/20%, and 25%/25% for coal, light and diesel oil, and heavy oil in 2015/1985.
  - 30% for all fossil fuels in 1955.

Note that uncertainties in 1985 were smaller than other years for some countries and regions because the data were based on detailed surveys of Kato et al. (1991).

Table 10.2. Uncertainties [%] of emission factors of fuel combustion in 2015 assumed in REASv3. Values in the table (W/X/Y/Z) are for power plants/iron and steel, and cement industries/other industries/residential and other domestic sectors, respectively.

	Coal fuels	Gas and oil fuels	Primary biofuels	Others
SO_2	±15/±20/±25/±30	±10/±10/±10/±10	±75/±75/±100/±125	±75/±75/±100/±125
NO_x	±30[a]/±40/±50/±60	±30/±40/±50/±60	±75/±75/±100/±125	±75/±75/±100/±125
CO	±50/±60/±70/±80	±40/±50/±60/±75	±75/±75/±100/±125	±75/±75/±100/±125
NMVOC	±50/±60/±70/±80	±40/±50/±60/±75	±75/±75/±100/±125	±75/±75/±100/±125
NH_3	±100/±100/±100/±100	±100/±100/±100/±100	±150/±150/±150/±150	±150/±150/±150/±150
CO_2	±15/±15/±15/±15	±10/±10/±10/±10	±50/±50/±50/±50	±25/±25/±25/±25
PM_{10}	±50[a]/±60[a] /±70[a] /±100[a]	±40/±50/±60/±75	±100/±100/±125/±150	±100/±100/±125/±150
$PM_{2.5}$	±50[a]/±60[a] /±70[a] /±100[a]	±40/±50/±60/±75	±100/±100/±125/±150	±100/±100/±125/±150
BC	±50[a]/±60[a] /±70[a] /±100[a]	±40/±50/±60/±75	±100/±100/±125/±150	±100/±100/±125/±150
OC	±50[a]/±60[a] /±70[a] /±100[a]	±40/±50/±60/±75	±100/±100/±125/±150	±100/±100/±125/±150

a. 10% smaller values were adopted for China.

Effects of emission controls

For removal efficiencies, the same as for emission factors, it is necessary to consider uncertainties in the data themselves and those caused by selection of data. In addition, uncertainties in settings of emission controls such as timing of introduction and penetration rates of abatement equipment need to be considered where there is no specific way to quantify the uncertainties neither. In REASv3, total uncertainties in effects of emission controls, namely U_R in equations (2) and (3) in Sect. 10.1 were roughly estimated as summarized in Table 10.3 based on the following assumption:

- U_R are assumed to be smaller if settings were generally based on local information and literatures. For example, those for Japan were generally smaller than other countries because their settings were based on domestic information such as MRI (2015) and MOEJ (2000).
- For emission sources where no emission controls were considered, corresponding U_R were assumed to be zero which means that uncertainties caused by neglecting emission controls were not considered. For example, U_R were assumed to be zero for all emission sources, species, and countries and regions in 1955.
- For emission sources where introduction rates of abatement equipment were small, uncertainties caused by settings of emission controls were assumed to be small.

Table 10.3. Settings of total uncertainties in effects of emission controls (U_R) adopted in REASv3. Note that U_R for sources without description here were assumed to be zero.

Countries and regions	Settings of U_R
China	● SO_2: U_R were only estimated in 2015. The values for power plants were assumed to be 20% and those for industry sectors were 10% higher than those for power plants (namely 30%). ● NO_x: The same as for SO_2, U_R for power plants were only estimated in 2015 and the values were assumed to be 25% (5% higher than those for SO_2). The same values were adopted for cement industries. ● PM species: U_R for power plants in 2015 and 1985 were assumed to be 15% and 20%, respectively. For industry sectors, 5% higher values were adopted (namely, 20% and 25% for 2015 and 1985, respectively).
India	● SO_2: Only for power plants as point sources with FGD, 20% were adopted for their U_R. ● PM species: Due to lack of information, 10% higher values were adopted for power plants and industry sectors as follows: In 2015 and 1985, 25% and 30% for power plants and 30% and 35% for industry sectors, respectively.
Japan	● SO_2: U_R in both 2015 and 1985 were assumed to be 20% for power plants. For industry sectors, 5% higher values than those for power plants were adopted (namely 25%). ● NO_x: The same settings for SO_2 were used for both power plants and industry sectors in 2015 and 1985. ● PM species: For power plants, U_R in both 2015 and 1985 were assumed to be 10%. For industry sectors, higher values than those of power plants were assumed as follows: 15% and 20% in 2015 and 1985, respectively.

Korea and Taiwan	• SO_2: U_R for power plants and industry sectors in 2015 were assumed to be 25% and 30%, respectively. In 1985, assuming relatively lower introduction rates of abatement equipment, 10% lower values than those for 2015 were adopted (15% and 20% for power plants and industry sectors, respectively). • NO_x: U_R were only estimated for power plants in 2015 and 5% higher values than those for SO_2 were assumed (namely 30%). • PM species: The same settings for China were adopted.
Thailand	• SO_2: U_R were only estimated for power plants in 2015. The values were assumed to be 25%. • PM species: The same settings for India ware adopted.
Other countries and regions	• SO_2: Only for power plants as point sources with FGD, 20% were adopted for their U_R. • PM species: U_R were assumed for power plants and industry sectors only for the year 2015. 5% higher values than those for Thailand were adopted (namely, 30% for power plants and 35% for industry sectors.)

S10.2.2 Stationary non-combustion sources: Industrial production and other transformation

Activity data

Activity data for emissions from industrial production and other transformation were such as production amounts of industrial products and input amounts of materials. The same as for the case of fuel consumption data as described in Sect. 10.2.1, uncertainties of the activity data depend on reliability and availability of their data sources and for settings of the uncertainties, following assumptions were taken into considered:

- In the same international statistics, uncertainties of data are lower for Japan, Republic of Kora, and Taiwan in 2015 and Japan in 1985 compare to other countries and regions.
- Uncertainties of activity data estimated by such as interpolation or extrapolation were larger than those directly taken from the statistics and literatures.
- Uncertainties of major industrial products such as metals and cement are smaller than minor ones such as lime and carbon black even tough data were taken from the same international statistics.

Uncertainties of activity data for emissions from industrial products and other transformation adopted in REASv3 are summarize in Table 10.4.

Table 10.4. Settings of uncertainties of activity data for industrial production and other

transformation adopted in REASv3. Note that settings for non-combustion sources of NMVOC and NH_3 were described in Sects. S10.2.3 and S10.2.6, respectively.

Sub-sector categories	Settings of uncertainties of activity data
Iron and steel production	● If data were directly taken from data sources, values of uncertainties were assumed as follows: ➢ 5% for Japan, Republic of Korea and Taiwan in 2015 and Japan in 1985 ➢ 10% for other countries and regions in 2015 and 1985 ● For all countries and regions, if data were estimated by interpolation or extrapolation, the uncertainties were assumed to be 15% in 2015 and 1985. ● For the year 1955, the uncertainties were assumed to be 20% for all countries and regions.
Non-ferrous metal production	● The same settings for iron and steel production were adopted.
Cement production	● The same settings for iron and steel production were adopted.
Lime production	● The same criteria for iron and steel production were assumed for differences of settings among countries and regions and years. For values of the uncertainties, 5% higher values than those for iron and steel production were adopted.
Brick production	● Due to lack of available data and information, high uncertainties were assumed as follows: 40%, 50%, and 75% for all countries and regions in 2015, 1985, and 1955, respectively.
Sulphuric acid production	● The same settings for iron and steel production were adopted.
Carbon black production	● The same settings for lime production were adopted.
Coke production	● The same settings for coal consumption in iron and industry in Table 10.1
Petroleum refineries	● The same settings for oil consumption in other industries in Table 10.1.

Emission factors and effects of emission controls

Causes of uncertainties of emission factors and effects of emission controls (U_R) for industrial production and other transformation sectors were basically the same as for those for fuel combustion. Table 10.5 summarizes the settings of uncertainties and related assumptions for emission factors and effects of emission controls adopted in REASv3. Note that except for SO_2 and CO_2, uncertainties of emission factors for the year 1985 and 1955 were assumed to be 10% and 20% larger than those in 2015, respectively, the same as the case for fuel combustion sources. Settings of uncertainties for SO_2 for non-ferrous metal production and CO_2 were not changed between 2015, 1985, and 1955.

Table 10.5. Settings of uncertainties of emission factors in 2015 and effects of emission controls (U_R) for industrial production and other transformation adopted in REASv3. Values were commonly used for all countries and regions unless otherwise indicated.

Sub-sector categories	Settings of uncertainties of emission factors and U_R
Iron and steel production	● Emission factors: 40% for CO, 15% for CO_2, and 60% for PM species. ● U_R: Settings for fuel combustion in iron and steel industry were adopted. For China, the uncertainties in 2015 were assumed to be 10% because the settings were based on local information of Wu et al. (2017).
Non-ferrous metal production	● Emission factors: 20% for SO_2 and 60% for PM species. ● U_R: Settings for fuel combustion in other industries were adopted for PM species. For SO_2, considering uncertainties in collection amounts for sulphuric acid production, high uncertainties of 30% were assumed for the years 2015 and 1985.
Cement production	● Emission factors: ➢ Japan: As described in Sect. S3.2 and S4.1.3, NO_x, CO, and PM species from fuel consumption in cement kilns were estimated using local information of cement production in each kiln type. Therefore, values of uncertainties for NO_x, CO, and PM species were assumed to be 20% lower than those for default settings in Table 10.2. ➢ PM species: 60% was adopted except for China and Japan. For China, because settings were based on local information of Lei et al. (2011a) and Wu et al. (2017), 20% lower values were adopted (namely 40%). ➢ CO_2: Considering uncertainties in clinker to cement ratios, relatively high uncertainties (20%) was adopted. ● U_R: Settings for fuel combustion in cement industry were adopted. For

	China, the uncertainties in 2015 were assumed to be 10% because the settings were based on local information of Hua et al. (2016).
Lime production	● Emission factors: 15% and 60% were adopted for CO_2 and PM species, respectively. ● U_R: The same settings for fuel combustion in other industries were adopted.
Brick production	● Emission factors: ➢ CO: 60% were adopted for countries and regions where emissions were estimated using amounts of brick production. ➢ PM species: 60% were adopted. ● U_R: The same settings for fuel combustion in other industries were adopted.
Sulphuric acid production	● Emission factors: 20% were adopted for SO_2. ● U_R: The same settings for fuel combustion in other industries were adopted.
Carbon black production	● Emission factors: 60% was adopted for PM species. ● U_R: The same settings for fuel combustion in other industries were adopted.
Coke production	● Emission factors: 40% for CO, 15% for CO_2, and 60% for PM species. ● U_R: The same settings for fuel combustion in iron and steel industry were adopted.
Petroleum refineries	● Emission factors: 20% for SO_2 and 60% for PM species. ● U_R: The same settings for fuel combustion in other industries were adopted.

S10.2.3 Non-combustion sources of NMVOC

Basically, causes of uncertainties of activity data and emission factors for non-combustion sources of NMVOC are the same as for those for combustion sources, industrial production and other transformation described in Sects. S10.2.1 and S10.2.2. Due to lack of available data and information, the uncertainties for non-combustion sources of NMVOC were generally assumed to be larger than other sources as described in this sub-section. Note that emission controls of NMVOC were not considered in REASv3 and influences of their uncertainties were neglected. In addition, note that uncertainties of non-combustion sources of NMVOC emissions in Japan and Republic of Korea which depended on other inventories were not estimated.

Extraction processes

Activity data for extraction processes were taken from energy statistics. The settings of the uncertainties were assumed to be the same as for those of gas and oil fuels in power plants, iron and steel, and cement industries in Table 10.1. For emission factors, the uncertainties were assumed to be

70% except for petroleum refinery where lower uncertainty of 50% was assumed. The settings for emission factors were commonly used for all countries and regions for all target years.

Solvent use

As described in Sect. S5.1, activity data of solvent use in REASv3 were based on limited available statistics and literatures and if appropriate data were not available, activity data of REASv2 during 2000-2008 were used as default. In addition, missing data were often estimated by extrapolation of GDP. Considering the above limitations, relatively high uncertainties were assumed for activity data as follows:

- If activity data were directly based on available statistics and literatures, the uncertainties were assumed to be 20%.
- If activity data were derived by interpolated or extrapolated from the available statistics and literatures, the uncertainties of them were assumed to be 30%, 40% and 50% in 2015, 1985, and 1955, respectively.
- If activity data were based on default, the uncertainties of them were assumed to be 40% for data of 2015 and 50% for those of 1985 and 1955.
- For vehicle treatment, activity data are number of registered vehicles and their uncertainties were described in Sect. S10.2.4.
- For domestic use of solvents, activity data are number of urban and rural populations. Considering uncertainties in urban and rural population ratios, the uncertainties were assumed to be 10% higher than those of total population number described in Sect. S10.2.6.
- For paint use for automobile manufacturing, activity data were production number of vehicles. For activity data directly taken from statistics in 2015 and 1985, the uncertainties were assumed to be 10% and 20%, respectively. If activity data were derived by interpolated or extrapolated from the available statistics and literatures, the uncertainties of them were assumed to be 20%, 30% and 50% in 2015, 1985, and 1955, respectively.

For emission factors, uncertainties of 70% were commonly used for all sub-categories, countries and regions, and target years.

Chemical industry

Uncertainties of activity data for chemical industry were assumed basically same procedures for those of solvent use as follows:

- If activity data were based on available statistics and literatures, the uncertainties of them were assumed to be 15%, 25%, and 40% for the years of 2015, 1985, and 1955, respectively. Considering the availability of statistics and literatures, values of uncertainties were assumed to be lower than those of solvent use.
- If activity data were based on default, the uncertainties of them were assumed to be 40% for data of 2015 and 50% for those of 1985 and 1955.
- For carbon black production, see Table 10.4 for settings of the uncertainties.

For emission factors, uncertainties of 70% were commonly used for all sub-categories, countries and regions, and target years. For carbon black production, lower uncertainties of 50% was assumed.

Other industry

Activity data of other industry are production amounts of bread, beer, coke, asphalt, crude steel, hot rolled steel, and pulp and paper. Uncertainties of them were assumed as follows:

- For bread, beer, and asphalt, pulp and paper production, the uncertainties of activity data were assumed based on the same procedures for chemical industry.
- For coke, crude steel, and hot rolled steel production, see Table 10.4 for settings of the uncertainties.

For emission factors, uncertainties of 70% were commonly used for all sub-categories, countries and regions, and target years except for coke, crude steel and hot rolled steel production where lower uncertainties of 50% was assumed.

Waste disposal

Activity data of waste disposal sector are amounts of municipal wastes and their uncertainties were assumed based on available data sources as follows:

- If data were directly taken from national or international statistics and literatures, the uncertainties were assumed to be 30% in 2015 and 40% in 1985.
- If data were estimated by interpolation or extrapolation, the uncertainties were assumed to be 40% for 2015 and 50% for 1985 and 75% for 1955.

For emission factors, uncertainties of 80% were commonly used for all sub-categories, countries and regions, and target years.

S10.2.4 Road transport

Activity data

Activity data of emissions from road transport were number of vehicles and annual distance travelled for NO_x, CO, NMVOC, NH_3, and PM species. Uncertainties of number of vehicles which were also used for estimation of NMVOC evaporative emissions were assumed based on data sources as follows:

- For data based on detailed national statistics, the uncertainties were assumed to be 10% for passenger cars, 15% for buses and motor cycles, and 20% for trucks. If data were interpolated or extrapolated based on the detailed national statistics, uncertainties in 1985 (1955) were assumed to be 15% (30%) for passenger cars, 20% (40%) for buses and motor cycles, and 25% (40%) for trucks.
- For data based on IRF (1976-2018), the uncertainties were assumed to be 20% for passenger cars, 25% for buses and motor cycles, and 30% for trucks. If data were interpolated or extrapolated based on international statistics, uncertainties in 1985 (1955) were assumed to be 25% (40%) for passenger cars, 30% (50%) for buses and motor cycles, and 35% (50%) for trucks.
- For data based on IRF (1976-2018) and national information, the uncertainties were assumed to be 15% for passenger cars, 20% for buses and motor cycles, and 25% for trucks. If data were interpolated or extrapolated based on national or international statistics, uncertainties in 1985 (1955) were assumed to be 20% (30%) for passenger cars, 25% (40%) for buses and motor cycles, and 30% (40%) for trucks.

Similarly, uncertainties of annual distance travelled were assumed based on data sources as follows:

- For data based on national information, the uncertainties were assumed to be 15% for passenger cars and motor cycles and 20% for buses and trucks.
- For data based on national data in Clean Air Asia (2012), the uncertainties were assumed to be 20% for passenger cars and motor cycles and 30% for buses and trucks.
- For other data such as average of Asian data in Clean Air Asia (2012), the uncertainties were assumed to be 30% for passenger cars and motor cycles and 40% for buses and trucks.
- For Japan where annual mileage data were directly obtained from literatures and statistics, uncertainties of the annual mileages were assumed to be 10%/15%/25% for cars, buses, and trucks and 15%/20%/30% for motorcycles and special purpose vehicles in 2015/1985/1955.

For SO_2 and CO_2, emissions from road transport were estimated based on fuel consumption as described in Sect. S6.2.3. The uncertainties of activity data were assumed to be the same values for oil consumption in power plants, iron and steel, and cement industries in Table 10.1.

Emission factors

For emission factors of exhaust emissions from road vehicles, uncertainties were estimated as summarized in Table 10.6 based on the following assumptions:

- The lowest uncertainties were assumed for Japan where detailed local information was available for estimation of emission factors.
- Uncertainties of emission factors for China and India referring studies of national emission inventories were also smaller than those of other countries and regions.
- Uncertainties of emission factors were assumed to be smaller for NO_x and larger for PM species and those of CO and NMVOC were between them. Due to lack of information, uncertainties for NH_3 were assumed to be the largest.
- The same settings were adopted for all vehicle types except for rural vehicles and special purpose vehicles where 10% higher uncertainties were considered.

Table 10.6. Uncertainties [%] of emission factors of exhaust emissions in 2015/1985/1955 for NO_x, CO, NMVOC, NH_3, and PM species. All data were commonly adopted for all vehicle types except for rural vehicles and special purpose vehicles where 10% higher uncertainties were used.

	China and India	Japan	Others
NO_x	±25/±35/±45	±20/±30/±40	±30/±40/±50
CO	±35/±45/±55	±30/±40/±50	±40/±50/±60
NMVOC	±35/±45/±55	±30/±40/±50	±40/±50/±60
NH_3	±100/±100/±100	±75/±75/±75	±100/±100/±100
PM species	±45/±55/±65	±40/±50/±60	±50/±60/±70

For CO_2 and SO_2, the uncertainties of emission factors were assumed to be 10% which are the same settings for stationary combustion. In addition, for SO_2, uncertainties of sulfur contents in gasoline and diesel oil were also taken from settings for stationary combustion provided in Sect. S10.2.1.

For estimation of NMVOC evaporative emissions, simple methodology of EEA (2016) were adopted as described in Sect. S6.3. Therefore, high uncertainties of 100% were assumed for the emission factors.

S10.2.5 Other transport

As described in Sect. S7, other transport sector includes railway, pipeline transport and non-specified sectors defined in the IEAWEB. Settings of the uncertainties of their activity data and emission factors were the same as for those of fuel combustion in other industries.

S10.2.6 Non-combustion sources of NH_3

In REASv3, for non-combustion sources of NH_3, uncertainties of emissions from fertilizer production, human, and latrines were estimated. The uncertainties of activity data and emission factors were estimated by the same procedures for those of NMVOC. Settings and assumptions for the uncertainties are described in this sub-section. Note that emissions from manure management and fertilizer application were not originally estimated and thus, their uncertainties were not estimated.

Fertilizer production

As described in Sect. S8.3, activity data of NH_3 emissions from fertilizer production considered in REASv3 are ammonia, ammonium nitrate, and urea and the uncertainties were assumed as follows:

- Ammonia: In 2015, data were taken from Minerals Yearbook (USGS) and their uncertainties were assumed to be 15%. For the year 1985, the uncertainties were assumed to be 20% for China and Japan where national trend factors were available and those for other countries were assumed to be 30%. In 1955, the uncertainties were assumed to be 40% for all countries and regions.
- Ammonium nitrate: For Japan where national statistics were available, the same settings for ammonia were adopted. For other countries, higher uncertainties were assumed as 30%, 40%, and 50%, respectively.
- Urea: For China and Japan where national statistics were available, the same settings for ammonia were adopted. For other countries, the settings for ammonium nitrate were used.

For emission factors, uncertainties of 50% were commonly used for all sub-categories, countries and regions, and target years.

Human perspiration and respiration

Activity data of NH_3 emissions from human perspiration and respiration is number of total population and the uncertainties were assumed as follows:

- Similar to the case for IEAWEB, low uncertainties of 2% were assumed for Japan in 2015 and 1985 and Republic of Korea and Taiwan in 2015.
- For others, uncertainties were assumed to be 5% in 2015 and 1985 and 10% in 1955.

For emission factors, uncertainties of 50% were commonly used for all sub-categories, countries and regions, and target years.

Latrines

Activity data of NH_3 emissions from latrines are number of population in no sewage service areas. Available data were very limited except for Japan and the uncertainties were assumed as follows:

- Uncertainties for Japan were assumed to be 10% in 2015 and 1985 and 30% in 1955.
- For other countries and regions, uncertainties were assumed to be 30%, 40%, and 50% in 2015, 1985, and 1955, respectively.

For emission factors, uncertainties of 70% were commonly used for all sub-categories, countries and regions, and target years.

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