Methodologies to estimate emissions from stationary sources

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Two types of Emission Inventory

Emission inventory is data set of emission amounts of air pollutants from their sources in target region and period.

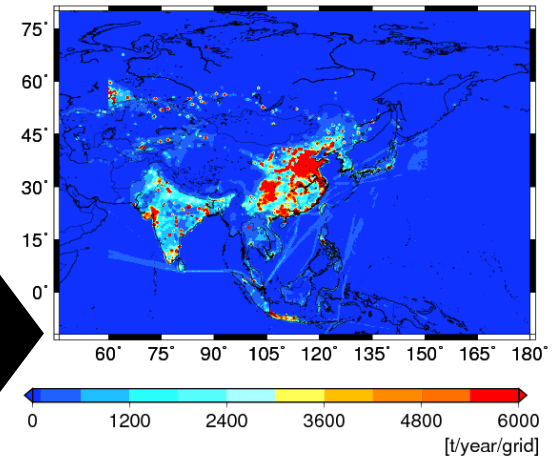
1. List of emissions from detailed sources in some administrative regions

SO2 [t/year]	2007	2008	2009	2010
1A1a_Electricity	1.1180E+05	1.0516E+05	8.7023E+04	1.1995E+05
1A1bc_Other-transformation	8.0001E+04	7.6085E+04	6.8720E+04	8.5502E+04
1A2a_Ind-Comb-Iron-steel	6.3541E+04	5.7620E+04	5.0148E+04	1.0782E+05
1A2b_Ind-Comb-Non-ferrous-metals	3.2111E+03	3.3404E+03	2.9191E+03	4.4002E+03
1A2c_Ind-Comb-Chemicals	5.3460E+04	5.1864E+04	4.5583E+04	5.7643E+04
1A2d_Ind-Comb-Pulp-paper	3.3764E+04	3.1585E+04	2.6185E+04	2.6466E+04
1A2e_Ind-Comb-Food-tobacco	6.4320E+03	8.7938E+03	7.3161E+03	6.4855E+03
1A2f_Ind-Comb-Non-metalic-minerals	4.9241E+04	5.0354E+04	4.3323E+04	4.8654E+04
1A2g_Ind-Comb-Construction	4.7216E+02	4.1463E+02	2.8737E+02	3.5191E+02
1A2g_Ind-Comb-transpequip	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00
1A2g_Ind-Comb-machinery	2.0796E+03	8.7746E+02	7.4672E+02	1.7001E+03
1A2g_Ind-Comb-mining-quarying	2.5574E+02	2.4088E+02	1.9968E+02	2.7619E+02
1A2g_Ind-Comb-wood-products	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00
1A2g_Ind-Comb-textile-leather	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00
1A2g_Ind-Comb-other	4.2602E+04	4.2768E+04	4.2616E+04	1.1919E+05
1A3ai_International-aviation	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00
1A3aii_Domestic-aviation	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00
1A3b_Road	1.2519E+03	1.2131E+03	1.1879E+03	1.0855E+03
1A3c_Rail	1.9067E+01	1.9361E+01	1.8968E+01	1.8379E+01
1A3di_International-shipping	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00
1A3dii_Domestic-naviation (shipping)	9.6735E+04	8.7238E+04	9.4692E+04	9.9941E+04
1A3eii_Other-transp	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00
1A4a_Commercial-institutional	8.9607E+03	8.3232E+03	8.0518E+03	7.6123E+03
1A4b_Residential	5.6456E+02	5.2867E+02	5.1321E+02	5.5695E+02
1A4c_Agriculture-forestry-fishing	1.2255E+04	1.0837E+04	1.0055E+04	9.8447E+03
1A5_Other-unspecified	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00

- Major sources contributing to air pollution can be identified.
- Effects of control measures can be examined and priority of them can be considered.

2. Gridded data of emissions from major aggregated categories in some area

LON	LAT	JAN	FEB	MAR	APR	MAY	JUN
156.50	76.75	1.22E-03	1.14E-03	1.23E-03	1.17E-03	1.23E-03	1.18E-03
156.75	76.75	2.07E-05	1.94E-05	2.08E-05	1.99E-05	2.08E-05	2.00E-05
138.00	76.00	1.61E-03	1.51E-03	1.62E-03	1.55E-03	1.62E-03	1.56E-03
138.25	76.00	6.27E-03	5.86E-03	6.30E-03	6.02E-03	6.30E-03	6.05E-03
138.50	76.00	9.81E-03	9.18E-03	9.86E-03	9.43E-03	9.86E-03	9.47E-03
138.75	76.00	1.13E-02	1.06E-02	1.13E-02	1.08E-02	1.13E-02	1.09E-02
139.00	76.00	7.68E-03	7.19E-03	7.72E-03	7.38E-03	7.72E-03	7.42E-03
139.25	76.00	3.42E-03	3.20E-03	3.44E-03	3.29E-03	3.44E-03	3.30E-03
139.50	76.00	4.45E-04	4.17E-04	4.48E-04	4.28E-04	4.48E-04	4.30E-04
141.00	76.00	3.53E-03	3.30E-03	3.55E-03	3.39E-03	3.55E-03	3.40E-03
141.25	76.00	3.35E-03	3.13E-03	3.37E-03	3.22E-03	3.37E-03	3.23E-03
141.50	76.00	5.99E-03	5.61E-03	6.03E-03	5.76E-03	6.03E-03	5.79E-03
141.75	76.00	5.19E-03	4.86E-03	5.22E-03	4.99E-03	5.22E-03	5.01E-03
142.00	76.00	7.81E-04	7.31E-04	7.86E-04	7.51E-04	7.86E-04	7.54E-04
135.50	75.75	1.05E-03	9.86E-04	1.06E-03	1.01E-03	1.06E-03	1.02E-03
135.75	75.75	1.36E-03	1.28E-03	1.37E-03	1.31E-03	1.37E-03	1.32E
137.00	75.75	3.52E-05	3.29E-05	3.53E-05	3.38E-05	3.54E-05	3.39E
137.25	75.75	1.63E-03	1.52E-03	1.64E-03	1.56E-03	1.64E-03	1.57E
137.50	75.75	1.17E-02	1.10E-02	1.18E-02	1.13E-02	1.18E-02	1.13E-02
137.75	75.75	1.47E-02	1.38E-02	1.48E-02	1.42E-02	1.48E-02	1.42E-02
138.00	75.75	1.49E-02	1.39E-02	1.50E-02	1.43E-02	1.50E-02	1.44E-02
138.25	75.75	1.49E-02	1.39E-02	1.50E-02	1.43E-02	1.50E-02	1.44E-02



- Understanding emission amounts and their trends from detailed source categories as <u>fundamental information</u> to consider air quality issues
- Considering effective and feasible measures to reduce emissions

- Spatial distribution and trends of air pollutants emissions in whole target area can be evaluated.
- <u>Input of Air Quality Model</u>
  - Contribution from different emission categories, effects of control measures, and source-receptor relationship can be examined.

Basic ideas to develop Emission Inventory

Activity data

Quantitative values causing or related to emissions of air pollutants by mainly anthropogenic activities

- Coal consumption
- Diesel oil consumption
- Cement production
- …

Emission factors

Emission amounts per unit of Activity Data

- SO_2 emissions per 1t combustion of coal
- NO_x emissions per 1t combustion of diesel oil
- BC emissions per 1t production of cement
- …

Removal efficiencies

Ratio of emission amounts removed before emitted to air by technologies, etc.

- FGD for SO_2
- Selective Catalytic Reduction for NO_x
- Electrostatic precipitator for BC
- …

Emissions of air pollutants from each source category in each country, region, city, etc.

Gridded emission data for air pollutants

- Emissions based on points of large plants, population, road network, etc.
- Input data sets for air quality and climate models.

Ex.1 Emissions from a coal-fired power plant without control measures

$$EM_y = A_y \times EF_y \times (1-R_y)$$

Emissions | Activity rates | Emission factors | Removal ratios

y Target years

- Coal consumption: 2.0kt, Net Calorific Value: 28.0 MJ/kg
- Emission factors: $PM_{2.5}$: 2.0 g/kg, NO_x: 300 kg/TJ
- No control measures: R=0

$$PM_{2.5}\ \text{emission [t]} = \underbrace{2.0 \times 10^6}_{\text{A kt}\rightarrow\text{kg}} \times \underbrace{2.0}_{\text{EF g/kg}} \times (1-\underbrace{0}_{\text{R}}) \times \underbrace{10^{-6}}_{\text{g}\rightarrow\text{t}} = 4.0$$

$$NO_x\ \text{emission [t]} = \underbrace{2.0 \times 10^6}_{\text{A kt}\rightarrow\text{kg}} \times \underbrace{28.0}_{\text{kg}\rightarrow\text{MJ}} \times \underbrace{10^{-6}}_{\text{MJ}\rightarrow\text{TJ}} \times \underbrace{300}_{\text{EF kg/TJ}} \times (1-\underbrace{0}_{\text{R}}) \times \underbrace{10^{-3}}_{\text{kg}\rightarrow\text{t}} = 16.8$$

S -> SO_2

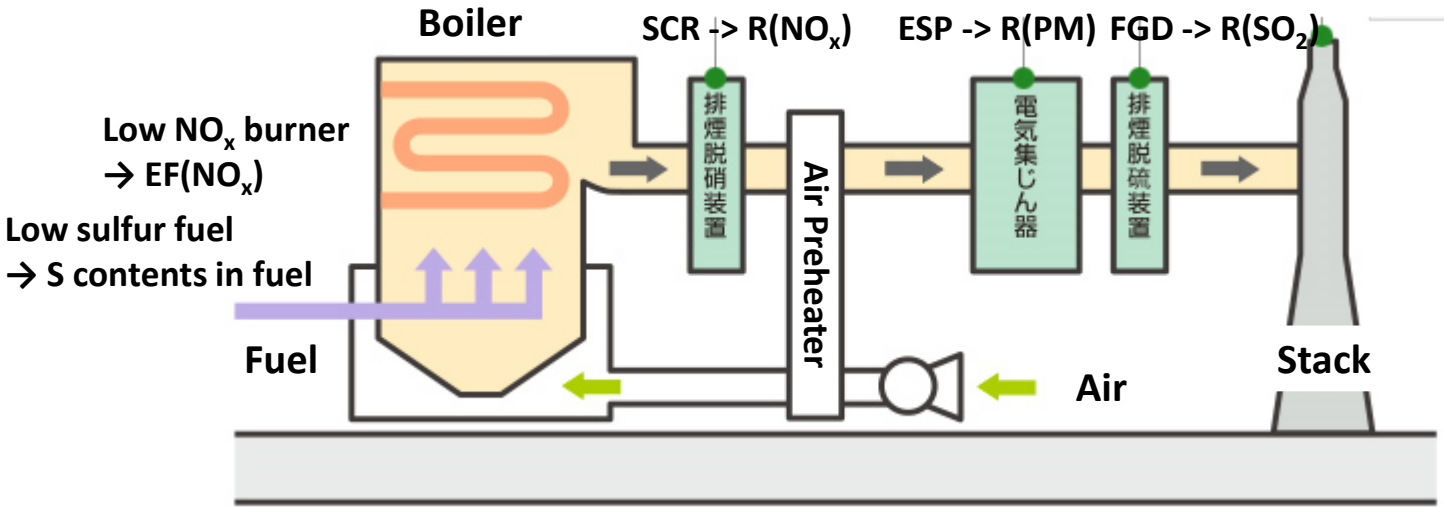
$$SO_2EM_y = A_y \times S_y \times (1-SR_y) \times (1-R_y) \times 2$$

SO_2 emissions from fuel combustion | Fuel consumptions | Sulfur content in fuels | Sulfur retention in ash | Removal ratios

- Sulfur contents in fuels: 1.5%wt
- Sulfur retention in ash: 10%
- No control measures: R=0

$$SO_2\ \text{emissions[t]} = \underbrace{2.0 \times 10^3}_{\text{A kt}\rightarrow\text{t}} \times \underbrace{0.015}_{\text{S in A}} \times (1-\underbrace{0.1}_{\text{S in Ash}}) \times (1-\underbrace{0}_{\text{R}}) \times 2 = 54.0$$

Ex.2 Emissions from a coal-fired power plant with control measures



- Coal consumption: 2.0kt
- Net calorific values: 28.0 MJ/kg
- Emission factors (without control measures)
  - $PM_{2.5}$: 2.0 g/kg
  - NO_x: 300 kg/TJ
- Sulfur retention in ash: 10%

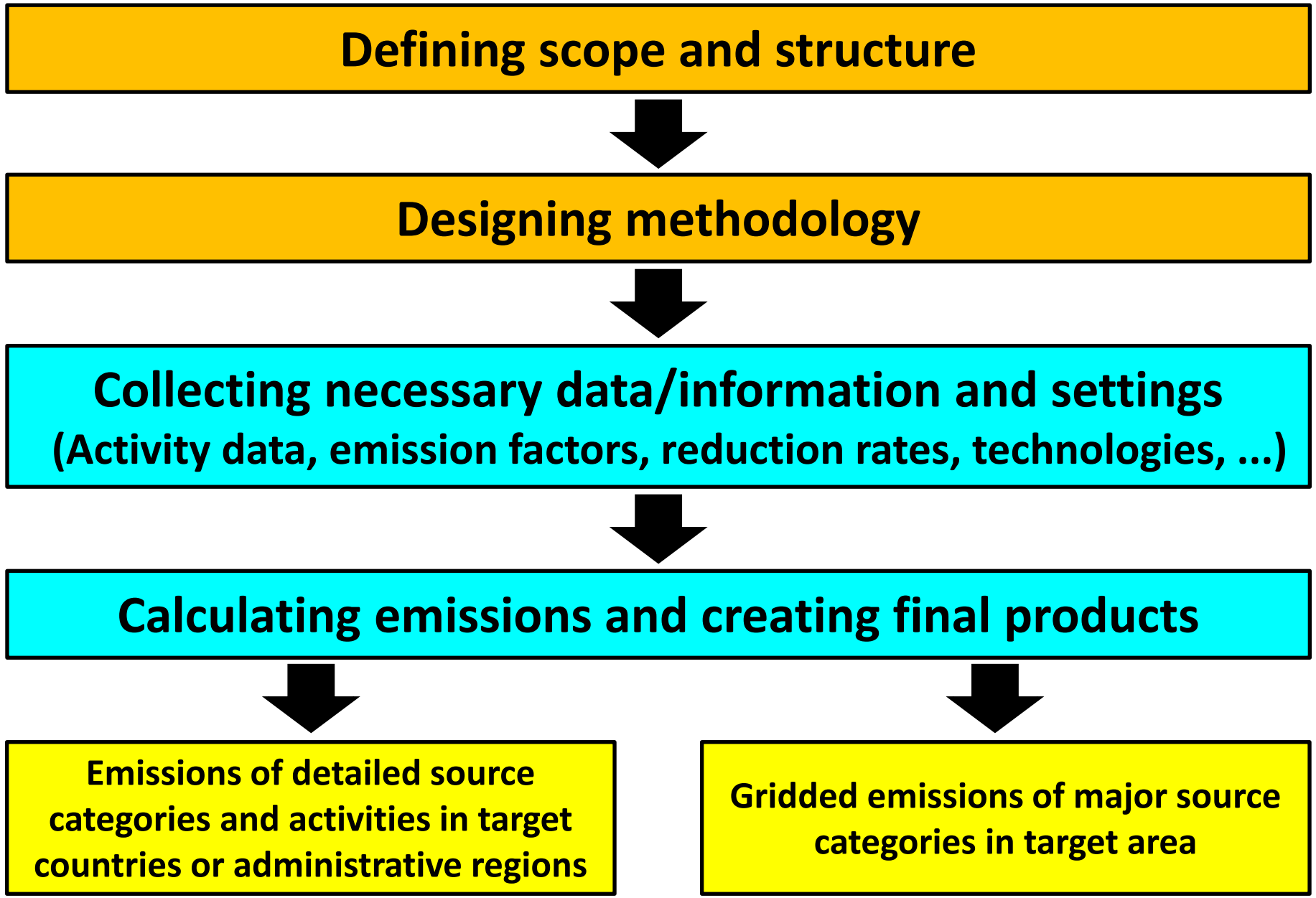
- Introduction of control measures (example)
  - Electrostatic Precipitators (ESP): $PM_{2.5}$ reduction 99%
  - Low NOx burner: 40 % reduction of NO_x emission factor
  - Selective Catalytic Reduction (SCR): NO_x reduction 80%
  - Low sulfur fuel: 80% reduction of sulfur content in fuel
  - Flue Gas Desulfurization (FGD)/Wet Scrubber: SO_2 reduction 90%

$PM_{2.5}$ emission [t] = $2.0 \times 10^6 \times 2.0 \times (1-\underbrace{0.99}_{\text{ESP}}) \times 10^{-6} = 0.04$ (← 4.0)

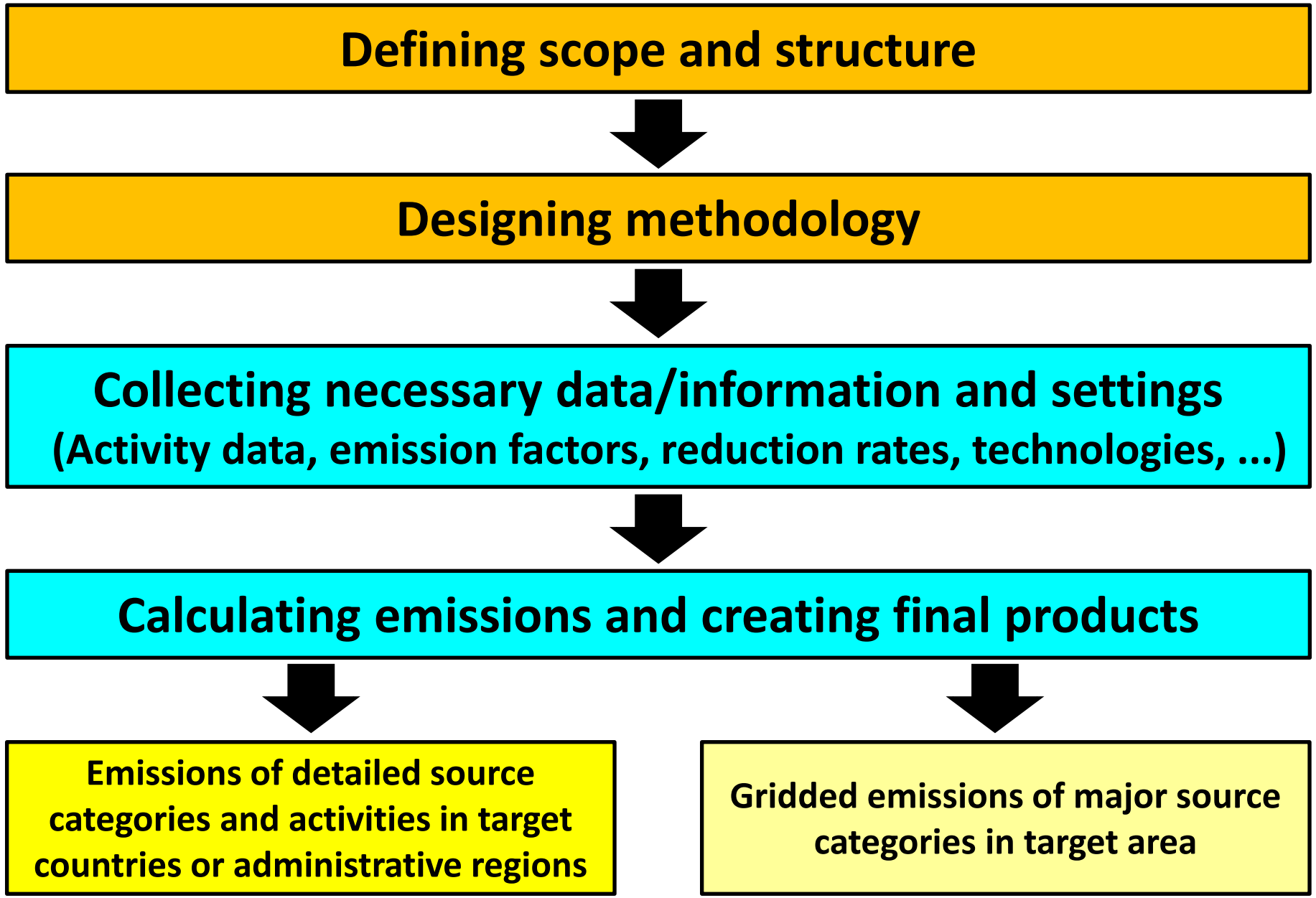
NO_x emission [t] = $2.0 \times 10^6 \times 28.0 \times 10^{-6} \times 300 \times \underbrace{0.6}_{\text{Low NOx burner}} \times (1-\underbrace{0.8}_{\text{SCR}}) \times 10^{-3} = 2.02$ (← 16.8)

SO_2 emission [t] = $2.0 \times 10^3 \times 0.015 \times \underbrace{0.2}_{\text{Low sulfur fuel}} \times (1-0.1) \times (1-\underbrace{0.9}_{\text{FGD}}) \times 2 = 1.08$ (← 54.0)

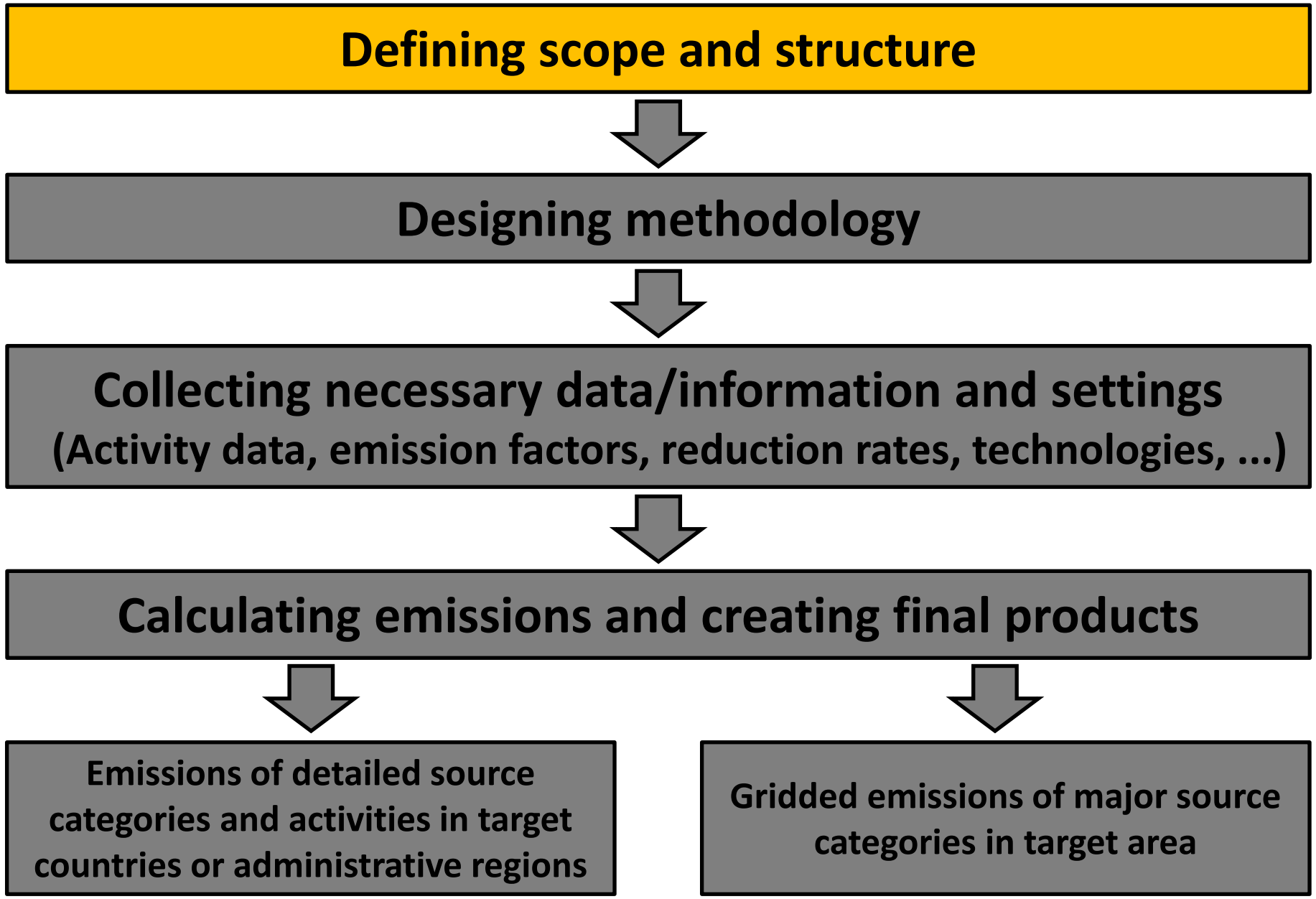
Process flow of developing Emission Inventory



Process flow of developing Emission Inventory



Process flow of developing Emission Inventory



Scope and structure of Emission Inventory

Item	Description for targets (Ex.)
Species	$PM_{2.5}$, BC, OC (for primary $PM_{2.5}$) SO_2, NO_x, CO, NMVOC, NH_3 (for secondary $PM_{2.5}$)
Years	2015, 2010-2015, 1990-2015, 1850-2015, ...
Areas	Global, Asia, Japan, Niigata
Sources	Fuel Combustion: Power plants, Industry, Road transport, Other Transport, Residential, Commercial and Public services, … Non-Fuel Combustion: Fugitive emission, Industrial process, Solvent use, Agriculture, Vegetation fires and forestry, Waste, ... Natural: Volcano, Vegetation, Soil, Natural Dust, ...
Horizontal resolution	Country, Administrative regions Points, 0.5°x0.5°, 0.25°x0.25°, 0.1°x0.1°, ...
Temporal resolution	Annual, Monthly Weekly, Diurnal

Sector categories for combustion sources

Transformation

- Power generation
- CHP: Cogeneration/Combined Heat and Power generation)
- Coke oven coke
- Charcoal production plant
- Petroleum refineries
- Petrochemical industry
- Gas works
- Others

Industry

- Iron and steel
- Chemical and petrochemical
- Non-ferrous metals
- Cement
- Machinery
- Paper and pulp
- Transport equipment
- Construction
- Others

Transport

- Road
- Aviation
- Navigation
- Railway
- Others

Others

- Commercial and public services
- Residential
- Agriculture and forest
- Fishing
- Others

Define sector categories especially considering major emission sources of target area.

Fuel types

Coal Fuels

- Bituminous coal
- Anthracite
- Coking coal
- Lignite
- Sub-bituminous coal
- Coke oven coke
- Lignite coke
- Brown coal briquettes/BKB, Patent fuel
- Others

Oil Fuels

- Crude oil
- Natural gas liquid (NGL)
- Motor gasoline
- Jet kerosene
- Kerosene
- Gas/diesel oil
- Residual fuel oil
- LPG (Liquefied petroleum gas)
- Others

Gas Fuels

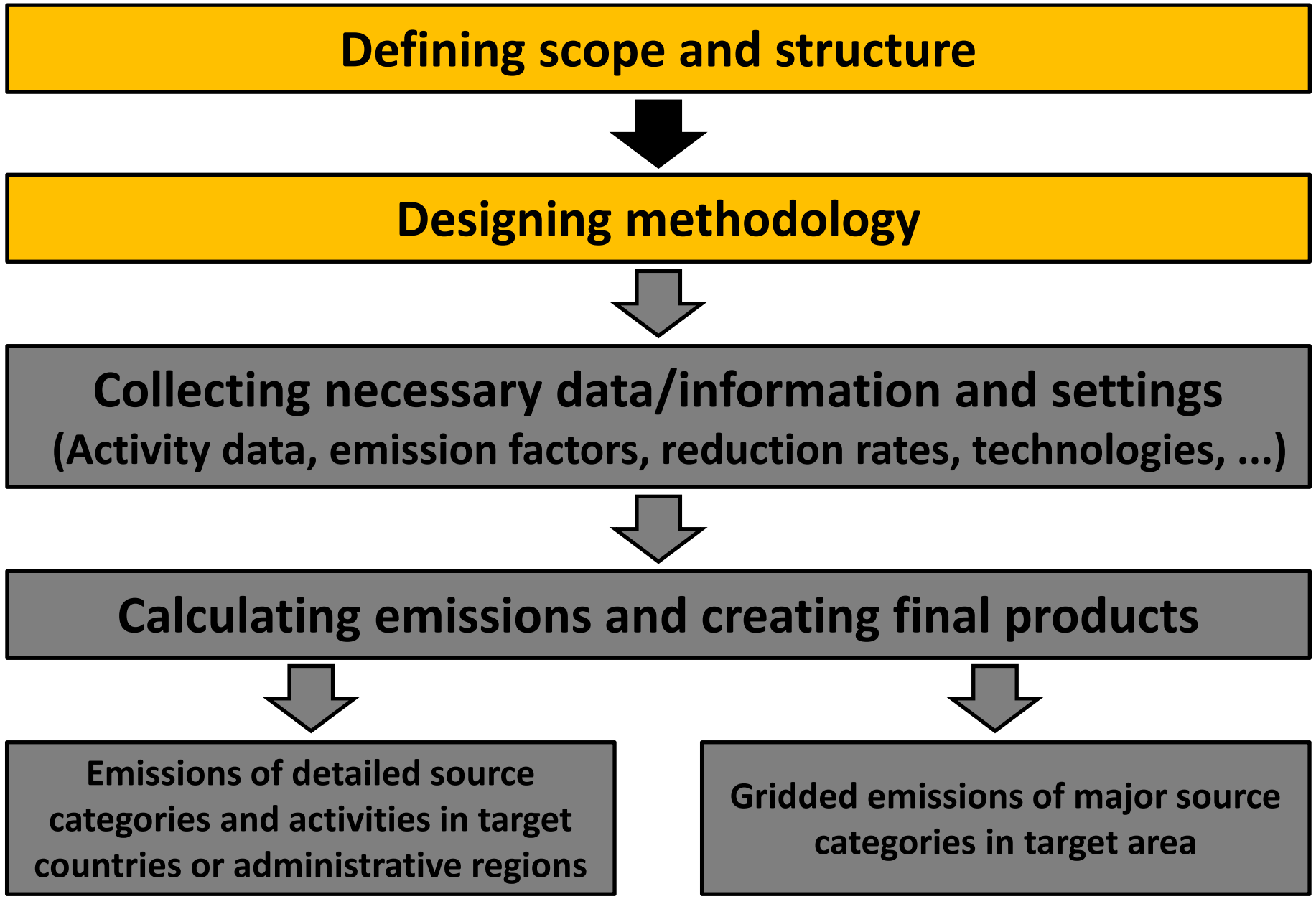
- Natural gas
- Gas works gas
- Coal-derived gases
  - Coke oven gas
  - Blast furnace gas
- Others

Other Fuels

- Fuel wood
- Crop residue (Agricultural waste)
- Animal waste (Ex. Dung cake)
- Char coal
- Municipal waste
- Others

Define fuel types considering decided sector categories and area and available data.

Process flow of developing Emission Inventory



Designing methodology

$$EM_{i,j,y} = A_{i,j,y} \times EF_{i,j,y} \times (1-R_{i,j,y})$$

i Fuel types
j Sectors
y Target years

Activity Rates

Fuel consumption of each fuel type in different sector categories.

Types of fuels:
Bituminous coal, Coking coal, Natural gas, Coke oven gas, Diesel oil, Residual fuel oil, Kerosene, fuelwood, …

Sector categories:
Power Plants, Coke ovens, Iron and steel, Cement, Residential, Commercial and Public, …

Emission Factors

Amounts of emissions per unit of fuel consumption in combustion equipment

Types of equipment:
Pulverized coal-fired boiler
Stoker boiler
Gas-fired turbine
Precalciner kiln, …
Heating stove

Control technique:
Low NO_x burner
Flue gas recirculation

Removal Ratios

Ratios of reduced emissions after burning by control equipment

Types of control equipment:
Multiple cyclones
Wet Scrubbers
Electrostatic precipitator
Using low sulfur fuels
Lime/Limestone wet scrubbers
Spray dryer absorption
Selective catalytic reduction
DESONOX, …

- There are many types of combustion technologies and control measures.
- It is important to specify what combinations of fuels and sectors should be focused for further surveys.

Designing methodology

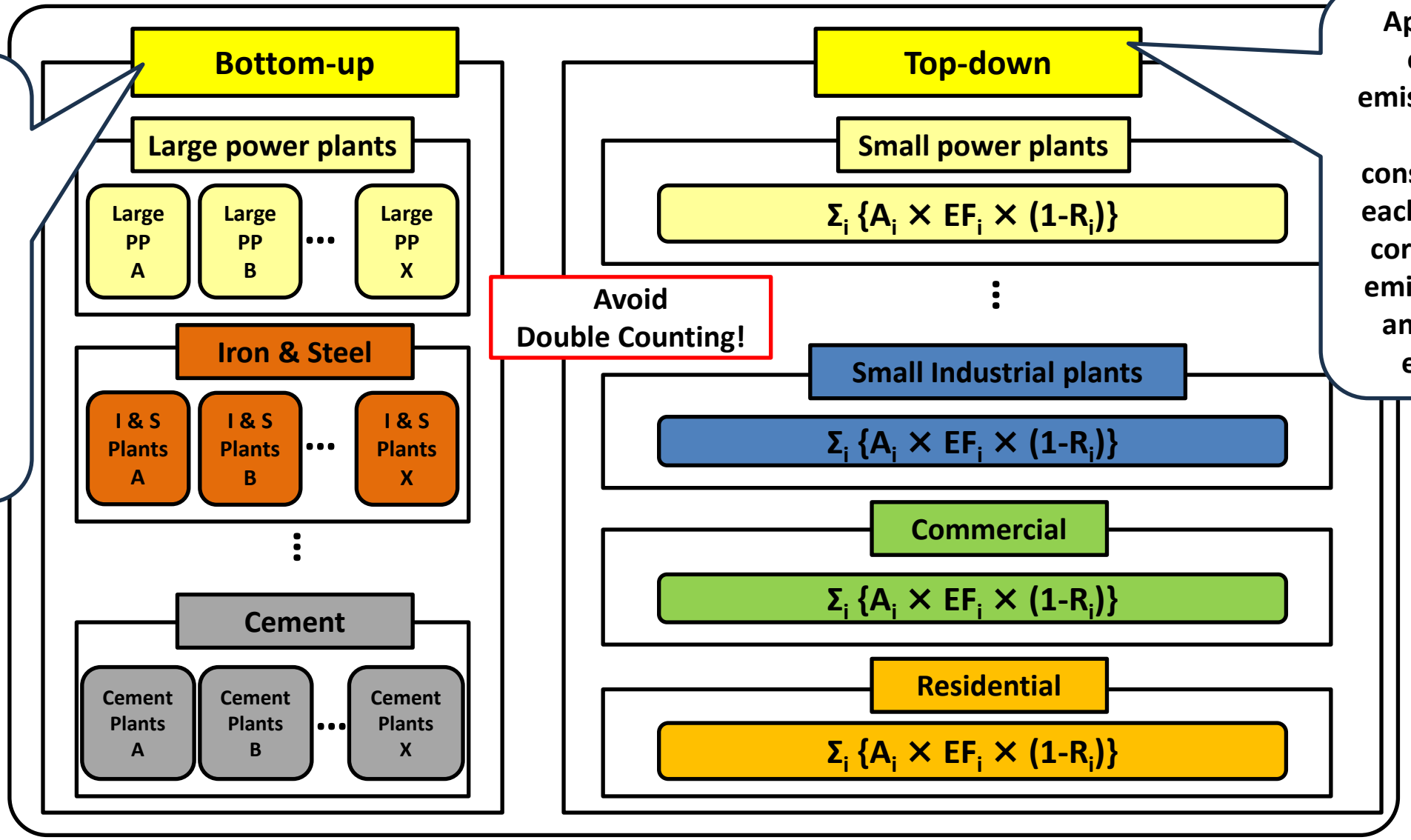
$$EM_{i,j,y} = A_{i,j,y} \times EF_{i,j,y} \times (1-R_{i,j,y})$$

i Fuel types
j Sectors
y Target years

Activity Rates	Emission Factors	Removal Ratios
Default Approach		
Fuel consumption in each sector from national or international statistics	Averaged EF for each sector assumed from available manuals.	Averaged R for each sector assumed from available manuals.
Technology Specific Approach		
● Fuel consumption in each plant/unit ● Fuels consumption in each technology in each sector	● EF for equipment in each plant/unit ● EF for each technology and ratios of introduced control	● R for equipment in each plant/unit ● R for each technology and penetration rates in each sector

Default Approach : No detailed information or rough estimation is enough
Technology Specific Approach : Detailed information is available or should be surveyed
-> Effects of control measures can be evaluated and examined.

Designing methodology



Approach to estimate emissions from each point source and emissions of sectors are sum of emissions of each plant

Avoid Double Counting!

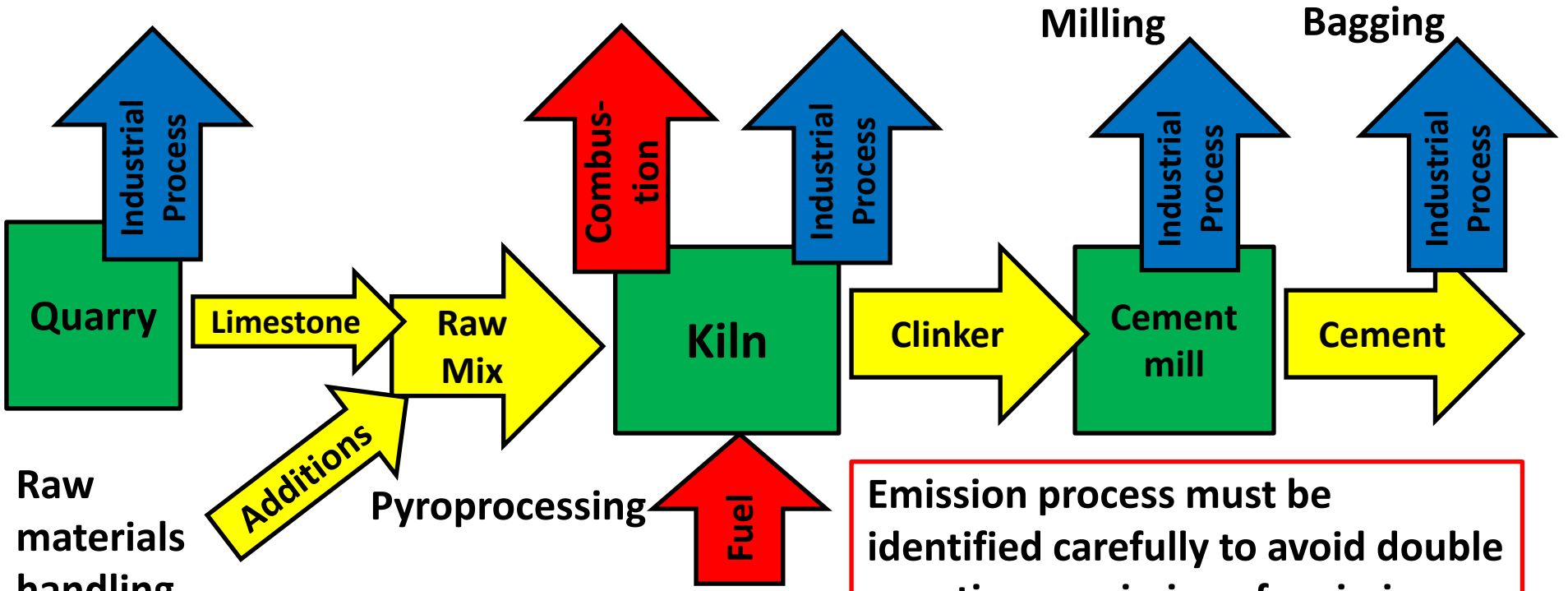
Approach to estimate emissions based on fuel consumption of each sector and corresponding emission factor and removal efficiency

Other "Top-down" Lecture 5 Other issues

Note that there are other definitions of "Bottom-up" and "Top-down" emission inventories.
Bottom-up: Emissions estimated based on activity data and emission factors ("Bottom-up" + "Top-down" above)
Top-down: Emissions estimated using observation data (often satellite data) and numerical algorithm

Stationary combustion & non-combustion sources

Ex. Industrial Process (Cement Production)



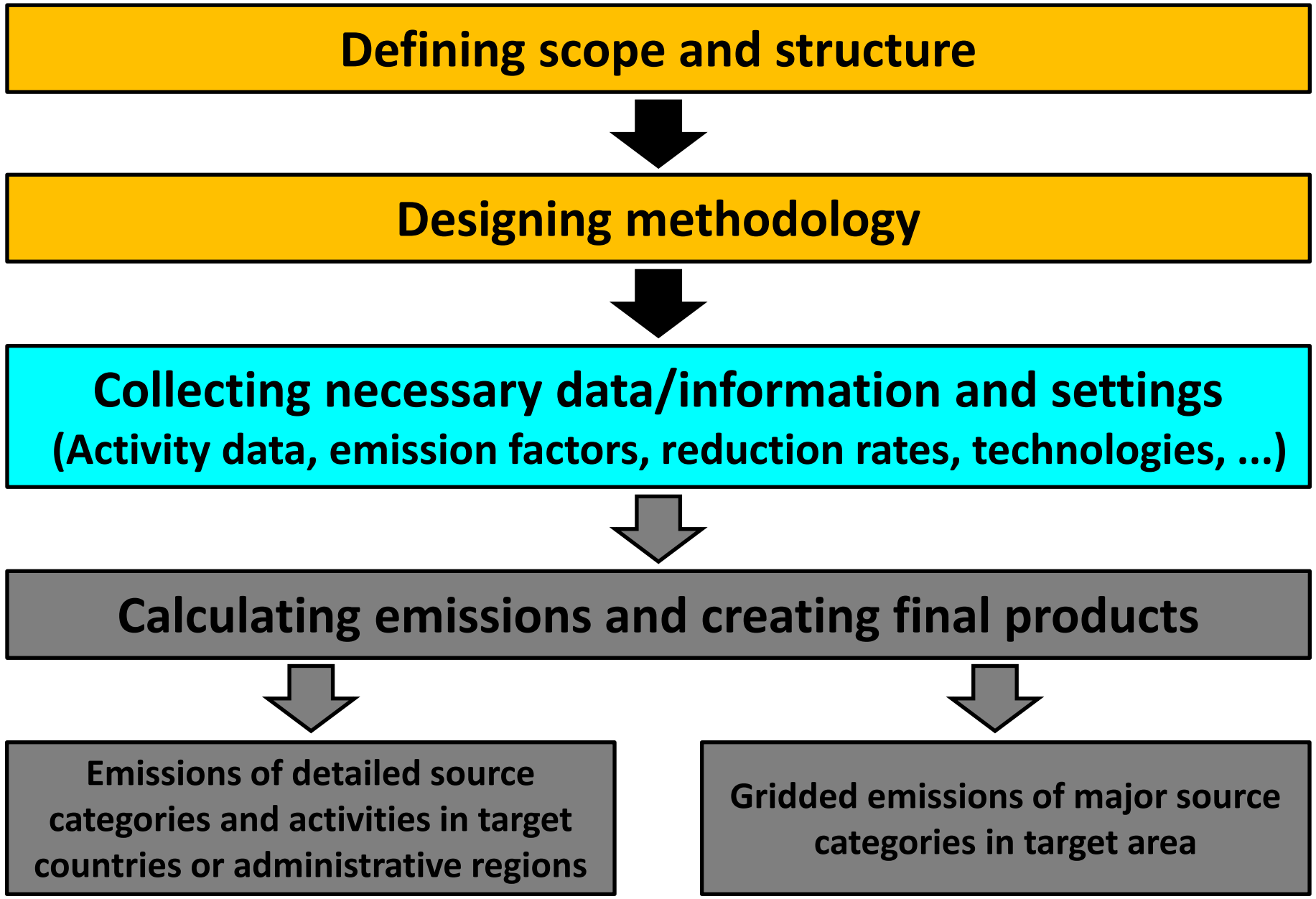
Emission process must be identified carefully to avoid double counting or missing of emissions.

$$EM_{j,y} = \Sigma_i\{A_{i,j,y} \times EF_{i,j,y} \times (1-R_{i,j,y})\}$$

i Processes
j Sectors
y Target years

- Mineral Products (Cement, Lime, Brick, Asphalt, ...)
- Chemical Industry (Ammonia, Nitric acid, Urea, Sulfuric acid, ...)
- Metals Production (Pig iron production, Copper/Lead/Zinc smelting, ...)
- Fugitive emissions of PM from major construction activities, ...

Process flow of developing Emission Inventory

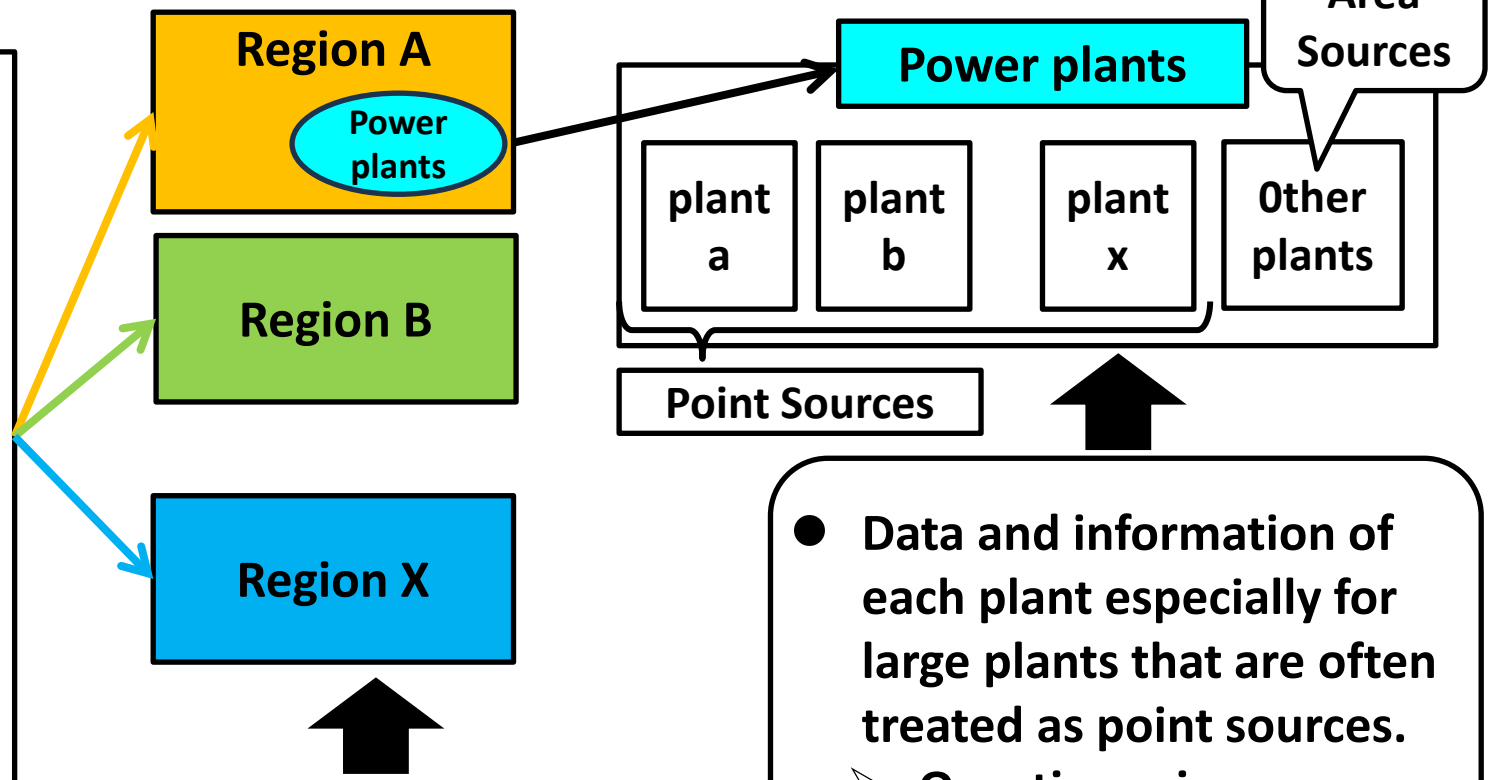


Collecting and distributing activity data

National data

- Fuel consumption in each defined fuel type and sector category
- Unit in weight (ex. kt) or energy (ex. PJ)
- Data in national total should be distributed to each region and plant in the same format if necessary data and information is available.
- Parameters related to activity data should be surveyed:
  - Sulfur contents in fuel
  - Net calorific value

- National Energy Statistics
- International energy statistics (ex. IEA Energy Balances, UNdata, etc.)
- Related literatures (local reports, scientific papers, etc.)



- Regional Energy Statistics
- Proxy data to distribute national fuel consumption to each region such as production amounts, generated power in each region.

- Data and information of each plant especially for large plants that are often treated as point sources.
  - Questionnaire survey
  - Estimation based on related data (generation power, production amounts, capacity, etc.
- Other plans (total minus sum of each plant) are treated as area sources.

Collecting and setting emission factors (EFs)

$$EM_{i,j,y} = A_{i,j,y} \times EF_{i,j,y} \times (1-R_{i,j,y})$$

i Fuel types
j Sectors
y Target years

Collecting data

- **Emission factors in each defined fuel type and sector category**
- Default EFs for $A_{i,j}$ if technology information is not available.
- EFs for technologies:
  - Boiler types for power and industrial plans
  - Kiln types for non-metallic minerals production
  - Combustion technologies to reduce emissions (ex. Low NO_x burner)
  - Stove types for residential sector
  - …

- Information of technologies including regulations for (i,j) in target countries
  - Literature survey
  - Questionnaire for target sectors

- Database for EFs
  - Emission inventory manuals (ex. AP-42, EMEP/EEA, IPCC, ABC Manual)
  - Scientific papers and local literatures

Setting EFs

- Selection of default EFs suitable for target countries
- It is preferable to set EFs based on technology information for target countries:
  - EFs for technologies installed in each plant
  - Averaged EFs for $A_{i,j}$ considering ratios of technologies used in (i,j) or distribution of $A_{i,j}$ to each technology
- It must be noted that ratios of technologies vary by target years.

Collecting and setting removal efficiencies (R)

$$EM_{i,j,y} = A_{i,j,y} \times EF_{i,j,y} \times (1-R_{i,j,y})$$

i Fuel types
j Sectors
y Target years

Collecting data

- **Removal efficiencies in each defined fuel type and sector category (including zero).**
- R for technologies:
  - SO_2: Limestone Forced Oxidation Scrubber, Lime Spray Dryer Scrubber, Dry Sorbent Injection, DESONOX, etc.
  - NO_x: Selective Non-Catalytic Reduction, Selective Catalytic Reduction, DESONOX Process, etc.
  - PM: Electrostatic Precipitators, Pulse-Jet Fabric Filter, Multiple Cyclones, Baghouse, etc.
  - …

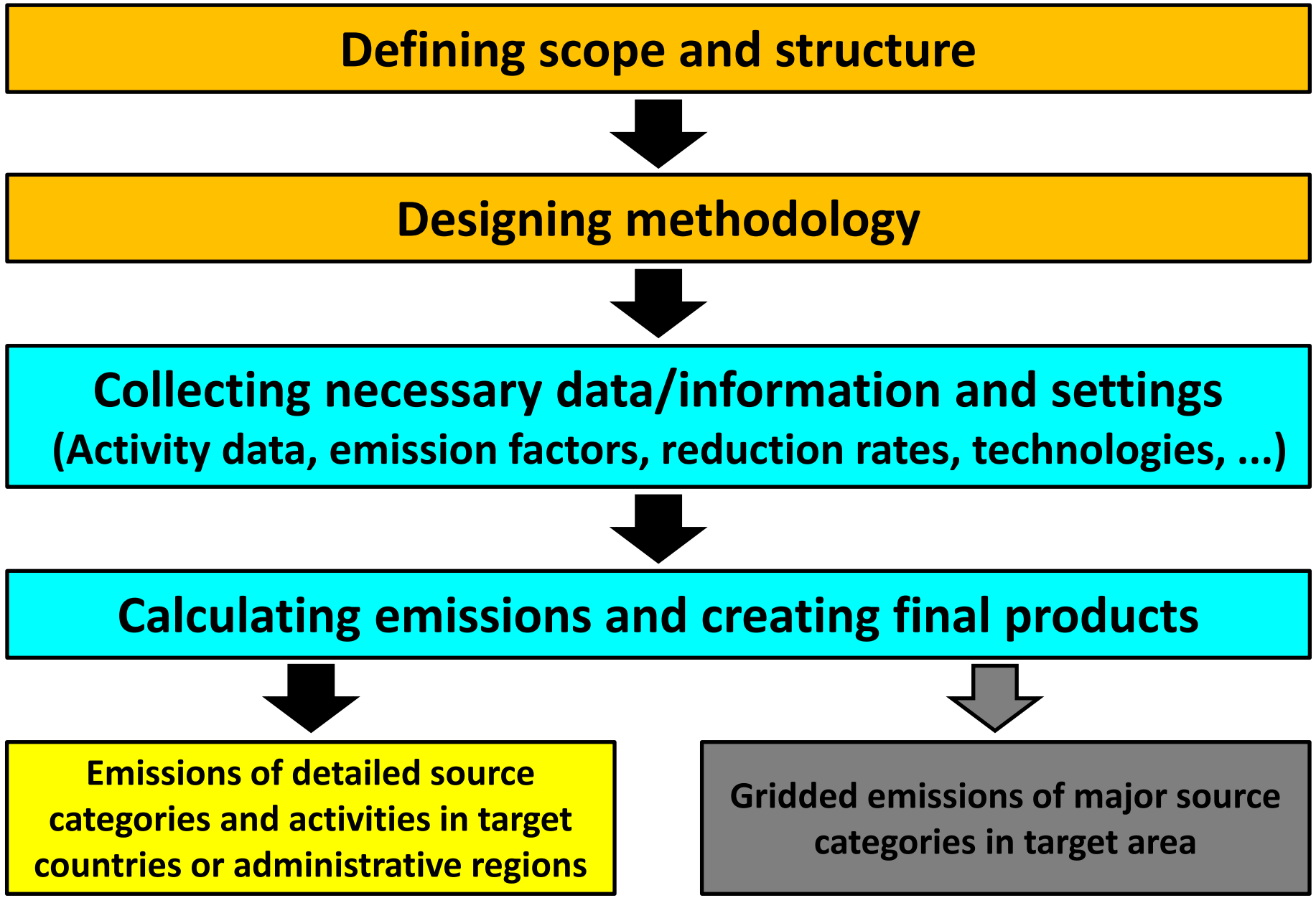
- Information of technologies including regulations for (i,j) in target countries
  - Literature survey
  - Questionnaire for target sectors

- Database for R
  - Emission inventory manuals (ex. AP-42, EMEP/EEA, IPCC, ABC Manual)
  - Scientific papers and local literatures

Setting R

- It is necessary to set R based on technology information for target countries:
  - R for technologies installed in each plant
  - Averaged R for $A_{i,j}$ considering ratios of technologies used in (i,j) or distribution of $A_{i,j}$ to each technology
  - It is preferable to consider combination of technologies for EFs and R. -> nonlinearity
- It must be noted that ratios of technologies vary by target years the same as for EFs.

Process flow of developing Emission Inventory



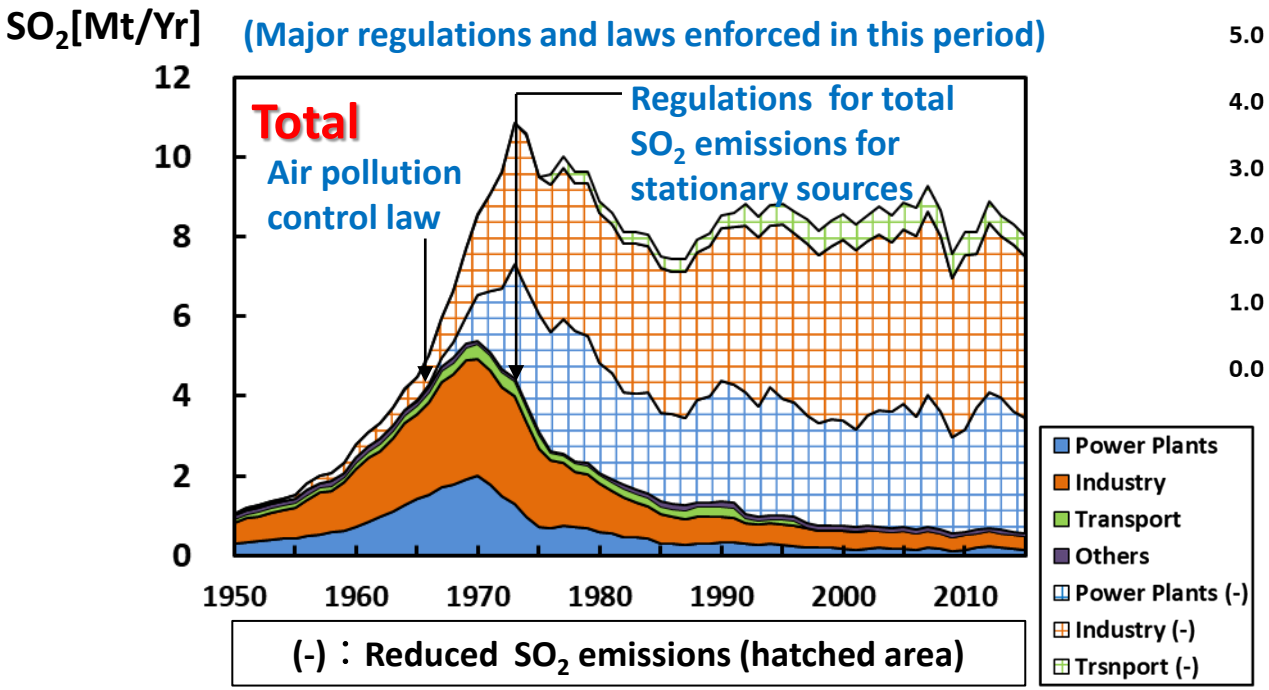
Calculating emissions and creating final products

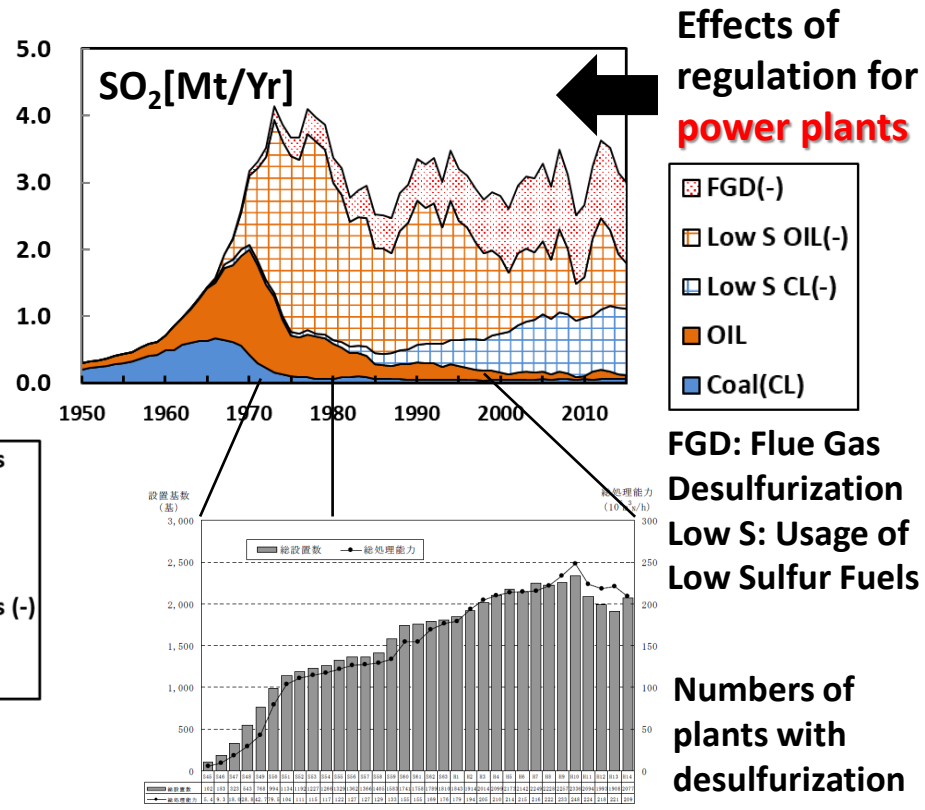
Actual works necessary to create Emission Inventory

- Prepare or develop systems to calculate emissions and create final products, namely Emission Inventory.
  - Use publicly available systems (Ex. The ABCs Emission Inventory Manual Excel Workbook. http://www.rrcap.ait.ac.th/abc/Pages/Emission-Inventory.aspx)
  - Develop original systems using programing languages (Ex. Fortran, Python, C, etc.) and/or Excel-based systems including utilizing publicly available systems
- Create input data (activity data, emission factors, removal efficiencies, ratios of technologies, other necessary data, parameters and information) in the required format of the systems.
- Conduct calculations and create Emission Inventory using the systems

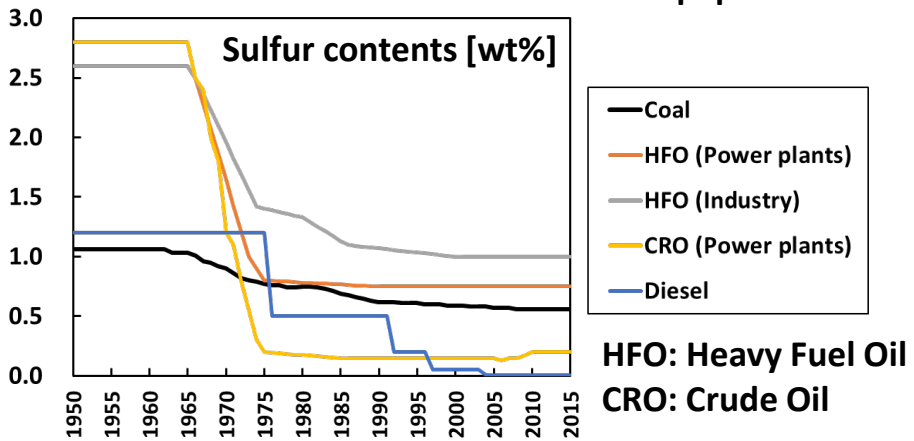
Utilize the data and information of Emission Inventory

A case study: Evaluation of emission controls for SO_2 in Japan





- SO_2 emissions in Japan grew rapidly from early 1960s but decreased keenly soon.
- This drastic change was mainly caused by rapid increase of heavy fuel oil usage in power plants and its substitution to low sulfur fuels.
- Number of plants with Flue Gas Desulfurization (FGD) started to increase from late 1970s.
- Even coal consumption in power plants increased after 1990s, SO_2 emissions were controlled in lower levels.



References for methodologies to develop Emission Inventory

Manuals

- EMEP/EEA air pollutant emission inventory guidebook 2023 (https://www.eea.europa.eu/publications/emep-eea-guidebook-2023)
- AP-42: Compilation of Air Pollutant Emissions Factors (https://www.epa.gov/air-emissions-factors-and-quantification/ap-42-compilation-air-emissions-factors)
- Atmospheric Brown Clouds (ABC) Emission Inventory Manual (http://wedocs.unep.org/handle/20.500.11822/21482)
- 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (https://www.ipcc-nggip.iges.or.jp/public/2019rf/index.html)

Scientific papers

- Scientific papers of emission inventories in Asian countries are useful not only for understanding the status of air pollutants emissions but also for learning methodology to estimate emissions and how to analyze the results.
  - Atmospheric Chemistry and Physics (https://www.atmospheric-chemistry-and-physics.net/)
  - Earth System Science Data (https://www.earth-system-science-data.net/)
  - Atmospheric Environment (https://www.journals.elsevier.com/atmospheric-environment)
  - Environmental Science & Technology (https://pubs.acs.org/journal/esthag)
  - … … ⇒ Google Scholar

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