Forecasting Sustainable Urbanization Tool

User Manual

(v 1.00)

Developed by Institute of Urban Environment-Chinese Academy of Sciences (IUE) and the United Nations Economic and Social Commission (ESCAP)

Acknowledgements

The Forecasting Sustinable Urbanization Tool has been developed by the United Nations Economic and Social Commission for Asia and the Pacific (UN-ESCAP) and the Institute of Urban Environment, Chinese Academy of Sciences (IUE, CAS). The Commonwealth Scientific and Industrial Research Organization (CSIRO) provided technical support and expertise to the development and testing of the tool.

License Agreement of Urban Metabolism Model

This tool requires VENSIM software, which is available through https://vensim.com/download/

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1. Background

The ESCAP project, "Forecasting Sustainable Urbanization: Support for sustainable infrastructure planning in cities," supported by the China ESCAP Cooperation Programme was developed to promote the implementation of resource-efficient and environmentally friendly planning policies in support of sustainable cities.

To achieve a sustainable future in the region, cities will require a decoupling of economic growth from resource consumption and a drastic reduction in resource intensities associated with urbanisation. The project assisted partner cities in Kyrgyzstan (Bishkek) and Tajikistan (Dushanbe) and Xiamen city in China to better plan sustainable infrastructure and manage urban growth based on a better understanding of the resource implications of urban growth. A core component of the project was the development and application of a forecasting urban metabolism framework and tool. By using the tool for policy assessment, partner cities can conduct infrastructure planning to create more resilient, resource-efficient and sustainable cities. This could include evaluations of nature-based solutions and other environmental policies for sustainable management of urban resources.

The urban forecasting tool could allow urban stakeholders to develop policy interventions to reduce environmental impacts and resource use intensity in Policy Pathways, and contribute to achieving SDGs and emission reductions indicated in Nationally Determined Contributions. Such impact can be replicated in other cities in the region.

. The Forecasting Tool allows city stakeholders to assess and forecast resource impacts over several years and create scenarios based on policy interventions, investigate technical solutions, or determine benchmarks (e.g. % improvement in resource efficiency, energy reduction, water efficiency, reduction in waste or recycling.). Additionally, a regional knowledge transfer workshop in Almaty, Kazakhstan, allowed for discussion of how the tool and approach could inform the sustainable management of urban resources in other cities in the region.

2. Overview

The Forecasting Sustainable Urbanization Tool is intended to be a simulation tool that can be applied widely by urban decision-makers to enable them to see how changes in economic and population conditions could affect their resource needs and environmental impacts. This model allows urban stakeholders to explore system interventions that could increase resource efficiency and reduce the environmental impacts in the areas of:

i. material use

ii. solid waste generation

iii. energy consumption

iv. greenhouse gas emissions

v. water consumption

vi. land use change

vii. air pollution emissions

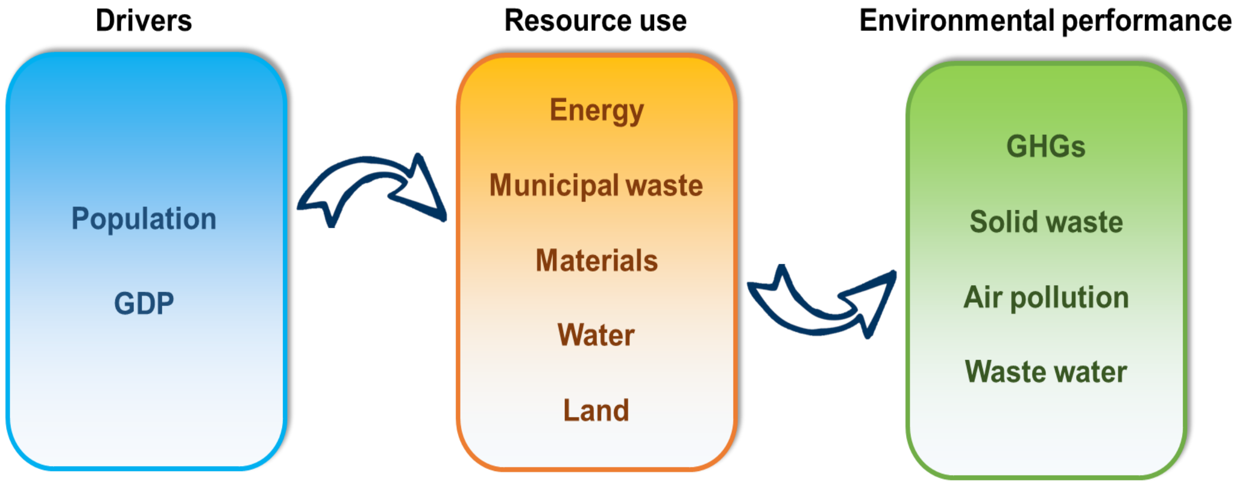


Figure 1. Framework

Two versions of the model have been developed:

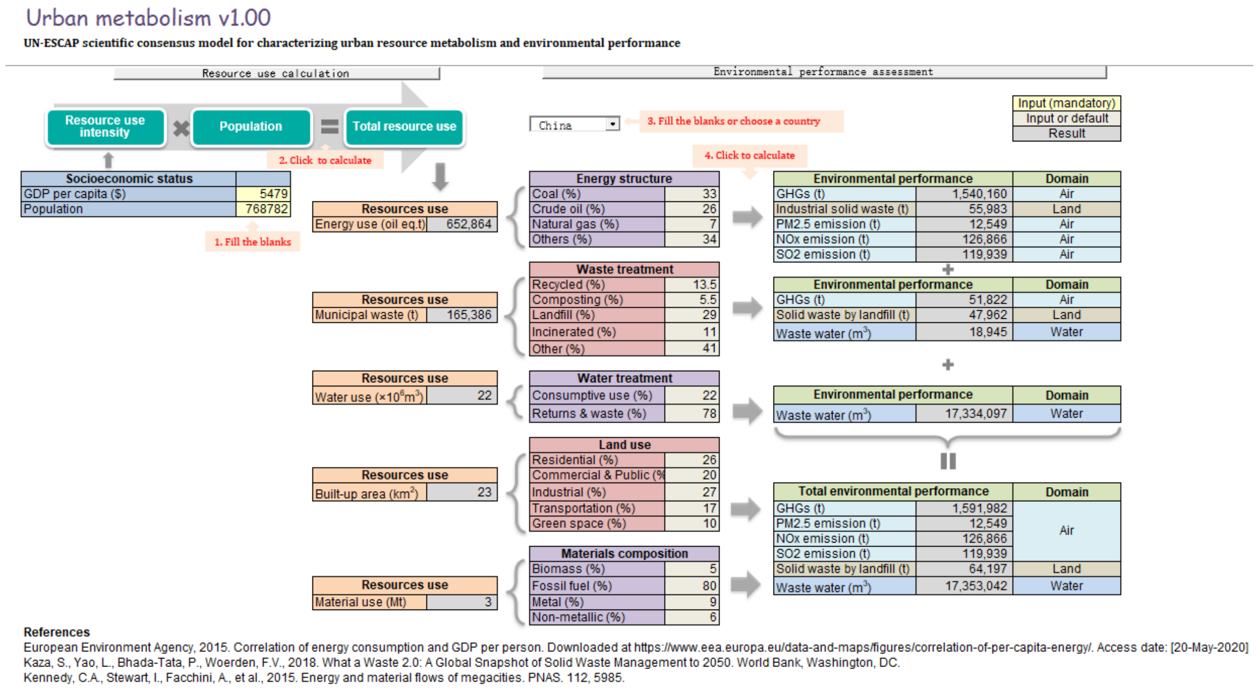
- Excel version (for single-year simulation)
- System dynamic version (for time series simulation)

3. Computing Environment

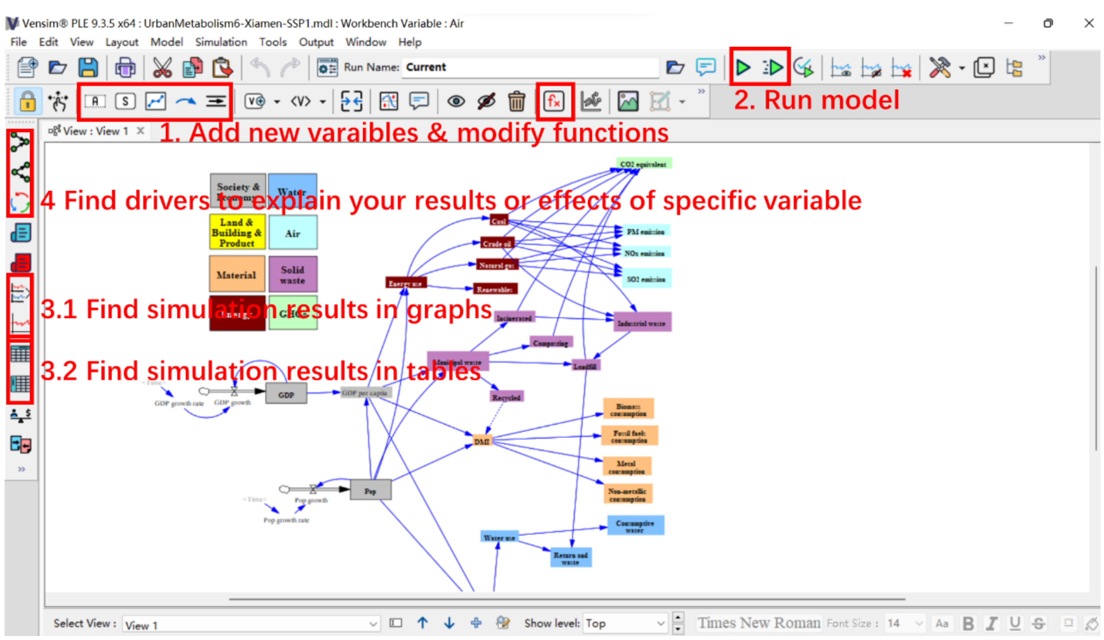
- Excel version: Microsoft Excel 2013 or higher and open Visual Basic for Application (VBA)
- System dynamic (SD) version: Vensim PLE (https://vensim.com/download/) (free)

4. User interface

– Excel version



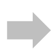
– SD version



5. Model Inputs

- Mandatory: GDP (in constant US$), Population (people)
- Selected input or using default values:
  - Energy structure: Coal (%), Crude Oil (%), Natural gas (%), Others and renewables (%)
  - Waste treatment: Recycled (%), Composting (%), Landfill (%), Incinerated (%), Others (%)
  - Water treatment: Consumptive use (%), Returns & waste (%)
  - Land use: Residential (%), Commercial & Public (%), Industrial (%), Transportation (%), Green space (%)
  - Material use/Domestic material consumption (DMC): Biomass (%), Fossil fuel (%), Metal (%), Non-metallic (%)

6. Running the model

- Excel version: click  or 
- SD version: click

7. Model outputs

The model can simulate tonnes of direct material consumption (DMC), tonnes of solid waste generation, energy consumption (oil eq. tonnes), water use & waste water generation (m^3), greenhouse gas emissions(tonnes), built-up area (km^2), and air pollutant emissions (tonnes of $PM_{2.5}$, NO_x, SO_2). The results can be accessed as:

- **Numbers (both in Excel and SD versions)**

  The excel version provides numeric results directly

- **Tables (in SD versions)**

  Choose the variable you want to analyse and click 

- **Figures (in SD version)**

  Choose the variable you want to analyse and click

8. Cause and effect links

- **Cause (in SD version)**

  Choose a variable and explore its driving factors

- **Effect (in SD version)**

  Choose a variable and show its effect on other variables

9. Modifying the model

Policy interventions, such as targeted percentage of improvements in resource efficiency and/or resource intensities can be inserted manually in the tool to generate estimated savings or benefits in specific resources or sectors.

- Excel version

  Right-click or , choose 'assign macro', edit 'Resource_Cal_Click' or 'EP_cal_'

- SD version

  Add new variables or modify existed ones:

  Modify functions:

It is expected that this tool will be continuously upgraded, including improvements to the user interface and additional functionality based on increasing availability of data in local communities and on disaggregated data on resource intensities across the region at national and local levels. Users are encouraged to inform the developers on the applicability of the tool and any indications on the accuracy or usefulness of the results generated by the tool.

ANNEX 1- Equations and Calculations

10.1 Urban resource use = resource use intensity * population

10.2 Resource use intensity assessment

Input (units)	Function	Output (units)	Reference
GDP per capita (2011 PPP $)	Energy use per capita= 0.1191*GDP per capita+196.67	Energy use per capita (kg oil-eq/person/year)	EEA, 2015
	Waste per capita= 1647.1-419.73*LN(GDP per capita) +29.43*LN(GDP per capita)^2	Waste per capita (kg/person/year)	World Bank, 2018
	DMI per capita=0.000773*GDP per capita-recycled waste	DMI per capita (tonnes/person/year)	Data from IRP
	Built-up area per capita= 0.005535* GDP per capita	Built-up area per capita (m2/person)	Kennedy, 2015
Built-up area per capita (km2/person)	Water use per capita= 953201* Built-up area per capita	Water use per capita (m3/person)	Kennedy, 2015

10.3 Resource use in each section or end-point (the detailed value of each section or end-point could be designed as 'input' in the user interface)

10.3.1 Energy use

Sources	Xiamen	Bishkek	Dushanbe
Coal	33%	6%	2%
Oil	26%	6%	2%
Natural Gas	7%	6%	2%
Renewables	34%	82%	94%

10.3.2 Municipal waste

End-point	Component*	Gain or Loss
Incinerated	11%	--
Composting	5.5%	--
Landfill	29%	+20% of industrial waste
Recycled	13.5%	--
Other	41%	--

*based on Xiamen's statistics

10.3.3 Industrial waste

Industrial waste = coal consumption * 25% + Oil consumption * 1.25% +Incinerated MSW * 5%

P.S. 25%, 1.25%, and 5% come from related industrial or sector survey in China

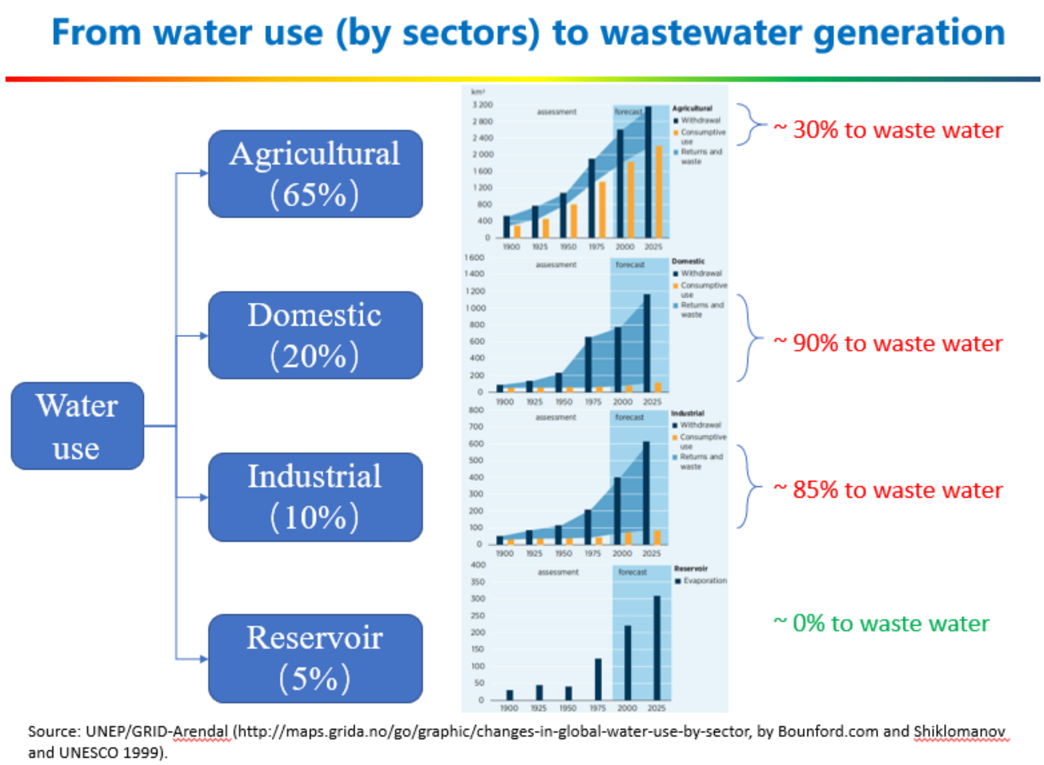
10.3.4 Direct Material Input (DMI)

Usage	Component*
Biomass	5%
Fossil Fuel	80%
Metal	9%
Non-metallic	6%

*based on Xiamen's estimation by EW-MFA

10.3.5 Water

Usage	Component	Gain or Loss
Consumptive	54% in Vensim	--
Waste (& Return)	46% in Vensim	+Landfill waste*0.395tonne of leachate per tonne of waste (=395L/t, 395L=0.395t)



e.g. Waste proportion (46%)=0.65*0.3+0.2*0.9+0.1*0.85=0.46
These values could be adjusted because reservoirs could be seen as non-consumptive. Therefore, we could use 46%+5%=51% and let consumptive value equals the rest of them=49%）

10.4 GHG and air pollutant emissions

Emissions $_{GHG}$=1* Emissions $_{CO2}$+28* Emissions $_{CH4}$+265* Emissions $_{N2O}$

Note:

Total GHG emissions are transformed into CO_2 equivalent. 21 and 310 are the global warming potential of CH_4 and N_2O.

Emissions $_{GHG}$= Emissions $_{GHG,\ fuel}$+ Emissions $_{GHG,\ waste}$

If fuel consumption structure data (fuel consumption in different sectors) for a city is not available, it could be estimated by historical country-level data reported by **IEA Head line Global Energy Data (2019 edition)**. Fuel consumption structure is listed in Excel 1 Global GHGs emissions from fuel consumption sheet 2-4. There are 54 regions and the time boundary is 1971-2017. **Example: (*There is an example in the excel file "Excel 1 Global GHGs emissions from fuel consumption sheet 1"*)**

Energy Consumption Per Capita=196.67+0.1191*GDP per capita

Note:

GDP per capita is 2011 PPP USD.

The unit of Energy Consumption Per Capita is kg crude oil equivalent.

Total Energy Consumption (TJ) = Energy Consumption Per Capita (kg oil-eq) *Population*41816*10^-9

Note:

Total Energy Consumption=amount of energy consumed by a city (TJ)

Population=amount of urban population

41816*10^-9 is the conversion coefficient (from 1 kg crude oil-eq weight to 1 TJ energy). 1 kg crude oil's heat value is 41816 KJ energy. 1 TJ energy is 10^12 J energy. Total Energy Consumption contains fuels, nuclear and renewable energy. Fuel consumption could be estimated according to energy structure (excel 1 sheet 2-4).

10.4.1 GHG emission from fuel consumption

Emissions $_{GHG,\ fuel}$=Fuel Consumption $_{fuel}$* Emission Factor $_{GHG,\ fuel}$/1000

Note:

Emission $_{GHG,\ fuel}$ =emissions of a given GHG by type of fuel (t GHG)

Fuel Consumption $_{fuel}$=amount of fuel consumed (TJ)

Emission Factor $_{GHG,\ fuel}$=default emission factor of a given GHG by type of fuel (kg gas/TJ). For CO_2, it includes the carbon oxidation factor, assumed to be 1.

1000 is transforming kg to t.

GHG emission factors

Unit: kg/TJ	CO_2			CH_4			N_2O		
	Coal	Crude oil	Natural gas	Coal	Crude oil	Natural gas	Coal	Crude oil	Natural gas
Energy industries	98300	73300	56100	1	3	1	1.5	0.6	0.1
Manufacturing industries & Construction	98300	73300	56100	10	3	1	1.5	0.6	0.1
Commercial/Institutional	98300	73300	56100	10	10	5	1.5	0.6	0.1
Residential and Agriculture/Forestry/Fishing/Fishing farms	98300	73300	56100	300	10	5	1.5	0.6	0.1
Transportation (road)		69300	56100		3.9	92		3.9	3

Note:

(1) Data source: https://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/2_Volume2/V2_2_Ch2_Stationary_Combustion.pdf; https://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/2_Volume2/V2_3_Ch3_Mobile_Combustion.pdf.

(2) For coal, the emission factor of CO_2 is from anthracite.

(3) In transportation (road) sector, crude oil refers to motor gasoline. The emission factors of CH_4 and N_2O are from motor gasoline-low mileage light duty vehicle vintage 1995 or later.

(4) In global model, detailed industries energy consumption data is not available. Since energy industries are important, we use the emission factors of energy industries for the whole industry sector.

10.4.2 GHG emission from waste disposal （*Example: steps are listed in Excel 2 Global GHGs emissions from waste disposal*）

Emissions $_{GHG,\ waste}$=Emissions $_{GHG,\ waste\ landfill}$+ Emissions $_{GHG,\ waste\ incineration}$ +Emissions $_{GHG,\ waste\ biological\ treatment}$

Waste in landfills could generate CH_4. The incineration of waste could generate CO_2, CH_4 and N_2O, ***but in this version of the model, we calculate CO_2 emission***. ***The biological treatment of waste could generate CH_4 and N_2O.***

(1) If the waste generation of a city is not available, it could be estimated using a global model as below:
Waste generation=population* waste generation per capita*1000
Waste per capita=1647.1-419.73*LN(GDP per capita) +29.43*LN(GDP per capita)^2
Unit: waste generation (t), population (million), waste generation per capita (kg), GDP per capita (2011 PPP International $). 1000 is for unit transformation.

(2) The waste composition data should be included in the model. If it is not available, global waste composition data could be used.

Global Waste Composition	Percentage
Food and green	44%
Glass	5%
Metal	4%
Other	14%
Paper and cardboard	17%
Plastic	12%
Rubber and leather	2%
Wood	2%

(3) Waste disposal data is needed in the model. If it is not available, global waste disposal data could be used.

Global Waste Composition	Percentage
Composting	5.5%
Incineration	11.0%
Controlled landfill	4.0%
Landfill (unspecified)	25.0%
Sanitary landfill (with landfill gas collection)	7.7%
Open dump	33.0%
Other	0.3%
Recycling	13.5%

(4) DOC=(0.15*A) +(0.2*B) +(0.4*C) +(0.43*D) +(0.24*E) +(0.15*F) (ready for landfill related CH4 calculation and bio-treatment related CH4 and N2O)
DOC is degradable organic carbon. In the global version of the model, DOC=0.14 t Carbon/waste

Equation 8.1 **Degradable organic carbon (DOC)**[52]

$$DOC = (0.15 \times A) + (0.2 \times B) + (0.4 \times C) + (0.43 \times D) + (0.24 \times E) + (0.15 \times F)$$

A	=	Fraction of solid waste that is food
B	=	Fraction of solid waste that is garden waste and other plant debris
C	=	Fraction of solid waste that is paper
D	=	Fraction of solid waste that is wood
E	=	Fraction of solid waste that is textiles
F	=	Fraction of solid waste that is industrial waste

(5) L_0=MCF*DOC*DOC_F*F*16/12 (for landfill-related CH4 calculation)
L_0 is methane generation potential. In the global model, L_0-Controlled landfill=0.06 and L_0-Landfill (unspecified)=0.03.

Methane generation potential, L_0	
MCF-Controlled landfill	1.00
MCF-Landfill (unspecified)	0.60
DOC	0.14
DOC_F	0.60
F	0.50
Stoichiometric ratio between methane and carbon	1.33
Results (sample, using MCF-controlled or unspecified)	
L_0-Controlled landfill	0.06
L_0-Landfill (unspecified)	0.03

Equation 8.4 **Methane generation potential, L_0**

$$L_0 = MCF \times DOC \times DOC_F \times F \times 16/12$$

Description			**Value**
L_0	=	Methane generation potential	Computed
MCF	=	Methane correction factor based on type of landfill site for the year of deposition (managed, unmanaged, etc., fraction)	Managed = 1.0 Unmanaged (≥5 m deep) = 0.8 Unmanaged (<5 m deep) = 0.4 Uncategorized = 0.6
DOC	=	Degradable organic carbon in year of deposition, fraction (tonnes C/tonnes waste)	Equation 8.1
DOC_F	=	Fraction of DOC that is ultimately degraded (reflects the fact that some organic carbon does not degrade)	Assumed equal to 0.6
F	=	Fraction of methane in landfill gas	Default range 0.4-0.6 (usually taken to be 0.5)
16/12	=	Stoichiometric ratio between methane and carbon	

Source: IPCC Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories (2000)

For landfill:

(6) CH_4 emissions=MSW_X*L_0*(1-f_{rec})*(1-OX)

f_{rec} value should be inputted by user. Here we assumed the value is 0.

Equation 8.3 **Methane commitment estimate for solid waste sent to landfill**

$$CH_4 \text{ emissions} = MSW_x \times L_0 \times (1-f_{rec}) \times (1-OX)$$

Description			Value
CH_4 emissions	=	Total CH_4 emissions in metric tonnes	Computed
MSW_x	=	Mass of solid waste sent to landfill in inventory year, measured in metric tonnes	User input
L_0	=	Methane generation potential	Equation 8.4 Methane generation potential
f_{rec}	=	Fraction of methane recovered at the landfill (flared or energy recovery)	User input
OX	=	Oxidation factor	0.1 for well-managed landfills; 0 for unmanaged landfills

Source: Adapted from *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories*

Landfill CH_4 emissions	
MSW_x-Controlled landfill	Input
MSW_x-Landfill (unspecified)	Input
L_0-Controlled landfill	0.06
L_0-Landfill (unspecified)	0.03
f_{rec}	0.00
OX	0.10
CH_4 emission (t)	**Calculated**

For incineration:

(7) CO_2 emissions=m*$\sum_i$(WF_i*dm_i*CF_i*FCF_i*OF_i)*(44/12)

CO_2 emission from incineration	
CO_2 emission factor	0.27 (t CO2/wet waste)
Mass of waste incinerated (t)	Input
CO_2 emission (t)	**Calculated**

Note: Here we use default emission factor of waste (wet weight) in China (CF_i=0.2, FCF_i=0.39, OF_i=0.95), data source is 《Guidelines for the Preparation of Provincial Greenhouse Gas Inventories (for Trial)》.

Equation 8.6 **Non-biogenic CO_2 emissions from the incineration of waste**

$$CO_2 \text{ Emissions} = m \times \sum_i (WF_i \times dm_i \times CF_i \times FCF_i \times OF_i) \times (44/12)$$

Description			Value
CO_2 emissions	=	Total CO_2 emissions from incineration of solid waste in tonnes	Computed
m	=	Mass of waste incinerated, in tonnes	User input
WF_i	=	Fraction of waste consisting of type i matter	User input[54]
dm_i	=	Dry matter content in the type i matter	User input (default values provided in Table 8.4 below)
CF_i	=	Fraction of carbon in the dry matter of type i matter	
FCF_i	=	Fraction of fossil carbon in the total carbon component of type i matter	
OF_i	=	Oxidation fraction or factor	
i	=	Matter type of the Solid Waste incinerated such as paper/cardboard, textile, food waste, etc.	

Note: $\sum_i WF_i = 1$

Source: 2006 IPCC Guidelines for National Greenhouse Gas Inventories

For bio-treatment:

(8) For GHGs emission from biological treatment, CH_4 and N_2O are estimated.

CH_4 and N_2O emission from biological treatment	
CH_4 emission factor (t CH_4/t wet waste)	0.004
N_2O emission factor (t N_2O/t wet waste)	0.0003
Mass of organic waste treated by biological treatment (t)	Input
CH_4 emission (t)	**Calculated**
N_2O emission (t)	**Calculated**

Mass of organic waste treated by biological treatment= Mass of waste treated by biological treatment* DOC.

CH_4 and N_2O emission factor are from composting (wet waste).

Equation 8.5 Direct emissions from biologically treated solid waste

$$CH_4\ Emissions = (\Sigma_i (m_i \times F\_CH4_i) \times 10^{-3} - R)$$

$$N_2O\ Emissions = (\Sigma_i (m_i \times EF\_N2O_i) \times 10^{-3})$$

Description			Value
CH_4 emissions	=	Total CH_4 emissions in tonnes	Computed
N_2O emissions	=	Total N_2O emissions in tonnes	Computed
m	=	Mass of organic waste treated by biological treatment type i, kg	User input
EF_ CH4	=	CH_4 emissions factor based upon treatment type, i	User input or default value from table 8.3 Biological treatment emission factor
EF_ N2O	=	N_2O emissions factor based upon treatment type, i	User input or default value User input or default value from table 8.3 Biological treatment emission factor
i	=	Treatment type: composting or anaerobic digestion	User input
R	=	Total tonnes of CH_4 recovered in the inventory year, if gas recovery system is in place	User input, measured at recovery point

Source: 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Volume 5, Chapter 4: Biological Treatment of Solid Waste

Table 8.3 Biological treatment emission factors

Treatment type	CH_4 Emissions Factors (g CH_4/kg waste)		N_2O Emissions Factors (g N_2O /kg waste)	
	Dry waste	Wet waste	Dry waste	Wet waste
Composting	10	4	0.6	0.3
Anaerobic digestion at biogas facilities	2	1	N/A	N/A

Source: 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Volume 5, Chapter 4: Biological Treatment of Solid Waste

10.4.3 Air pollutant emissions from fuel consumption

$Emissions_{air\ pollutant,\ fuel}$=Fuel $Consumption_{air\ pollutant,\ fuel}$ * Emission $Factor_{air\ pollutant,\ fuel}$

Note:

$Emissions_{air\ pollutant,\ fuel}$=emissions of a given air pollutant by type of fuel (kg air pollutant)

Fuel $Consumption_{fuel}$=amount of fuel consumed (TJ)

Emission $Factor_{air\ pollutant,\ fuel}$ =default emission factor of a given air pollutant by type of fuel (kg air pollutant/TJ).

Emission factors (kg/TJ)	Fuels	Industries	Residential& Commercial/Institutional	Road Transportation
NO_x	Coal	300	100	
	Gasoline	200	100	600
	Diesel	200	100	800
	Natural Gas	150	50	600
$PM_{2.5}$	Coal	13	60	
	Gasoline	110		1
	Diesel	111		1

	Natural Gas	4	4	
PM_{10}	Coal	44	61	
	Gasoline	115		22
	Diesel	116		25
	Natural Gas	4	4	
SO_2	Coal	287	287	
	Gasoline	46	46	46
	Diesel	141	141	141
	Natural Gas	13	60	

References:

(1) NO_x emission factor is an uncontrolled emission factor in IPCC emission factor database (https://www.ipcc-nggip.iges.or.jp/EFDB/main.php).

(2) $PM_{2.5}$ and PM_{10} emission factors are transformed from weight unit to heating value unit. The emission factor of coal is from anthracite (heating value is 34890 KJ/Kg).

(3) $PM_{2.5}$ and PM_{10} emission factors of Industries, Residential& Commercial/Institutional are from unabated pulverised coal-fired boilers and data source is Huang, Ye, et al. "Quantification of global primary emissions of $PM_{2.5}$, PM_{10}, and TSP from combustion and industrial process sources." Environmental science & technology 48.23 (2014): 13834-13843.

(4) $PM_{2.5}$ and PM_{10} emission factors of road transportation come from 《Technical guideline for compilation of air pollutant emission inventory of vehicles (in Chinese)》

(5) SO_2 emission factor is from IPCC emission factor database (https://www.ipcc-nggip.iges.or.jp/EFDB/main.php). Here we assume the Sulphur content in coal, gasoline, and diesel are 0.5%, 0.1%, 0.3%.