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Greenhouse gas emissions inventory data acquisition and analytics for low carbon cities

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ABSTRACT

This paper studied greenhouse gas inventory data acquisition and analytics for municipalities in Thailand. A complete and transparent GHG inventory of eight municipalities was developed to document the current situation, and to help decision-makers to clarify their priorities for reducing greenhouse gas emissions. The Global Protocol for Community-Scale Greenhouse Gas Emissions Inventories guidelines was used to investigate and calculate the greenhouse gas emissions and assess data accuracy. The results indicated that the data source, data format, and data collection of each municipality are relatively similar. Moreover, the activity data needed to be obtained from several authorities. The results showed that Nonthaburi Municipality had the highest greenhouse gas emissions at 2,286,838 tCO_2e/yr and Buriram Municipality, the lowest at 239,795 tCO_2e/yr. On a per-capita basis, Lamphun Municipality was the highest with 10.1 tCO_2e/capita and Buriram Municipality the lowest with 3.8 tCO_2e/capita. The results suggest that the municipalities should continually develop a GHG database by creating a routine procedure. An information management system should be produced in the shape of big data which can lead to state policies, plans, and actions for city development to ensure the reduction of greenhouse gas emissions. This in turn will lead to a low carbon city.

1. Introduction

Climate change is a global critical issue causing increased awareness of greenhouse gas (GHG) emission management (Misila et al., 2017). This had a high impact on developing countries, including Thailand, which has been challenged by the need to low-carbon city development plans. Climate change is a result of human activities (Gossop, 2011) such as fossil fuel burning (manufacturing, electricity generation, transportation, and household heating), forestry and agriculture (livestock, wetlands, fertilizers, land clearing, timber production), and waste disposal (landfills and incineration) (Wilbanks and Kates, 1999). Climate action planning is one of the top priorities of cities to reduce GHG emissions and strengthen climate-resilience as pointed out by the New Urban Agenda and the Paris Agreement (Pietrapertosa et al., 2019). The Paris Agreement under the United Nations Framework Convention on Climate Change (UNFCCC) aims to limit global warming to well below 2, preferably to 1.5 °C, compared to pre-industrial levels which would substantially reduce the risks and impacts of climate change (UNFCCC, 2015). In support of these goals, there has been an international effort to tackle climate change. For example, the European Union (EU) has recently set out a clear vision in the European Green Deal on how to achieve climate neutrality by 2050 (Mateo Pla et al., 2021). The EU has set an ambitious target on reducing greenhouse gas emissions to at least 55% below 1990 levels by 2030. (European Commission, 2020). Thailand signed the Paris Agreement on April 22, 2016 and ratified it on September 21, 2016. The Nationally Determined Contribution (NDC) of Thailand intends to reduce GHG emissions by 20–25% from the projected business as usual level by 2030 with the deployment of renewable energy technologies and energy efficiency improvement measures in both the supply and demand sectors (Rajbhandari et al., 2019).

Cities are recognized as playing a significant role in the global climate action (Heidrich et al., 2013; Reckien et al., 2014) and are one of the key players in realizing GHG control targets (Yang et al., 2018). They are places of high overall primary energy consumption and high GHG emissions based on their being centers of wealth and resources with high population densities. The largest source of GHG emissions comes from

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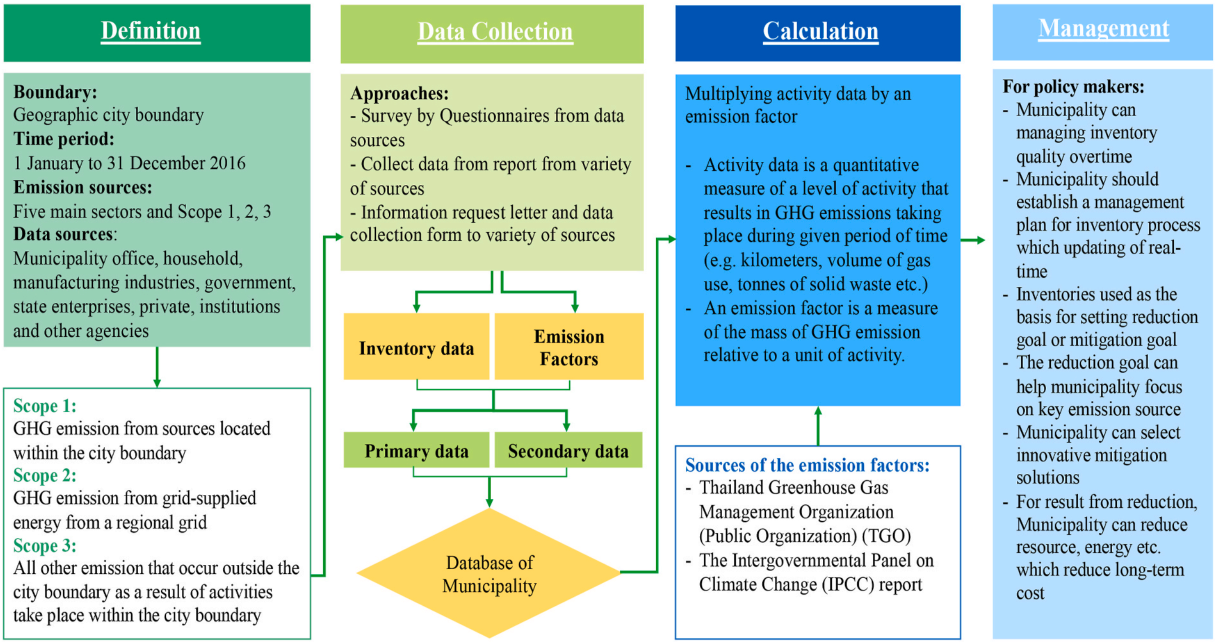

Fig. 1. The stepwise methodology for this study. (Source: World Resources Institute, 2014;).

human activities within urban areas accounting for more than 70% of the world's emissions (Sanna et al., 2014). Thus, cities should assume a major role in GHG emissions reduction to mitigate the effect of global climate change. To achieve this goal, quantifying the amount of CO_2 generated by emission sources such as energy consumption, solid waste management, and wastewater treatment, i.e., creating a CO_2 emissions inventory for each city, is an important first step (Yu et al., 2012). Therefore, cities are ideal for implementing low-carbon policies and adaptation strategies through a strategic planning process shared with citizens and local stakeholders (Pietrapertosa et al., 2019). The local governments intend to support the strategic policies of Thailand and contribute to better assess the driving factors and sectors behind GHG emissions at urban scale (Ibrahim et al., 2012; Lorenzo-Sáez et al., 2020).

The concern of many cities regarding climate change has led a variety of entities to develop approaches and tools for developing and reporting GHG inventory on a local scale. One such example is the International Local Government Greenhouse Gas Emissions Analysis Protocol (IEAP) (ICLEI, 2009). Further examples include the Greenhouse Gas Protocol, which is a Corporate Accounting and Reporting Standard (World Resources Institute/World Business Council for Sustainable Development, 2004), the Sustainable Energy Action Plan (SEAP) by the Covenant of Mayors (Covenant of Mayors, 2010), and the Global Protocol for Community-Scale Greenhouse Gas Emissions Inventories (GPC). This is the result of a collaborative effort between the World Resources Institute (WRI), the C40 Cities Climate Leadership Group, and the Local Governments for Sustainability (ICLEI). In general, all the methods established by these entities essentially follow the Intergovernmental Panel on Climate Change (IPCC) guidelines under UNFCCC since the IPCC guidelines are the international standard for national GHG inventories and reporting, which are hence applied to develop inventories of local governments. However, research and practices related to local-level GHG inventories are few, especially in developing countries including Thailand. Several studies show that the approach in the development of city-level GHG inventory. For example, Arioli et al. (2020) reviewed to identify what city-scale GHG inventory methods are being applied in cities as a result of the progress that has been made in GHG accounting as well as explored how cities are overcoming the known challenges of completing an inventory. Ghaemi and Smith (2020) reviewed on the quantification of life cycle GHG emissions at urban scale. Lu and Li (2019) attempted to build an investigation-based GHG emission inventory framework for Baoding city (China). Li et al. (2017) have investigated and calculated the GHG emissions in Beijing by following the GPC guidelines. Dahal and Niemelä (2017) calculated the GHG emissions in three cities—Helsinki, Stockholm, and Copenhagen—based on statistics collected at both the national and local levels by the GPC guidelines. And finally, Yu et al. (2012) showed that the tools for developing GHG inventories for cities include an IPCC-based method by using the Sustainable Energy Action Plan (SEAP) for estimating citywide CO_2 emissions of four Chinese cities in a typical region from 2004 to 2010 by collecting statistical data, analyzing the characteristics of emissions in recent years, and deducing future trends.

In Thailand, municipalities are one of the key players in realizing GHG control targets to implement mitigation activities. Municipalities have become interested in GHG emissions caused by their daily activities (Monni and Syri, 2011) which are very important to quantify and report for implementation of the policy in order to reduce GHG emissions in their bid to move towards becoming a Low Carbon City (LCC). The most frequently used analytic tool is the GHG emissions inventory, which estimates the emissions associated with the activities of the city being studied (Kennedy et al., 2010). Although inventories of GHG emissions serve as the basis for identifying mitigation efforts, knowing the bundle of GHGs generated locally enables the emitters to address their specific sources. Unfortunately, except for some cities, there are limited data sets of cities emissions available, and even when desired, they are usually difficult to compile (Wilbanks and Kates, 1999). In Thailand, closer inspection shows that the municipalities have not explicitly prepared for establishing inventories of GHG emissions. This in turn proves difficult to understand which activities produce significant GHG emissions, and the municipalities are thus unable to formulate a concrete action plan for reducing GHG emissions. Although the Thailand Greenhouse Gas Management Organization Public Organization (TGO) has published a guideline for municipalities on how to prepare a greenhouse gas database following the Global Protocol for Community-Scale Greenhouse Gas Emissions Inventories (GPC) guidelines, and even provides support to the municipalities to create a GHG database by themselves, it still cannot cover all municipalities. Since the GHG emission reporting is voluntary and GHG inventory being relatively new, the Thai municipalities still lack understanding of the data acquisition process and analytics approach. They think that they do not have the data to build a

GHG database and do not understand how to use the GHG assessment results in their policies. As a result, most municipalities have not reported their cities' GHG emissions and have no policies to reduce the GHG emissions.

Thus, this paper studied the GHG inventory data acquisition and analytics for 8 municipalities in Thailand. The focus of the study is on the data collection process for municipalities that can continuously collect data to develop into a national database. The study defines an inventory boundary for municipalities, identifies the GHG emission sources and data collection method including data research, data format, data sources, a data collection approach focusing on primary data, and calculates the GHG emissions from the GHG inventory data by using the GPC guidelines. Finally, the limitations of the established GHG inventory database for municipalities were identified. The results in this study will help municipalities develop GHG inventory for managing the data quality and improvement of the cities' GHG emission inventories. This should prove useful for widespread GHG emission reduction policymaking by being able to focus on significant emission sources by selecting innovative solutions suitable for each city. Thailand and other developing countries possess limited investment, time, and manpower for concrete action plans to reduce GHG emissions. Therefore, policymakers should make decisions based on GHG data for effective implementation.

2. Methodology

This study is based on the GPC guidelines which provide detailed guidance on data collection and calculation of GHG emissions (World Resources Institute, 2014). The approach used in the accounting of GHG can significantly impact the results of the GHG inventory in the cities (Sudmant et al., 2018). The GPC guidelines provide a robust framework for accounting and reporting of city-level GHG emissions. A municipality's ability to take effective action on mitigating climate change and monitoring progress depends on having access to good quality data on GHG emissions. Climate action plans begin with developing a GHG inventory. An inventory enables cities to understand the emissions contribution of different activities in the community. It allows cities to determine where to best direct mitigation efforts, create a strategy to reduce GHG emissions and use them to set emission reduction targets, and inform their climate action plans and track their performance. The steps of this study following GPC are presented in Fig. 1.

2.1. Definition

2.1.1. Setting the city boundary

"City" is defined by aligning with the administrative boundary, such as province, municipality, or special administrative region. The 8 municipalities that are considered in this study are those that have joined, on a voluntary basis, the call of TGO to support the municipalities to create a GHG database by themselves. These include Ubon Ratchathani (UBN) Municipality, Nonthaburi (NBI) Municipality, Lamphun (LPN) Municipality, Mahasarakham (MKM) Municipality, Yasothon (YST) Municipality, Sisaket (SSK) Municipality, Buri Ram (BRM) Municipality, and Khu Khot (KKT) Municipality. The inventory data acquisition and analysis of GHG emissions of these municipalities were studied.

Generally, each city has different basic contexts: the area, economics, society, environment, number of households, population, number of non-registered population, and number of tourists; all these are factors affecting GHG emissions in the city.

Cities shall establish a geographic boundary that identifies the spatial dimension or physical perimeter of the inventory's boundary. Any geographic boundary may be used for the GHG inventory, and cities shall maintain the same boundary for consistent inventory comparison over time. Depending on the purpose of the inventory, the boundary can align with the administrative boundary of a local government, a combination of administrative divisions, a metropolitan area, or another geographically identifiable entity. The boundary should be chosen independently based on the location of buildings or facilities under municipal control, such as power generation facilities or landfill sites outside of the city's geographic boundary. Thus, this study set the city boundaries by considering the geographic boundary and operation control since some activities take place outside the administrative district but are under the municipality's operation, such as GHG emission activity from landfill disposal outside the city area operated by the municipality. Boundary setting is an important process for GHG evaluation because it allows the municipality to correctly identify the GHG emission sources.

2.1.2. Identifying GHG emission sources

In this study, GHG emission sources are identified by scope. The scope definition of GPC accounts for all direct and indirect emission sources from activities taking place within the community's geopolitical boundary, the energy-related indirect emissions resulting from the consumption of grid-supplied electricity, and heating and/or cooling within the community's geopolitical boundary (Sanna et al., 2014). The GHG emission sources have been classified into six sectors: (1) Stationary energy (2) Transportation (3) Waste (4) Industrial Process and Product Use (IPPU) (5) Agriculture, Forestry, and other Land Use (AFOLU) and (6) Any other emissions occurring outside the geographic boundary as a result of city activities may be reported separately (Baltar de Souza Leão et al., 2020).

Activities taking place within a city can generate GHG emissions that occur inside the city boundary as well as outside the city boundary. To distinguish between these, the GPC groups emissions into three categories based on where they occur: Scope 1, Scope 2, or Scope 3 emissions. Scope 1 refers to all GHG emissions produced within the geographic boundary of the city and are consistent with national-level GHG reporting including stationary energy, transportation, waste, IPPU, and AFOLU. Scope 2 includes the GHG emissions that occur due to the consumption of grid-supplied electricity, heat, and steam and/or cooling within the city boundary. GHG emissions associated with electricity are one of the biggest areas of variability among cities and can be essential in order to mitigate emissions (Andrade et al., 2017). Scope 3 considers all other GHG emissions that occur outside the city boundary because of activities taking place within the city boundary. The GPC includes Scope 3 accounting for a limited number of emission sources, including transmission and distribution losses associated with grid-supplied energy, and waste disposal and treatment outside the city boundary as well as transboundary transportation. The GPC gives cities the option of selecting between two reporting levels: BASIC and BASIC+. These levels cover specific scopes in different categories of activities. The BASIC covers Scope 1 and Scope 2 emissions from stationary energy, in-boundary transportation, and in-boundary generated waste. The BASIC + has a more comprehensive coverage of BASIC sources plus IPPU, AFOLU, and any other emissions occurring outside the geographic boundary due to city activities. For the reporting level, the BASIC + has been selected for this study.

2.1.3. Setting a time period

The GPC is designed for city GHG emissions within a single reporting year. The inventory shall cover a continuous period of 12 months, ideally aligning to either a calendar year or a financial year and be consistent with the time periods most commonly used by the city. Data for this study were collected from 1st January to December 31, 2016.

2.2. Data collection

Baltar de Souza Leão et al. (2020) showed the approach for making a GHG inventory from documents issued by Brazilian cities and other secondary sources. Even though no questionnaire was applied, they contacted the ICLEI by phone and e-mail. Yu et al. (2012) studied the CO_2 emissions inventories of four Chinese cities in a typical region by

Table 1
Data, Sources, Data processing, assumptions and limitations used to compile the GHG inventory for municipalities.

Activity Data	Data	Source	Data Processing	Assumptions/limitations
STATIONARY ENERGY				
Electricity Consumption	Quantity of electricity consumption for each type Type 1 Residential buildings Type 2 Small-sized business Type 3 Medium-sized business Type 4 Large-sized business Type 5 Specific business Type 6 Government institutions and Non-profit organizations Type 7 Water pumping for agricultural purposes Type 8 Temporary electricity Type 9 Public electricity	Metropolitan Electricity Authority or Provincial Electricity Authority	Send a letter and form to the MEA or PEA for the summary of electricity consumption for each type within the city boundary	Allocation by mass using the number of electricity consumers in each category
Energy consumption in residential buildings	- Amount of LPG usage - Amount of charcoal usage	- Residential buildings - LPG store	Survey with questionnaire by Village Health Volunteer (VHV) or Municipal Officer	A questionnaire collected 20 percent of the total number of households.
Energy consumption in commercial and institutional buildings and facilities	Amount of fuel combustion for equipment's operation	Commercial and institutional buildings and facilities, for example, schools, hospitals, offices, department stores, etc.	- Send a letter and data collection form to commercial and institutional buildings - Some municipalities organize a meeting to clarify the details before sending data collection form	A questionnaire collected 20 percent of the total number of commercial and institutional buildings and facilities.
TRANSPORTATION				
On-road	- The volume of fuel sold - Activity data in public transportation o Type of vehicle o Origin - Destination o Distance o Number of trips o Type and quantity of fuel	Authority which controls fuel sales of service station such as Provincial Energy Office, Provincial Administrative Organization (PAO), or fuel service station Public transportation authority or business owner	- Send a letter and data collection form to relate authority - Survey with questionnaire by Municipal Officer	Worst-case scenario of the sales for vehicles used to transport only within the city A questionnaire collected 20 percent of the total public transportation authority or business owners
Activity Data	Data	Source	Data Processing	Assumptions/limitations
WASTE				
Landfilling of waste	- Waste disposal information (e.g., Site opening and closing year, type of Solid waste disposal (managed sites or unmanaged sites)) - Solid waste types - Quantity of waste which is generated inside the city boundary. Information from the opening year to 2016 - Quantity of waste which is generated outside the city boundary in case it is operated by the municipality itself. Information from the opening year to 2016 (In this case, the municipality's operation) - Auxiliary data of community waste inside and outside city boundary Note: No data collection of the quantity of biogas due municipality not collecting or utilizing biogas	Municipality and contractor, hired by the Municipality	- Data collection form - Related reports or documents	None
Composting	- Data of the quantity of waste in the city area for fertilizer	Municipality and contractor, hired by the Municipality	- Data collection form - Related reports or documents	None
Incineration burning	- Data of the quantity of waste in the city area - Type of incineration waste - Type of fuel for incinerator - Amount of fuel for incinerator per 1 ton of waste	- Municipality or authority who is responsible for waste collection and disposal, for example, hospital, clinic etc. - Contractor	- Survey to collect clinic data in the area - Send data collection form to hospital and contractor	None
Municipal wastewater treatment plants (WWTPs)	- Wastewater treatment plant information - Biochemical oxygen demand (BOD) - Amount of wastewater	- Municipal authority	- Data collection form - Related reports or documents	None
Wastewater from city area	- Amount of water usage in the city area	- Metropolitan Waterworks Authority or Provincial Waterworks Authority	- Send a letter and data collection form regarding water usage in the city area	The total wastewater as 80% of the water supply.
AFOLU				
Livestock	- Livestock category - Livestock population per year - Dung management Model	- District Livestock Office or Provincial Livestock Office	- Send a letter and data collection form	None
Rice planting	- Rice farm category			None

(*continued on next page*)

Table 1 (*continued*)

Activity Data	Data	Source	Data Processing	Assumptions/limitations
	- Planting area (rai)[a] - Planting times per year - Duration of planting	- District Agricultural Office or Provincial Agricultural Office	- Send a letter and data collection form	
Fertilizer usage in agricultural sector	- Plant category - Planting area (rai)[a] - Amount of chemical fertilizer usage - Quantity of chemicals usage, such as lime	- District Agricultural Office or Provincial Agricultural Office	- Send a letter and data collection form	None

[a] Rai is equal to 0.16 ha.

collecting statistical data. To carry out this study, primary and secondary data sources were used. The GHG emission inventory of the city was developed by collecting activity data, sources of data, data processing, assumptions, and limitations by category as summarized in Table 1. In the GPC, data collection is an integral part of developing and updating a GHG inventory. This includes gathering existing data, generating new data, and adapting data for inventory use. The activity data can be classified into the three scopes objectively defined to cover all relevant GHG emissions and avoid double counting. In cases where there is a lot of activity data, random sampling was applied as a representation of data. This study set representativeness at 20 percent of all data.

In the stationary energy sector, the activity data were electricity and energy consumption from primary sources. Firstly, the electricity consumption was collected in kilowatt-hour (kWh) from the Metropolitan Electricity Authority (MEA) or the Provincial Electricity Authority (PEA). Electricity consumption data were divided according to nine types of electricity users, consisting of Residential buildings, Small-sized businesses, Medium-sized businesses, Large-sized businesses, Specific businesses, Government institutions and Non-profit organizations, Water pumping for agricultural purposes, Temporary electricity, and Public electricity. Second, for energy usage activities in residential buildings, the amount of fuel combustion as liquefied petroleum gas (LPG) and charcoal usage in kilograms (kilograms) was collected by using questionnaires. Twenty percent of the sample was collected from all households by distributing questionnaires. Finally, data on energy consumption in commercial and institutional buildings and facilities were collected based on the stationary fuel combustion from activities such as portable generators, and fire or water pumps.

For on-road transportation, the data collection methods were a combination of top-down and bottom-up approaches. Top-down approaches started with fuel consumption as a proxy for travel behavior, but bottom-up approaches began with detailed activity data. Bottom-up approaches generally relied on an ASIF (Activity, Share, Intensity, Fuel) framework which relates travel activity, the mode share, energy intensity of each mode, fuel, and vehicle type, and carbon content of each fuel to total emission. In this study, the activity data on the volume of fuel sold within the city boundary were obtained from the authorities which control fuel sales at service stations, for example, Provincial Energy Office, Provincial Administrative Organization (PAO), or a fuel service station. For the travel activity, data were obtained from a public transportation authority or business owners within the city boundary.

For the waste sector, data were collected on the solid waste and wastewater generated within the city boundary, regardless of whether they were treated inside or outside the city boundary. Defining the solid waste types was first done before data collection. Waste type categories and waste collection methods vary by country. Generally, the type of solid waste includes municipal solid waste (MSW), collected by municipalities or other local authorities, sludge, industrial waste, and other waste (clinical waste and hazardous waste). Primary data were obtained from the municipalities. Although some municipalities might have hired other agencies to manage their waste disposal, the information was reported to the municipality. For the AFOLU sector, the activity data were the annual statistical data. Livestock data were obtained from the District Livestock Office or Provincial Livestock Office, and agriculture data were obtained from the District Agricultural Office or the Provincial Agricultural Office.

The GHG inventory database is an integral part of developing and updating new data annually. Activity data can be obtained from a variety of sources; thus, it is a good practice to collect activity data with an initial screening of available data sources. One major problem municipalities face in Thailand is having no data, or not having an updated GHG inventory database. Hence, creating a full-time data gathering and processing job is absolutely essential, which would lead to a continuous improvement of the data sets used in the inventory.

2.3. Calculation

The assessment of GHG emissions includes all the seven types as specified in the Kyoto Protocol, namely, carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), sulfur hexafluoride (SF_6), and nitrogen trifluoride (NF_3). Emissions data should be reported as metric tonnes of each GHG as well as CO_2 equivalents (CO_2e) which were calculated and converted to CO_2 equivalents (CO_2e) by multiplying the 100-year Global Warming Potential (GWP) coefficients of each gas, as prescribed in the Fourth Assessment Report of the IPCC. The GHG emissions (GHG_i) can be calculated from Eq (1).

$$GHG_i = \sum (A_i \times EF_i) \tag{1}$$

Activity data (A_i) is a quantitative measure of a level of activity that results in GHG emissions taking place during a given period of time (e.g., volume of gas used, kilometers driven, tonnes of solid waste sent to landfill, etc.). An emission factor (EF_i) is a measure of the mass of GHG emissions related to a unit of activity. For example, estimating GHG emissions from the use of electricity involves multiplying data on kilowatt-hours (kWh) of electricity used by the emission factor ($kgCO_2e$/kWh) for electricity depending on the technology and type of fuel used to generate the electricity.

GHG emissions from stationary energy sources are calculated by multiplying fuel combustion by the corresponding emission factors for each fuel. GHG emissions from stationary combustion energy in Scope 1 can be calculated from Eq (2). GHG emissions from the use of grid-supplied electricity in Scope 2 can be calculated from Eq (3).

$$GHG_{fuel} = \left(A_{fuel} \times EF_{fuel}\right) \times 10^{-3} \tag{2}$$

where, GHG_{fuel} is the GHG emissions from stationary combustion energy source (tCO_2e); A_{fuel} is the volume of fuel used (unit) and EF_{fuel} is the emission factor of each fuel type ($kgCO_2e$/unit) referring to the IPCC report.

$$GHG_{electricity} = \left(A_{electricity} \times EF_{electricity}\right) \times 10^{-3} \tag{3}$$

where, $GHG_{electricity}$ is the emissions from electricity consumption (tCO_2e); $A_{electricity}$ is the amount of electricity consumption (kWh) and $EF_{electricity}$ is the emission factor of electricity consumption ($kgCO_2e$/kWh) which in this study is the local emission factor referred from the Thailand Greenhouse Gas Management Organization (Public

Organization: TGO) (Thailand Greenhouse Gas Management Organization , 2017) which is equal to 0.5821 $kgCO_2e/kWh$. For the transportation sector, the GHG emission can be calculated from Eq (2) as well as stationary energy sectors. The GHG emissions from waste sector, solid waste disposal (waste management by open dump or landfill) can be calculated from Eq (4).

$$GHG_{waste} = A_{SW} \times \left\{ \left[\sum_x CH_4generated_{x,T} - R_T \right] \times (1 - R_T) \right\} \times 25 \quad (4)$$

where, GHG_{waste} is the emissions of waste management (tCO_2e); A_{SW} is the amount of solid waste (tonne); CH_4 generated is the amount of methane generated (tCH_4/year); x is the component of solid waste; T is the inventory year; R_T is recovered methane in year T and 25 is the 100-year GWP of methane. The emission from wastewater management can be calculated from Eq (5) referring to equation 8.9 in the GPC guidelines.

$$GHG_{Wastewater} = \left\{ \sum \left[\left(\frac{V_i - BOD_i}{1,000} \right) \times 0.6 \times MCF_j \right] \times 10^{-3} \right\} \times 25 \quad (5)$$

where, $GHG_{Wastewater}$ is the emission from wastewater treatment (tCO_2e); V_i is the volume of wastewater per month (m^3); BOD_i is the Biochemical Oxygen Demand (BOD) concentration (mg/L); 0.6 is the default value of maximum CH_4 producing capacity ($kgCH_4$/kg BOD); MCF_j is the methane correction factor for each treatment and handling system referring to Table 6.3 of volume 5, chapter 6: wastewater treatment and discharge (IPCC, 2006); 25 is the 100-year GWP of methane. In the agriculture sector referring to the GPC guidelines including enteric fermentation could be calculated from Eq (6) and manure management could be calculated as CH_4 and N_2O emission from Eqs (7) and (8), respectively.

$$GHG_{enteric,CH_4} = N_{(T)} \times EF_{(Enteric,T)} \times 10^{-3} \times 25 \quad (6)$$

$$GHG_{manure,CH_4} = N_{(T)} \times EF_{(T)} \times 10^{-3} \times 25 \quad (7)$$

$$GHG_{manure,N_2O} = \left[\sum_s \left[\sum_T \left(N_{(T)} \times Nex_{(T)} \times MS_{(T),(S)} \right) \right] \times EF_{(s)} \right] \times 44 \Big/ 28 \times 10^{-3} \times 298 \quad (8)$$

Where $GHG_{enteric,CH_4}$ is the CH_4 emissions from enteric fermentation (tCO_2e); T is the species or livestock category; N is the number of animals (head); $EF_{(Enteric,T)}$ is the emission factor for enteric fermentation (kg of CH_4 pe head per year); GHG_{manure,CH_4} is the CH_4 emissions from manure management (tCO_2e); $EF_{(T)}$ is the emission factor for manure management (kg of CH_4 pe head per year); GHG_{manure,N_2O} is the N_2O emissions from manure management (tCO_2e); S is the manure management system (MMS); is the annual N excretion for livestock category T (kg N per animal per year); MS is the fraction of total annual nitrogen excretion managed in MMS for each livestock category; $EF_{(s)}$ is the emission factor for direct N_2O–N emissions from MMS (kg N_2O–N per kg N in MMS); 44/28 is the conversion of N_2O–N emissions to N_2O emissions; 298 is the 100-year GWP of nitrous oxide.

Finally, GHG emissions from forestry and other of land use could be calculated from CO_2 reabsorption by above-ground biomass of stem plus of above-ground biomass of branch and leaves (Sununta et al., 2019).

2.4. Accuracy assessment

The accuracy of GHG emission accounting is affected by activity data and emission factors. Emission factors, which are the standard value used for calculations, were referred from IPCC or TGO. Therefore, only the quality of the collected data is able to affect the accuracy of the GHG emissions. Monte Carlo simulations are recommended by IPCC and were widely used in previous research such as in Lang et al. (2014), Shan et al. (2017), and Cai et al. (2019) who used them to calculate the uncertainties of activity data and emission factors in China. On the other hand, Li et al. (2017) defined the accuracy of data into eight levels and simple scoring measures which are shown in Table 2. In this study, the accuracy assessment approach followed Li et al. (2017) to calculate the accuracy of the eight municipalities because it is a simple assessment approach which the municipality can understand and evaluate by themselves. The results of accuracy assessment are important for municipalities both for GHG emission inventory establishment and for improvement (Jonas et al., 2014).

Table 2
The accuracy levels and scoring for accuracy assessment.

Accuracy	Score	Description
A	10	Yearly statistics/reports specific to city
B	9	Official/government statistics/reports/survey specific to city but not published yearly
C	8	Simple calculations from A and/or B
D	7	Processed from A and B, with uncertainty
E	6	Activity data/parameter from academic literature
F	5	Processed from a mixture of the foregoing data sources and from other sources
NE	1	Emission activities do occur in city but could “Not be Estimated” or reported because of no proper data
NENO	0	“Not Estimated” because there was “NO way to know” if the activity exists in city or not

3. Results and discussion

3.1. GHG emissions inventory data acquisition

The GHG inventory of cities must be continuously developed to upgrade its accuracy, completeness, and reliability. The data evaluated for the GHG emission allows the municipality to know the status of GHG emissions and which activities contribute significantly. This can assist the management to correctly prepare policies, identify plans, and operate according to these plans for reducing GHG emissions in line with the established goals. During the operation following the plan, data must be collected to monitor the results. After the municipality acknowledges the results, the GHG inventory becomes big data that can be applied towards a sustainable city development.

The results of this study of the city’s basic character allow us to distinguish GHG emission sources by sector and Scope 1, Scope 2, and Scope 3 emissions as shown in Table 3. All eight municipalities have no GHG emission activity in the IPPU sector because they have no industries, but land use is for small, medium, and large-sized businesses, residential buildings, government authorities, education institutions, religious institutions, facilities, agriculture, and livestock. For the stationary energy sector, most of the GHG emission activities are fuel and electricity consumption in residential buildings, businesses, and government authorities. As for the transportation sector, roads are the main transportation route in all municipalities and other transports have been operated as a pass-through route; for example, SSK has electric train transportation while NBI has water transportation that originates and terminates outside the city boundary.

In terms of waste management, it was found that all municipalities have landfills outside the city boundary. However, there are two distinct operational categories: (1) operated by the municipality itself which are SSK, YST, MKM, and BRM, and (2) operated by another municipality or a private company with a procurement process which are UBN, NBI, KKT, and LPN. Moreover, only NBI and YST municipalities have biological treatment. Most of the waste from clinics is disposed of via incineration and burning by a private company hired by the municipality. There are wastewater treatment systems in UBN, NBI, MKM, BRM, YST, and LPN operated by the municipality; but these cannot support all the wastewater generated, so some wastewater has to be drained naturally. On the other hand, the wastewater treatment of both KKT and SSK only

Table 3
Greenhouse gas emission activities within the boundary of municipalities.

Sectors and sub-sectors	Scope																						
	UBN			NBI			KKT			SSK			YST			MKM			BRM			LPN	
	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
1. STATIONARY ENERGY																								
- Residential Building	✓	✓		✓	✓		✓	✓		✓	✓		✓	✓		✓	✓		✓	✓		✓	✓	
- Commercial and institutional buildings and facilities	✓	✓		✓	✓		✓	✓		✓	✓		✓	✓		✓	✓		✓	✓		✓	✓	
- Manufacturing industries and construction		✓		✓	✓						✓													
- Energy industries	✓			✓						✓			✓											
- Energy generation supplied to the grid																								
- Agriculture, forestry, and fishing activities		✓									✓						✓							
- Non-specified sources		✓			✓			✓			✓			✓			✓			✓			✓	
- Fugitive emissions from mining, processing, storage, and transportation of coal																								
- Fugitive emissions from oil and natural gas systems																								
2. TRANSPORTATION																								
- On-road	✓		✓	✓		✓	✓		✓	✓		✓	✓		✓	✓		✓	✓		✓	✓		✓
- Railways																								
- Waterborne navigation																								
- Aviation																								
- Off-road																								
3. WASTE																								
- Disposal of solid waste generated in the city			✓			✓			✓	✓			✓			✓			✓					✓
- Disposal of solid waste generated outside the city										✓			✓			✓			✓					
- Biological treatment of waste generated in the city				✓									✓											
- Incineration and open burning of waste generated in the city			✓			✓						✓			✓			✓			✓			✓
- Wastewater generated in the city	✓			✓			✓			✓			✓			✓			✓			✓		
4. INDUSTRIAL PROCESSES AND PRODUCT USE (IPPU)																								
- Industrial processes																								
- Product use																								
5. AGRICULTURE, FORESTRY AND OTHER LAND USE (AFOLU)																								
- Livestock	✓			✓						✓														
- Land	✓			✓						✓			✓											
- Aggregate sources and non-CO_2 emission sources on land	✓			✓						✓			✓											

Table 4
GHG inventory data of municipalities in 2016.

Activity Data	Unit	UBN	NBI	KKT	SSK	YST	MKM	BRM	LPN
Area	km^2	29.04	38.90	12.475	36.66	9.71	24.14	6.00	6.00
Household	household	30,993	144,124	23,909	19,693	8,732	20,418	14,217	7,000
Population	person	77,306	255,793	45,527	41,604	20,237	53,704	27,776	12,358
- Male	person	36,039	120,948	22,188	19,578	9,846	22,801	13,118	5,662
- Female	person	41,267	134,845	23,339	22,026	10,391	30,903	14,658	6,696
STATIONARY ENERGY									
Electricity	MWh	342,118	3,490,156	99,898	184,892	24,126	316,736	67,013	168,015
Diesel	L	1,097,953	3,582,963	265,055	440,308	606,407	606,451	1,323,658	260,164
Gasoline	L	48,289	16,829	84,224	82,329	65,132	88,834	7,017	24,239
LPG	kg	6,636,548	244,132	2,196,060	3,548,626	1,576,123	3,680,592	3,339,403	1,266,051
Charcoal	kg	3,755,160	15,565,392	1,434,540	3,544,740	830	2,450,160	1,959,853	168,000
Natural gas	kg	–	4,712,171	–	1,599	1,571,925	–	–	–
fuel oil	L	–	692,247	–	–	–	–	–	–
Kerosene	L	–	7,029	–	–	–	–	1,256	–
TRANSPORTATION									
On-road									
- Diesel	L	3,033,555	476,569	29,136,332	6,447,600	24,947,349	4,678,316	8,146,308	5,629,441
- Gasoline	L	3,165,000	347,082	21,242,104	6,578,640	11,316,961	4,459,137	4,111,040	556,765
- LPG	kg	38,700,201	199,612	840,384	60,000	–	164,766	–	–
- Natural gas	kg		2,811	10,060,804	–	–	–	843,008	–
WASTE									
Landfilling of waste									
- Solid waste generated in the city	ton	30,538	110,049	19,377	16,791	4,644	15,346	14,734	6,247
- Solid waste generated outside the city	ton	–	–	–	12,007	6,547	8,743	19,472	–
Biological treatment of waste generated in the city	ton	–	99	–	–	2,989	–	–	–
Incineration of waste generated in the city	ton	12	697,286	–	156	12	250,432	338	1,017
Wastewater generated in the city	m^3	12,467,955	30,922,984	345,215	4,991,925	1,372,951	5,480,874	6,302,314	852,663
AFOLU									
Livestock									
- Cattle	cattle	62	25	–	412	–	621	–	–
- Buffalo	buffalo	42	–	–	46	–	48	–	–
- Goat	goat	–	263	–	–	–	–	–	–
- Pig	pig	–	–	–	46	–	–	–	–
- Chicken	chicken	12,960	5,134	–	3,911	–	9,370	–	–
- Duck	duck	4,356	42	–	394	–	1,812	–	–
- Goose	goose	–	–	–	–	–	26	–	–
Land									
- Rice cultivation	ha	8.32	4	–	8,304	163	–	–	–
- Other cultivation	ha	–	410	–	–	–	–	–	–

supports natural drainage. The volume of water supply within the city is collected for the calculation of the total wastewater as 80% of the water supply. This assumption is from the municipal wastewater treatment manual of the Pollution Control Department (PCD).

3.2. GHG inventory of the city

The results of GHG inventory data acquisition in 2016 are presented in Table 4. When considering the number of households per km^2, NBI has the largest number at 3,705 households per km^2. It shows that NBI has the density of residential buildings according to the character of this city, which is a suburb located next to Bangkok with the largest population among the municipalities of Thailand. However, this study does not include the non-registered population which is 6,576 persons per km^2. On the other hand, SSK has the smallest number of households and population per km^2 but has the 2nd largest area of the city boundary, with NBI having the largest area. The results of this study were compared using per capita which is the key indicator that represents a city's emission level (Yang et al., 2018). Every municipality has a population data that can be used for comparison. The details of the data collection of each sector are as follows.

3.2.1. Stationary energy

Activities in the stationary sector are the main sources of GHG emissions. Stationary energy includes electricity consumption, and energy consumption in residential, commercial, institutional, and facilities.

The data on electricity consumption are provided by the Provincial Electricity Authority, except for NBI, which are from the Metropolitan Electricity Authority. The data are the amount of electricity usage within the city boundary divided into categories, except for KKT where only the aggregate data are available. Therefore, the evaluation of GHG emission for KKT cannot indicate the amount of electricity usage within the city boundary in each sub-sector. Regarding YST and UBN, the data are the amount of electricity usage within city boundary divided into categories, but this amount includes the amount of electricity usage of another city which has an overlapping area, so the data are allocated when calculating the GHG. Data accuracy level of the data was determined to be a "B", except KKT which was "D"; YST and UBN were "C".

Referring to the data amount of annual electricity consumption per capita, NBI and LPN have quite similar values which are 13.64 and 13.60 MWh, although NBI has 21 times the number of capita than LPN. When considering the basic character of the city, LPN is a municipality located next to the Northern Region Industrial Estate, which ensures that the residential businesses have been extended support and access to labor from other areas. The number of households has been counted by the house number of civil registrations. For example, a residential business registers 1 house number for a 10 room-apartment. The results of this study show the importance of the latent population arising from migrating to work. At present, the latent population of each municipality does not have any data sources that can be referenced. The occurrence of immigration of people to work in urban areas is one of the reasons for the increase in GHG emissions. On the other hand, YST has the least annual electricity consumption of 1.19 MWh per capita. YST is a small town where most of the population travel to work outside the area while LPN is a city where the population come to work.

Table 5
GHG emissions of municipalities in 2016 (unit: tCO_2e).

Sectors and sub-sectors	Scope											
	UBN			NBI			KKT			SSK		
	1	2	3	1	2	3	1	2	3	1	2	3
1. **STATIONARY ENERGY**												
- Residential Building	30,028.09	66,316.27		133,749.90	671,095.32		11,582.32			23,101.93	34,048.63	
- Commercial and institutional buildings and facilities	5,340.52	50,539.46		1,082.92	265,064.22		1,040.41			1,383.71	31,827.71	
- Manufacturing industries and construction		75,950.25		11,809.77	1,056,090.95						38,635.63	
- Energy industries	1,154.55			32.26						0.53		
- Agriculture, forestry, and fishing activities		642.20									72.78	
- Non-specified sources		1,836.82			15,624.16			58,150.56			1,222.34	
- Electricity for public road	3,861.92				23,745.29			867.91			1,818.67	
2. **TRANSPORTATION**												
- On-road	138,848.18		9.49	2,727.68			137,028.81		15,759.48	32,607.84		
3. **WASTE**												
- Disposal of solid waste generated in the city			38,680.15			96,526.07			15,261.85	6,152.27		
- Disposal of solid waste generated outside the city										3,487.48		
- Biological treatment of waste generated in the city				0.10								
- Incineration and open burning of waste generated in the city			0.02			1,150.52						256.97
- Wastewater generated in the city	3,740.39			7,977.68			103.56			1,497.58		
4. **INDUSTRIAL PROCESSES AND PRODUCT USE**												
- Industrial processes												
- Product use												
5. **AGRICULTURE, FORESTRY AND OTHER LAND USE (AFOLU)**												
- Livestock	232.11			115.72						643.25		
- Land	31.46			15.41						3,240.05		
- Aggregate sources and non-CO_2 emission sources on land	0.02			29.75						3.98		
BASIC	**416,938.84**			**2,286,676.85**			**224,035.42**			**172,626.59**		
BASIC+	**417,211.93**			**2,286,837.72**			**239,794.90**			**176,513.87**		

Sectors and sub-sectors	Scope											
	YST			LPN			MKM			BRM		
	1	2	3	1	2	3	1	2	3	1	2	3
1. **STATIONARY ENERGY**												
- Residential Building	10,243.54	7,611.30		4,494.62	55,406.54		19,782.33	50,997.97		16,936.24	8,542.17	
- Commercial and institutional buildings and facilities	1,797.98	5,456.97		776.57	37,508.94		1,853.93	53,116.22		3,734.44	14,334.01	
- Manufacturing industries and construction		225.57						75,574.22			14,609.88	
- Energy industries	0.53											
- Agriculture, forestry, and fishing activities								648.63				
- Non-specified sources					3,148.53			1,837.50			202.03	
- Electricity for public road		549.59			1,737.27			2,197.64			1,320.43	
2. **TRANSPORTATION**												
- On-road	92,864.30		1.16	3,077.07		13,619.31	23,341.74		1.72	14,844.09		18,607.54
3. **WASTE**												
- Disposal of solid waste generated in the city	6,423.60					4,336.91	15,140.24					
- Disposal of solid waste generated outside the city	25,852.42						12,495.52					
- Biological treatment of waste generated in the city	0.51											
- Incineration and open burning of waste generated in the city			0.02			1.68			413.21			557.27
- Wastewater generated in the city	398.89			140.69			1,388.09			821.43		
4. **INDUSTRIAL PROCESSES AND PRODUCT USE**												
- Industrial processes												
- Product use												
5. **AGRICULTURE, FORESTRY AND OTHER LAND USE (AFOLU)**												
- Livestock							942.25					
- Land												
- Aggregate sources and non-CO2 emission sources on land	0.07											
BASIC	**125,572.81**			**110,628.82**			**246,291.72**			**85,600.13**		
BASIC+	**125,574.04**			**124,248.13**			**247,235.68**			**104,207.67**		

Regarding fuel usage activity in the business and government sector, diesel or gasoline are used for machines or equipment, such as a generator for a large-sized building whether it is a department store, hospital, or another type of building. In terms of household usage, both LPG and charcoal are used for cooking. Due to the large quantity of information, only 20% of all data were used for sampling. The data collection was conducted via a survey with a questionnaire and data collection form, or data accuracy, was “D”.

3.2.2. Transportation

Regarding the transportation sector, all municipalities have only on-road transportation. The data on fuel usage within the city boundary is derived from the amount of fuel sales of all service stations in the area and is considered as a worst-case scenario assuming that the sales are for vehicles used for transport only within the city. Table 4 shows the amount of fuel used for on-road transportation. It is the total fuel usage from both inside and outside the city boundaries. The data are from three sources: Provincial Energy Office (NBI), Provincial Administrative Organization (KKT, YST, LPN), and fuel service stations (UBN, MKM, BRM, SSK). The accuracy level of data from the Provincial Energy Office and Provincial Administrative Organization was evaluated as “B,” and the fuel service station was “D.” For UBN, the data from two sources were assessed as “D.” The transboundary journeys occurring outside the city boundary were determined as “D.” The municipalities UBN, KKT, YST, MKM, BRM, and LPN have the survey data. NBI and SSK were not surveyed due to a lack of sufficient human resources and time to survey during the study period. Therefore, the data accuracy was marked “NE”.

NBI has the lowest fuel usage by population; diesel and gasoline are 2 and 1 L/capita respectively while LPG is 1 kg/capita. It shows that people in the city mainly use public transportation. However, the public transportation system in NBI is a pass-through route, whether it is a railway of an electric train, water, or on-road. Other municipalities use more diesel than gasoline in accordance with the vehicles which are used mainly for business purposes or long-distance trips. The most fuel usage of diesel and gasoline per population is YST at 1,233 L/capita and 559 L/capita, respectively. On the other hand, UBN uses more LPG than any other fuel. This study found that UBN has 3 LPG service stations and one of them is a large station which sold 32,000,000 kg in 2016. Nevertheless, it supplies businesses within the city boundary, especially the taxi service, which is an important business in UBN. Although KKT is a city near Bangkok, the main public transportation system is on-road and there is no electric train system like NBI. Therefore, the amount of fuel usage of the on-road per population is 2nd after YST. Moreover, this municipality has the largest amount of natural gas usage at 221 kg/capita.

GHG emissions from this sector are mostly from the road segment due to the use of private cars. Most residents of municipalities do not use public transport to travel. This may be due to a lack of adequate public transport to meet local needs. Many municipalities, for example, YST or BRM, have campaigned for people to use bicycles in their daily commute. However, there are many factors that make it inconvenient to travel by bicycle, such as lack of bicycle lanes and safety. Many municipalities have a policy to develop public transport. For example, UBN has a bus transportation system project in municipal areas aiming to solve the problem of traffic congestion and reduce greenhouse gas emissions.

3.2.3. Waste

The GPC divided the waste sector into four sub-sectors. The scope concept was applied to this sector, with wastes generated and treated within the city boundary which was Scope 1. If generated within the city but treated outside of the city boundary, it was Scope 3. The data of waste sector were collected from municipalities because it was an activity in operation control. For the landfill of waste, the accuracy of data was assessed as “B”, except KKT which was assessed as “D” because the data were from the contracting company. In the past, KKT monitored data of landfill waste in terms of budget, not the amount of waste; therefore, the data obtained have an uncertainty. For NBI and YST which have biological treatment of waste generated in the city, the amount of waste is obtained from the monthly report. The data has uncertainty arising from the weighing sampling, therefore, the data accuracy was assessed as “D.” Incineration of waste is used for infectious waste. The amount of infectious waste was surveyed from hospitals and clinics within the city boundary; the accuracy level was assessed as “D”. However, for NBI which obtained data from the Provincial Administrative Organization employed by the municipality to operate, the accuracy level was assessed as “B.” The accuracy of wastewater is “B” for municipalities having a sewage system in the city. It is “C” for municipalities that do not have a sewage system, therefore, the volume of wastewater is calculated as 80 percent of the amount of tap water used and discharged into natural water sources.

When considering the amount of waste into landfills and wastewater generated within the city boundary, NBI was found to be the highest with 110,049 tonnes of waste to landfills and 30,922,984 m^3 of wastewater followed by UBN, KKT, SSK, MKM, BRM, LPN, and YST respectively. NBI is the municipality with the largest area and being close to Bangkok, it grows faster than the other municipalities, whether it be a large number of households, hidden populations arising from people outside the area commuting to work in the area, businesses, or activities that directly vary with the amount of waste and wastewater generated within the city. On the other hand, although LPN and BRM have the least area, waste and wastewater per 1 km^2 caused by the area’s emission activity are greater than YST. BRM has a total of 2,370 households/km^2 while LPN has a total of 1,167 households/km^2, and YST has a total of 899 households/km^2. The most common solid waste management system is sanitary landfilling, except for KKT which is open dumping. Consequently, waste management system is a crucially important subject that presents challenges for municipalities. They have a target to reduce the amount of waste which requires public awareness and participation, for example, through the implementation of 3R (reduce, reuse, recycle) programs for waste management. The result of data collection showed that YST can reduce waste being dumped to the landfill by about 30% of the total waste collected. Food waste is disposed of by biological treatment.

If we consider the waste per capita, BRM had the highest value at 0.53 tonnes of waste to landfill and 227 m^3 of wastewater followed by LPN, NBI, KKT, SSK, UBN, MKM, and YST, respectively. Although BRM has the least area and is the third least populated municipality, it is a tourist destination with football stadiums, racing tracks, and major tourist attractions. Moreover, BRM is considered the provincial center even though those locations are outside the BRM boundaries attracting a lot of tourists to visit this area. This affects the amount of waste and wastewater generated unlike YST, where most of the waste and wastewater will come from households, with only small and medium-sized businesses in the area.

3.2.4. Agriculture, forestry, and other land use (AFOLU)

Livestock is for personal usage, not for a business activity such as a livestock farm in the city boundary; the same applies to agricultural areas which are a family run businesses, and not large-sized businesses. These data have been updated annually by the District Livestock Office and the District Agricultural Office. The accuracy level was assessed as “D” because the data does not have a validation process. KKT, BRM, and LPN have no activities in the AFOLU sector, as they are municipalities with only a residential and commercial nature. For UBN, NBI, and SSK, there are activities related to livestock and agriculture. NBI is next to Bangkok, but some people in the area have livestock and agricultural activities. For YST, there is rice cultivation in 163 ha, accounting for 17% of the total area.

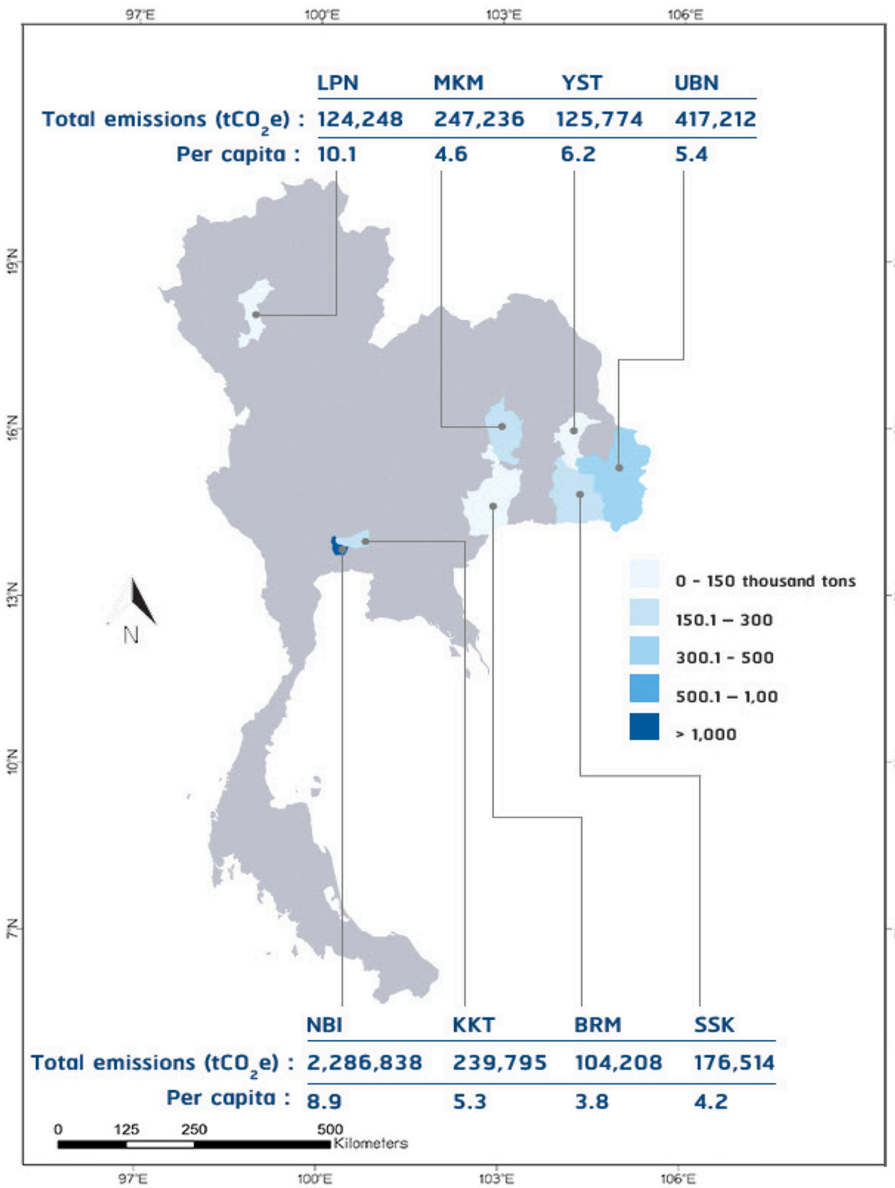

Fig. 2. Amount of GHG emission from all eight municipalities in 2016.

3.3. GHG emissions of cities in 2016

Table 5 summarizes the results of the GHG emissions. The total GHG emission of each municipality is shown by scope, BASIC and BASIC+. Most of the municipalities in this study have the highest GHG emissions in Scope 2 including NBI (89%), LPN (79%), MKM (75%) SSK (61%), and UBN (48%). The total GHG emissions of eight municipalities, in order from highest to lowest, are as follows: NBI, UBN, MKM, KKT, SSK, YST, LPN, and BRM.

GHG emissions per capita have been focused because they are basic values that are easily understood and compared. From the results of the study, it was found that the municipality with the most GHG emissions were not those with the most area and population. In the same way, the municipality with the least area and population may not have the highest GHG emissions. The GHG emissions per capita were 3.8–10.1 tCO_2e/capita. BRM with a population of 27,776 has the least per capita GHG emissions (shown in Fig. 2). The activities that have significance in GHG emissions for BRM are energy usage in the on-road transportation sector (32%), electricity usage in the business sector (26%), fuel-burning in residential buildings (16%), and landfill disposal operated by the municipality (11%). However, the amount of GHG emissions for BRM in 2016 was 104,208 tCO_2e which is not the lowest number compared with the other municipalities in this study. The municipality which has the largest per capita GHG emissions in 2016 is LPN where there is a registered population of 12,358 and 7,000 households, the lowest compared with the other municipalities. The proportion of GHG emissions from electricity usage in the business sector is 58% of all GHG emissions. This is followed by GHG emissions from electricity usage in residential buildings contributing 29%.

The evaluation of the GHG emissions from all eight municipalities categorized by activity in this study are shown in Fig. 3. The GHG emissions from residential fuel combustion are from 0.3 to 0.6 tCO_2e/capita. Several municipalities have similarly high numbers (BRM, SSK) and the lowest number is from KKT, which is a residential city, but its population works outside the city. Therefore, fuel usage in residential buildings is lower than in the other municipalities. GHG emissions from business fuel combustion are from 0.0 to 0.1 tCO_2e/capita. GHG emissions from residential electricity consumption vary between 0.3 and 4.5 tCO_2e/capita; the lowest number is from BRM and the highest from LPN. LPN is the highest because the residences in LPN are small and cheap

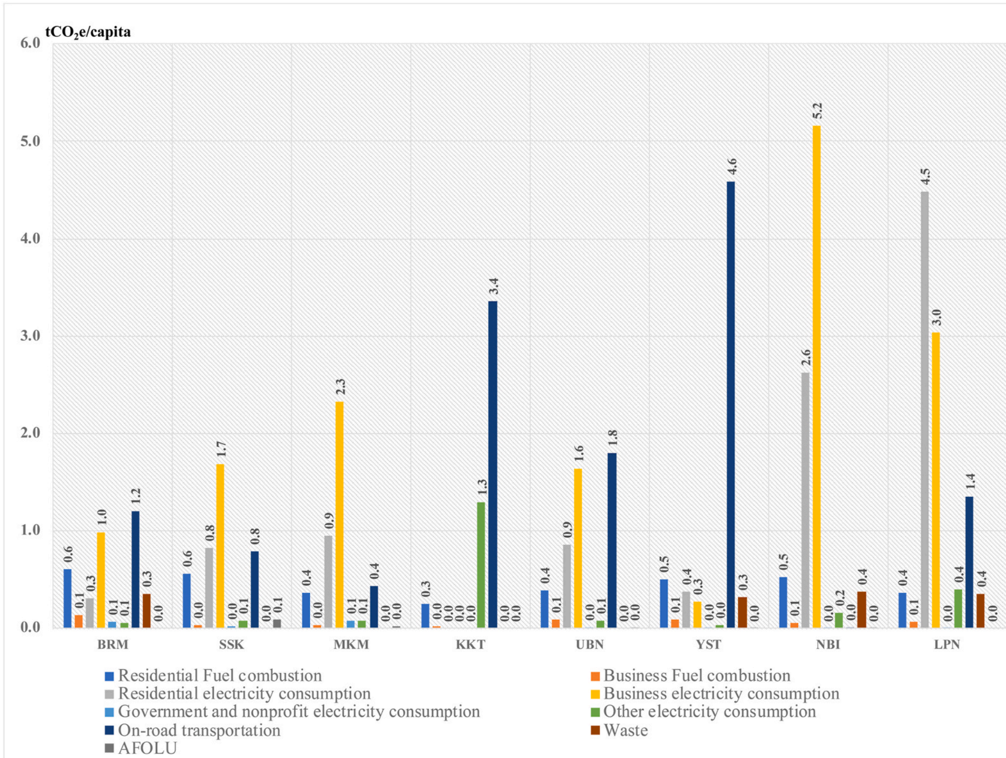

Fig. 3. Amount of GHG emission of all eight municipalities in 2016 categorized by activity.

rental rooms to support labor from the Northern Region Industrial Estate. In general, the homeowners have not changed the type of electricity from residential to business with the Provincial Electricity Authority. Therefore, the municipality should inform the homeowner to change the type of electricity use which will increase the accuracy of data and planning to reduce GHG emissions correctly with the activity. The GHG emissions from business electricity consumption are from 0.3 to 5.2 tCO_2e/capita. The highest number is for NBI which has large-sized businesses. GHG emissions from government and nonprofit organizations' electricity consumption are in the range of 0.0–0.1 tCO_2e/capita which is quite small compared with other categories of electricity usage. Lastly, GHG emissions from other electricity consumption are from a combination of electricity usage in the agricultural sector, public electricity, and temporary electricity; they vary between 0.1 and 0.4 tCO_2e/capita, except for KKT which is 1.3 tCO_2e/capita. However, it is the total GHG emissions from all categories of electricity usage which cannot be classified like the other seven municipalities. GHG emissions from on-road transportation vary between 0.0 and 4.6 tCO_2e/capita. The highest number is for YST and the lowest for NBI, which has the largest public transportation system compared with other municipalities in this study. Referring to the GHG emissions in the waste management sector which vary from 0.2 to 0.5 tCO_2e/capita, the highest is UBN and the lowest from SSK. Lastly, the GHG emissions from AFOLU are from 0.0 to 0.1 tCO_2e/capita; this activity has the lowest or no significance to GHG emissions of the municipality.

The decision-maker can apply results to achieve the mitigation targets and plans. The municipalities should be focusing on activities that have significant GHG emissions; they can select appropriate activities and technologies with possibilities of reducing GHG emissions. For example, NBI has 89 percent of total GHG emissions from electricity consumption. Therefore, policy makers can design, implement, monitor, and improve planning and instruments for energy efficiency improvements such as switching to LED bulbs, using solar energy instead of fossil fuels, and encouraging the construction of energy-saving buildings. GHG inventories and emissions of cities can effectively enhance understanding of the essential relationships between spatial organizations of cities and their energy usage and make it possible for before-after comparisons. Thailand and other developing countries have limitations in terms of budget, technology, and personnel. As a result, focusing on reducing GHG emissions in significant activities is essential to have a policy and action plan.

3.4. *The development of GHG inventory for municipalities in Thailand*

The municipality is the key to driving the city towards sustainable development; it may not be possible to choose whether the city will develop according to sustainable approaches or not, but the only way is to apply sustainable city development guidelines. Changing from the old system to a sustainable development system is a huge challenge for the municipality because there are many shortcomings like accessing internal information, personnel development, and educating and understanding the people.

This study found that the development of GHG inventory in Thailand has many limitations. The first limitation is the commitment of the city administration affecting the understanding of the population and all sectors of the city, who should know their roles and duties in becoming a part of sustainable development. If the core is not strong, it is difficult to drive the city to develop and achieve the target. Another limitation is that some municipalities still lack clear policies emanating from their administrators as serious importance has not been given to the implementation of the evaluation of GHG emissions in the development of the city. The results of the study showed that municipalities in which the administrator gives priority to GHG emissions reduction will influence the municipality's team to work effectively; this is different from the municipality where the administrator has not seen the importance of the implementation.

The second limitation is the data acquisition, resulting in the lack of accurate estimates of the city's GHG emissions. The reliability of the inventory information is relatively small and there is incompleteness of the inventory information. The primary data on GHG emissions

Table 6
The accuracy level of GHG inventory during 2016.

	UBN		NBI		KKT		SSK		YST		MKM		BRM		LPN	
	Level	Accuracy	Level	Accuracy	Level	Accuracy	Level	Accuracy	Level	Accuracy	Level	Accuracy	Level	Accuracy	Level	Accuracy
6. STATIONARY ENERGY																
- Electricity	C	8	B	9	D	7	B	9	C	8	B	9	B	9	B	9
- Diesel	D	7	D	7	D	7	D	7	D	7	D	7	D	7	D	7
- Gasoline	D	7	D	7	D	7	D	7	D	7	D	7	D	7	D	7
- LPG	D	7	D	7	D	7	D	7	D	7	D	7	D	7	D	7
- Charcoal	D	7	D	7	D	7	D	7	D	7	D	7	D	7	D	7
- Natural gas			D	7			D	7	D	7						
- fuel oil			D	7												
- Kerosene			D	7									D	7		
7. TRANSPORTATION																
On-road																
- Diesel	D	7	B	9	B	9	D	7	B	9	D	7	D	7	B	9
- Gasoline	D	7	B	9	B	9	D	7	B	9	D	7	D	7	B	9
- LPG	D	7	B	9	B	9	D	7			D	7				
- Natural gas			B	9	B	9							D	7		
- Transboundary journeys occurring outside the city boundary	D	7	NE	1	D	7	NE	1	D	7	D	7	D	7	D	7
8. WASTE																
Land fill of waste																
- Solid waste generated in the city	B	9	B	9	D	7	B	9	B	9	B	9	B	9	B	9
- Solid waste generated outside the city							B	9	B	9	B	9	B	9		
- Biological treatment of waste generated in the city			D	7					D	7						
- Incineration of waste generated in the city	D	7	B	9	D	7	D	7	D	7	D	7	D	7	D	7
- Wastewater generated in the city	C	8	B	9	C	8	C	8	B	9	D	7	B	9	B	9
9. AFOLU																
- Livestock	D	7	D	7			D	7			D	7				
- Land	D	7	D	7			D	7	D	7						

activities are from many sectors where the data collection may not be in the form that can directly be used for the evaluation. For example, the amount of fuel (diesel, gasoline, etc.) consumption is in terms of cost (in Thai baht) but the data which will be used is in number of liters; data on the amount of waste is in the number of trips of the garbage trucks, but the data for evaluation is GHG emissions in kilograms or tonnes. Some sectors do not have data, or the data are not updated, or the data in the same activity from multiple sources do not match. However, in the current implementation, there has been little cooperation from the relevant authorities for acquiring data from various sectors. This may be due to the lack of understanding of what the information is used for, what the benefit is, and how the sectors are involved.

The third limitation is that the government does not have a clear policy towards the various agencies to support the preparation of greenhouse gas inventory for municipalities. Consequently, the municipalities must request information from various departments by themselves; sometimes, the agencies do not cooperate.

Table 6 shows the quality of the data. All activity data and all municipalities do not obtain data from yearly statistics and reports specific to the city in which case the accuracy levels would be “A". In all eight municipalities, most of the data were obtained from surveys for which accuracy levels were “D". The best accuracy levels were “B" in which municipalities must request data from the authorities every year, such as electricity consumption from the Provincial Electricity Authority. In fact, each branch of the Provincial Electricity Authority has data of several municipalities. All municipalities must request information to be used in their GHG assessments. Therefore, to increase the level of accuracy of data, the Provincial Electricity Authority should provide a yearly report on the electricity consumption of every municipality. The data obtained should be based on calculation and allocation in the same way to avoid double-counting.

The GHG inventory should be an important data set for decision-makers for the sustainable development of the city. This data allows the management to specify the policy, plan, and action plan of the city. This study found that the data for GHG inventory at the municipality level can be collected as a routine job because the municipality normally collects the related data anyway. However, additional data may need to be collected, or some data may have to be collected with a different approach in order to obtain GHG data covering all activities within the city boundary.

This study found that the operation of a municipality in Thailand is related to many areas of data collection according to the contextual duties of each department or authority. This study found that each authority collects data in reference to duties and responsibilities. In case that the municipality integrates data and compiles a data inventory center, the information management system will be created as big data that benefits the city administration, whether it is budget-saving, time-saving and/or accurate operations. Nevertheless, the governing activities to reduce GHG emissions in a municipality should be performed based on these data. The correct GHG inventory acquisition leads to accurate calculation of GHG emissions data that can identify the activities which have significant GHG emissions. Therefore, the city management can decide a budget for executing governing activities or projects related to city development with GHG emissions reduction in mind. In brief, municipalities in Thailand must adjust themselves to administer the city by making decisions based on data for the sustainable development of the city.

4. Conclusions

This study focuses on the preparation of GHG inventories for municipalities in Thailand using the GPC guidelines. The results of the study will allow municipalities to know where data on each GHG emission source can be gathered and what data formats can be used in the assessment. In the first year of data collection, the data may not have completeness and accuracy, but it can also be used as a guideline for updating data in the following years by increasing the level of data quality, as well as assessing greenhouse gases based on five key principles: Relevance, Completeness, Consistency, Accuracy, and Transparency.

Therefore, every municipality will be able to define boundaries, identify sources of GHG emissions, collect data from each emission source, gather emission factors, and analyze GHG emissions. As a result, the municipality can continually develop a GHG database by creating a routine procedure and make policies and plans that reflect the goals of the municipality and the country. The approaches from this study can be an example for other developing countries with smaller forms of government. In the past, GHG inventories were prepared on a top-down basis. If the national-level data is scaled down to the level of local government, it cannot clearly reflect the amount of GHG emissions and policies to reduce the city’s GHG emissions. Therefore, the bottom-up data preparation or generating information at the municipal level is important to support cities to reduce their GHG emissions.

The annual GHG emissions report provides municipality level information on GHG emissions, which can be used as a comparison of municipalities and monitoring progress towards emission reduction targets. A key issue is that the development of GHG emissions report is dependent on the quality and availability of municipality level inventory database in Thailand. The availability of data, such as fuel consumption, electricity consumption, road transportation, agricultural activity and waste management, all depend heavily on the data sources. Thus, the municipality should develop the GHG inventories database to be an efficient routine job and make timely communication of the GHG inventories results to decision-makers and citizens, as the ultimate goal of emission inventories is to support the emission reduction actions.

One of the main challenges in developing a GHG inventory of municipalities is changing from the old management system to a sustainable development system. Some of the challenges facing this move are access to internal information, personnel development, educating and understanding the people in the area in all sectors, and lack of solid support from the government, whether in terms of policy, rules, and/or regulations. The important issue is to continuously develop a GHG inventory to be considered as big data as protocol to develop the city into a sustainable city in the future.

A poor database is caused by a lack of proper collection approach, storage, and utilization of the data. This study tried to gather the approaches of obtaining information on each GHG emission source as a guideline for the municipality. If these approaches are designed as a platform, collecting data for municipalities can be systematic. This can include converting data from hard copy into a storage system that can be easily retrieved and updated, and can then be applied to other cities both in Thailand and abroad. In addition, if the data format is developed to be open data, it will benefit from the sharing of data and the data being more useful both at the municipal level in Thailand, and in other developing countries. The results of this study can lead to further research to develop an online platform for collection and analysis of data called “EcoCitOpia”.

CRediT authorship contribution statement

Ratchayuda Kongboon: Conceptualization, Methodology, Resources, Data curation, Writing – original draft, preparation. **Shabbir H. Gheewala:** Writing – review & editing. **Sate Sampattagul:** Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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