ESTIMATING METHANE EMISSIONS FROM MUNICIPAL SOLID WASTE LANDFILL CASE STUDY FOR NAM SON LANDFILL, HANOI, VIETNAM

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DECLARATION

I certify that this thesis does not incorporate without acknowledgment any material previously submitted for a degree or diploma at any university; and that to the best of my knowledge and belief it does not contain any material previously published or written by another person except where due reference is made in the text.

Nguyen Thi Phuong Hoa

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ABBREVIATIONS

Afvalzorg	Multiphase landfill gas generation and emission model
CBA	Cost-Benefit Analysis
CH_4	Methane
CO_2	Carbon dioxide
DONRE	Department of Natural Resources and Environment
EIA	Environmental Impact Assessment
ERA	Environmental Risk Assessment
FOD	First-Order Decay
GasSim	Gas Law Model
GHGs	Green House Gases
IPCC	Intergovernmental Panel on Climate Change
ISO	The International Standardization Organization
Land GEM	Landfill Gas Emissions Model
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LFG	Landfill Gas
MCF	Methane Correction Factor
MFA	Material Flow Analysis
MONRE	Ministry of Natural Resources and Environment
MSW	Municipal Solid Waste
NEERI	National Environmental Engineering Research Institute
SETAC	The Society of Environmental Toxicology and Chemistry
UN-FCCC	United Nations Framework Convention on Climate Change
USEPA	The US Environmental Protection Agency

ABSTRACT

Greenhouse gas (GHG) emissions associated with solid waste management practices are one of the critical concerns in rapidly developing cities. Landfill sites throughout the world are considered a primary source of GHG emissions, contributing to global warming and climate change. This is due to the existence of methane (CH_4) and carbon dioxide (CO_2) within landfill gases. The aim of this research is to examine scenarios for municipal solid waste (MSW) management in Hanoi to enable progression towards a low carbon economy.

Life Cycle Assessment (LCA) is a method used to evaluate the potential of environmental impacts of landfill regarding CH_4 emissions. Based on the framework of LCA, scenarios for MSW management in Hanoi were developed to express possible options for the future management. Potential for CH_4 emissions and the variation in generation of CH_4 with time for emission inventory in the Nam Son Landfill site in Hanoi, Vietnam were modelled by using two accounting models: the IPCC Default and Triangular model.

Five scenarios were designed (S0, S1, S2, S3, S4). The baseline scenario describes the current “Business as usual”, and the rest of the scenarios presented alternative options to explore the potential reduction of CH_4 emissions through composting, recycling, and gas capture. The results obtained from the calculation by using two accounting models for all scenarios confirm that a combination of composting, recycling and flaring gas is the best solution to improvement of the existing MSW management in Hanoi by reducing CH_4 emissions by 83% in comparison to the “Business as usual” scenario. In addition, the emission process of the Nam Son Landfill site in scenario S4 will reach a peak in 2009, the age of Landfill will extend to 2030.

CHAPTER 1 INTRODUCTION

In this Chapter, there are six substantial parts, including (1) Greenhouse gas emissions and waste management, (2) research objectives, (3) research questions, (4) study area, (5) significance of study, and (6) Structure of study.

1.1 Greenhouse gas emissions and waste management

Global warming and climate change is the most significant threat facing the world today. This is due to the trapping of enormous quantities of GHG in the atmosphere that leads to an increase in ambient temperatures of the earth (Kumar et al. 2004a). There is a strong consensus within the scientific community, according to Cook et al. (2016), that human activities are changing the climate of the earth over the most recent 50 years, by emitting higher concentrations of GHGs, primarily CO_2 and CH_4. Eggleston et al. (2006) reported that CH_4 are considered as one of the most important GHGs, although CH_4 emissions is far less than CO_2 emissions. Global warming potential of CH_4, as explained by Solomon et al. (2007), is more than 21 times CO_2 because of its more than 21 times better at trapping heat in the atmosphere. So far, atmospheric CH_4 concentration has been increasing by 1 to 2% per year (Eggleston et al. 2006).

Among the efforts to respond to climate change, and to reduce its consequences, identifying measures to reduce GHGs emissions and promoting long-term storage of carbon in soil and forests are the leading targets. Lu et al. (2008) argued that alternative options for MSW management have provided many valuable opportunities, directly or indirectly because the waste sector is also the source of significant GHGs emissions. So far, scientists have recognized the importance of quantitative assessment for GHGs emission from waste management. As the Intergovernmental Panel on Climate Change (IPCC 2015) put it, GHG emissions associated with the solid waste sector contribute 3%

of total global GHGs emissions, and particularly, CH_4 from landfill site are the largest source of GHGs. Other primary sources of global GHG emissions are energy-related production, accounting for 65% (mainly from electricity and heat: 28%, transportation: 12%, and manufacturing: 12%), agriculture (14%), land-use change and forestry (12%), and others (6%) (Eggleston et al. 2006).

Many research attempts were made to assess the potential of MSW management systems to mitigate climate change over years. The US Environmental Protection Agency (USEPA) carried out an investigation of GHG emissions throughout the United States in 2004 (USEPA 2006). They reported that landfill site was the largest source of CH_4 emissions in the United States, accounting for about 90% of total CH_4 emissions from the waste sector and approximately 25% of annual CH_4 emission of the country. Scientists in the European Union (EU) also recognized the significant effects of GHGs emitted from solid waste sector on global warming and climate change. GHG emissions in Europe mostly come from CH_4 released from landfill sites with about one-third of CH_4 emissions being attributed to this source (Pikoń & Gaska 2010).

Few studies have introduced GHG emissions into the management framework of waste sector. However, these studies are lacking consideration to gain insight into how the fate and operation of waste management system influences GHG emissions. This leads to difficulties in reflecting the impacts of the entire process that serves to improve the existing solid waste management, to combat climate change and further instituting environmentally sustainable strategies (Lu et al. 2008). In addition, another challenge of previous research that was witnessed in many developing countries is the limitation and absence of national statistics on solid waste activity, leading to difficulties in quantifying and large uncertainty in estimating GHG emissions (Kumar et al. (2004a); Kumar (2016)).

As McElwee et al. (2010) put it, Vietnam is among the countries that are hardest hit by the change in climate and the rise of sea level. Recently, to contribute to global efforts in responding to climate change, the Vietnamese government has announced national development strategies to enable progression towards low carbon economy. GHGs emissions associated with MSW management are regarded as one of the critical concerns in this regard. Spies et al. (2010) pointed out that developing countries have potential to mitigate national emissions by around 5% and eventually up to 10% when integrated solid waste management is implemented. So far, in Vietnam, there are several studies on GHG emissions from solid waste management, however there has not been such specific studies on simulating the GHGs emission process of solid waste management or landfill. Difficulties in adopting appropriate approaches has led to difficulties in establishing the targets of a GHG inventory and reduction in the waste sector.

Therefore, this study intends provide a comprehensive, transparent, and scientific understanding impacts of GHG emissions caused by solid waste-related activity in the large city of Hanoi, Vietnam. This is significant, contributing to national strategies to reduce GHGs emissions and to combat climate change. Assessment of GHG emissions from landfill sites contributes to evaluating the state of long-term stabilization that may give guideline on appropriate operations, maintenance of landfill sites for environmental safety.

1.2 Research objectives

The goal of this study is to take a holistic method at characterising GHG emissions associated with MSW management in Hanoi, Vietnam, applying for quantitative evaluation of CH_4 emissions from the Nam Son Landfill site as a case study. In addition, the research is to examine alternative solutions to investigate the potential reduction of GHG emissions and to improve the existing MSW management. This supports solid waste managers involved with decision making for Hanoi, as well as national policy makers to reduce GHGs emissions and to combat climate change. The study will focus on objectives as follows:

(1) Review existing CH_4 emissions accounting methods.

(2) Review the current situation of MSW management in Hanoi, Vietnam.

(3) Develop scenarios to reduce CH_4 emissions and emission factors for the different waste management processes.

(4) Quantify CH_4 emissions from Nam Son Landfill in Hanoi, Vietnam.

1.3 Research questions

Hanoi is a rapidly developing city in Vietnam. Daily generation of thousands of tonnes of solid waste is an inevitable consequence of the socio-economic growth and the rapid urbanization and industrialization of the city. The quantity of solid waste is projected to increase significantly in the coming years, creating many challenges regarding solid waste management for Hanoi. Moreover, due to the limitation of appropriate treatment methods, the lack of suitable facilities for collection and transportation, and the lack of community involvement in separation at source, the existing solid waste management system is going through a critical phase. Landfill is currently the most popular treatment in Hanoi, and is regarded as a primary source of environmental impacts, and a source of GHG emissions, causing global warming and climate change. Identification of alternatives for solid waste management towards the low carbon economy is essential for Hanoi in order for Vietnam to help meet its obligations to reduce GHG emissions. Therefore, the research attempts to answer the following questions:

What is the best MSW management for Hanoi to reduce GHG emissions?

Like other governments, under the framework of UNFCCC, required to submit annual inventories of GHG emissions from all fields, the Vietnamese Government carried out a national inventory of GHG emissions under the guidelines provided by IPCC for reporting. Some studies in Vietnam so far have limited their estimation of total emissions of GHG associated with solid waste management. There has not been such specific studies on simulating the GHGs emission process of solid waste management systems over time. In addition, the lack of available data presents difficulties in adopting an appropriate approach, leading to difficulties in establishing the targets of GHG inventory and reduction in the waste sector. Therefore, the followed sub-questions to answer are:

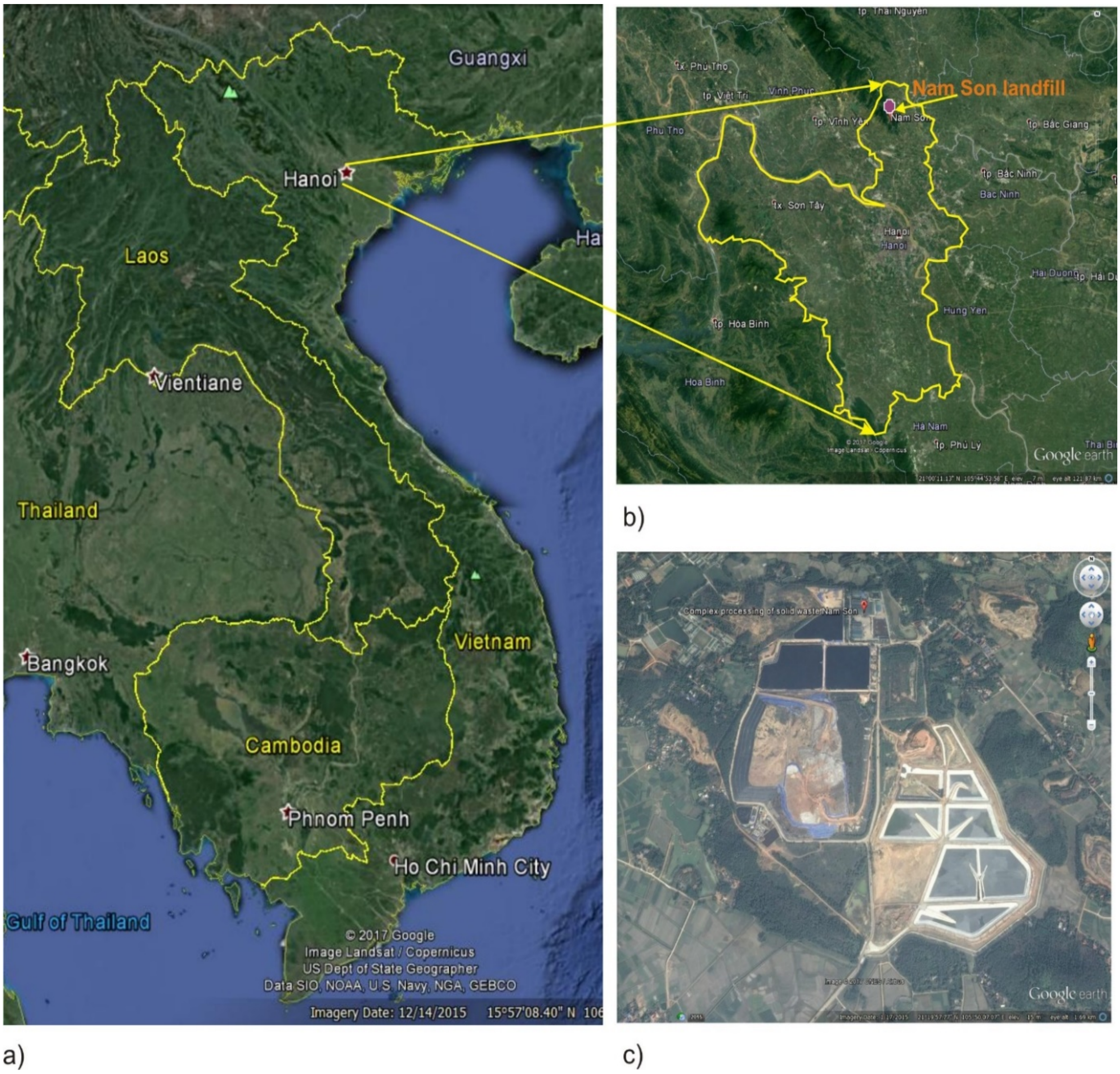
- What are the best methods of accounting CH_4 emissions from Nam Son Landfill site, Hanoi, Vietnam?
- What are GHG outputs for a range of scenarios of MSW management in Hanoi?

1.4 Study area

Nam Son landfill is located in three communes of the Soc Son district (Nam Son, Hong Ky and Bac Son) in Hanoi City, Vietnam. The terrain of the landfill site is fairly flat (20 - 30 m). The site is situated in the rainy tropical monsoon climate zone, with the yearly average temperature being 23.4ºC and average annual rainfall being 1,690 mm (Nguyen & Nguyen 2017).

The landfill site was established and started operating in 1999 and is planned to close by 2020. The landfill has a total land area of 73.5 ha, in which 13.5 ha is for the landfill Phase 1 which has been partially operated since 1999. The remaining 60 ha is for landfill Phase 2, starting operating from 2004 to 2020. The designed capacity of the landfill site in Phase 2 is 20 million tonnes of waste. The site will treat the solid waste of Hanoi in a sanitary and environmentally sound and cost-effective manner over the period of around 20 years.

Currently, the volume of garbage accepted by the landfill site is greater than 4,000 tonnes/day. Garbage is composed of many components, including 53.8% of organic waste, 6.5% of paper, 13.6% of plastic, 0.9% of metal, 1.9% of glass, and the rest of others (MONRE 2011).



a) Map of Vietnam, b) Hanoi area, c) Nam Son landfill area *(Source: Google Earth, 2017)*

Figure 1. 1 Location of the Nam Son Landfill site in Hanoi, Vietnam

1.5 Significance of study

The most crucial contribution emerging from this study is helping fulfil the development of a holistic and scientific approach at characterising GHG emissions from landfill site, particularly providing a foundation for the development of holistic landfill Life Cycle Assessment studies for Vietnam where high quality data is presently lacking. Further, by developing and examining alternative emission scenarios, the research will provide valuable alternative solutions to the planning and strategy development for solid waste management system. This will optimise the existing issues from MSW management systems and reduce GHG emissions to help combat climate change. As a result, findings may support to better decision making for Hanoi City. Furthermore, the findings of this study might serve as a valuable resource for Vietnam in GHG emission inventories, and for other countries with similar situations, including absence of observation data of landfill sites.

1.6 Structure of study

The thesis is organised into six chapters, starting with introduction that gives an overall information about the study to identify the gap of issue in the study area. The structure of the thesis is presented in detail as follows.

Chapter 2 is the Literature Review. This review presents the characteristics of the process of LFG production. The composition of LFG, how it is produced, and the conditions of landfill site that affect its production. It also provides an overview of LCA used as the main method to assess environmental impacts of LFG emissions. Finally, the chapter evaluates and compares between mathematic models to select the proper calculation methods for Life Cycle Inventory (LCI) for landfill sites for the local context.

Chapter 3 is a description of Methodology and Materials. Phases of LCA are analysed and applied in order to identify the scope and boundary system of the study. Under the LCA theoretical basis, this chapter also presents the scenario development, two accounting models, and selection of model parameters for Nam Son landfill site.

Chapter 4 presents the existing MSW management system in Hanoi, focussing on summarizing generation, characteristics and management of MSW. A range of scenarios is developed to investigate changes to the current MSW management. Which can lead to possible lower GHG emissions for Hanoi.

Chapter 5 presents Results and Discussion. Selection of input parameters for accounting models is made under the local situation of the study area. The findings are presented by the potential CH_4 emissions and the process of emissions that results from analysing and comparing every single scenario.

Finally, Chapter 6 summarized the principal findings of the research and recommendation for MSW in Hanoi, Vietnam.

CHAPTER 2 LITERATURE REVIEW

This chapter includes four main sub-sections. They are (1) Greenhouse gas generation from landfill sites, (2) Life Cycle Assessment approach, and (3) Emissions inventory models.

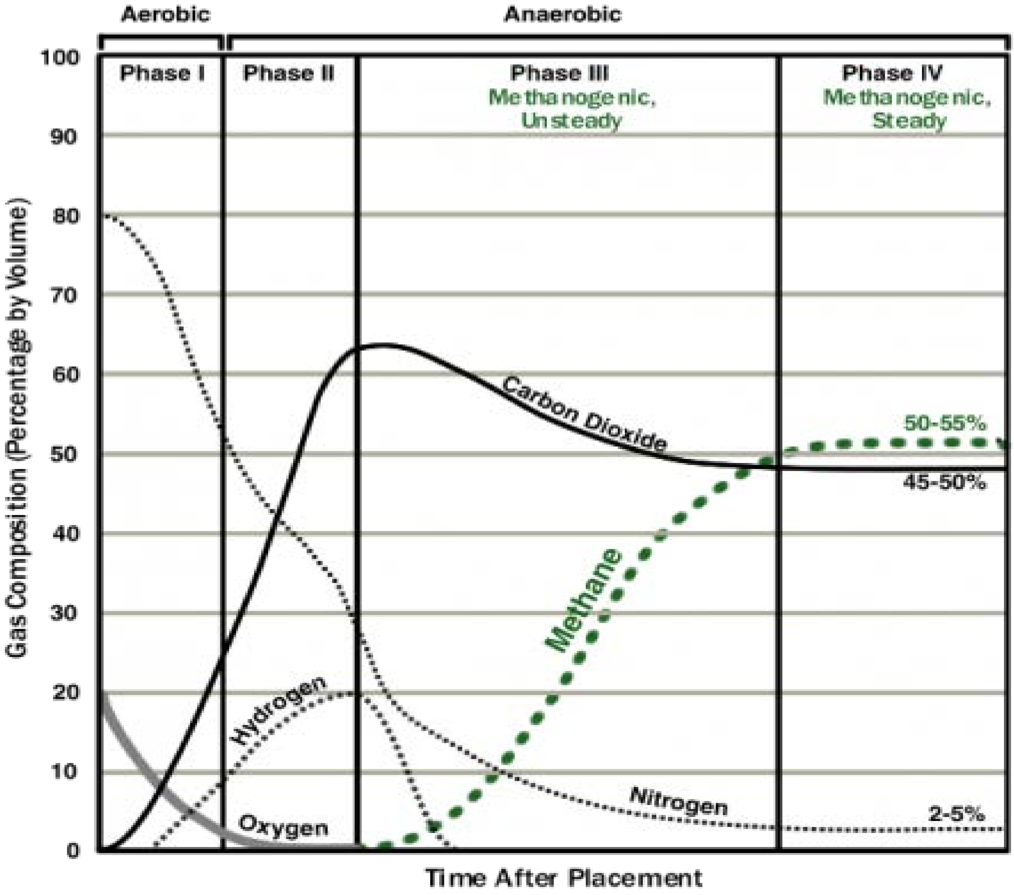
2.1 Greenhouse Gas generation from landfill

A landfill site is the place for the disposal of MSW by burial. Landfill is the oldest form of MSW treatment that continues in many locations around the world (Nabavi-Pelesaraei et al. 2017). Disposal of solid waste by burial in landfill sites generates LFG due to waste decay. When waste is buried, the organic fraction is decomposed and converted into LFG (Oonk 2010). Landfill is regarded as one of the primary sources of GHG emissions (Oonk 2010). Landfill gas is widely known to comprise about 50-60% of CH_4, and the remainder primarily CO_2 and other compounds in lesser amounts (Bogner and Matthews (2003); Scheutz et al. (2009); Atabi, Ehyaei and Ahmadi (2014)). CH_4 and CO_2, according to Atabi, Ehyaei and Ahmadi (2014), are two among six gases listed as being particularly harmful GHGs, namely nitrous oxide (N_2O), hydro fluorocarbons (HFCs), per fluorocarbons (PFCs) and sulphur hexafluoride (SF_6).

Thompson and Tanapat (2005) conceptualized a landfill site as a giant biochemical reactor. When MSW is buried in landfill site, biodegradable matter is decomposed under anaerobic conditions by a complex series of microbial reactions (Wangyao et al. 2010). The biodegradable matter includes readily degradable food waste, degradable components from garden and park wastes, and cellulosic components in paper. It is estimated that solid wastes in developed countries typically contain 60–75% of total biodegradable components, with approximately 15–25% of degradable organic carbon (DOC), with a range of 42 to 80% in developing countries (Bogner and Matthews (2003);

Dhokhikah and Trihadiningrum (2012)). In many developing countries, solid waste is buried at open dumps and at non-engineered sites with a top cover, leading to a large fraction of the degradable organic carbon, according to Bogner and Matthews (2003), being decomposed aerobically to CO_2 rather than anaerobically to CH_4. However, because burial is a continuous process with the old waste being buried with layers of younger wastes, Bogner and Matthews (2003) argued that CH_4 generation still occurs at such sites.

Berger and Mann (2001) and Kumar et al. (2004b) described the gas production from landfill sites through four sequential phases. There is the initial adjustment phase (Phase I), acid phase (Phase II), methane fermentation phase (Phase III), and maturation phase (Phase IV) (See Figure 2.1). The process of LFG production starts with an aerobic decomposition of easily degradable waste to CO_2 and may last for some weeks, until all readily available oxygen inside the landfill site has been exhausted. As oxygen (O_2) is consumed, the waste gradually enters the acid phase, Phase II, where the complex organic matter is broken into simpler organic acids (acetic acid (CH_3COOH), carboxylic acids) and hydrogen (H_2). In the acidification phase, CO_2 is the principal gas generated until the end of the phase. The CH_4 production starts in Phase III under anaerobic conditions, with methanogens utilizing CO_2 and hydrogen ions that were produced during the acid phase. The process ends in Phase IV, maturation phase.



Source: Berger and Mann (2001)

Figure 2. 1 Phases of landfill gas production

To be able to make meaningful interpretations of results of LFG emission measurements, it is important to consider which factors are affecting the rate of LFG generation (Fredenslund (2010); Amini, Reinhart and Mackie (2012)). According to Wreford (1996), these factors include yearly waste acceptance rate, the composition of the waste stream, temperature, pH, moisture content, hydrogeology of the site, cover material and the landfill methods, for example open dumpings or sanitary landfill sites. Further, Guo (2013) pointed out that the top soil cover and landfill gas collection can effectively reduce GHG emissions. Another major issue is how the process of CH_4 emissions occurs over time and the peak where the most of the anaerobic decomposition is expected to occur. It is assumed the CH_4 production from landfill site to be instantaneous and steady based on quality and quantity of waste disposal (Bogner & Matthews 2003). With the common characteristics of high propotion of readily degradable organic waste, CH_4 emissions could begin for a few weeks after burial (Bogner & Matthews 2003). Hence, the knowledge of the biochemical process in landfill sites and the timeframe of emission are vital for the choice of a proper method to estimate CH_4 emissions, especially to account for the variables at the study site (Shekdar 1997).

2.2 Life Cycle Assessment method

This section will present a definition and historical development of Life Cycle Assessment. The application of Life Cycle Assessment in solid waste management will also be analysed.

2.2.1 Definition and historical development of LCA

There is a number of methods available for assessment that support decision-making. These methods include Life Cycle Assessment (LCA), Environmental Impact Assessment (EIA), Material Flow Analysis (MFA), Environmental Risk Assessment (ERA), and Cost-Benefit Analysis (CBA) (Finnveden and Moberg (2005); Wittmaier, Langer and Sawilla (2009); Finnveden et al. (2009)). Most tools are based on modelling materials and energy flows (Wittmaier, Langer & Sawilla 2009). However, “Life Cycle” approach is regarded as a more appropriate evaluation tool and has been widely adopted in various waste management practices (Del Borghi, Gallo & Del Borghi 2009). The focus on assessing life cycle of a product has some important implications in exploring a diversity of potential effects and the nature of impacts as well. Life Cycle Assessment helps to compare across impact categories under the same conditions, which is in contrast to other tools. Therefore, the tool provides the best estimate in modelling of all impacts (Finnveden et al. 2009).

Life Cycle Assessment, over the last three decades, has developed and applied rapidly. In the 1970s, LCA was to serve energy analysis and then expanded to comprehensive analysis of environmental burden (Guinee et al. 2010). The interest in adopting LCA grew rapidly in the 1990s. The International Organization for Standardization (ISO 14040 1997) established principles and framework for conducting and reporting LCA studies, which is presented in the ISO 14040 series. Life Cycle Assessment, as defined in ISO 14040, “is a technique for assessing the environmental aspects and potential impacts associated with a product/system”. To date, LCA has been successfully utilized in various forms to evaluate comprehensive environmental impacts of different fields throughout their life cycle, especially in developed countries where advanced assessment methods have provided more reliable data (Del Borghi, Gallo and Del Borghi (2009); (Finnveden et al. 2009)).

The LCA structure in the framework generally includes four main sequential stages that are described in detail in the ISO 14040 series from 14041 to 14043 (ISO 14040 1997). They are Goal and Scope Definition, Life Cycle Inventory (LCI), Life Cycle Impact Assessment (LCIA), and Interpretation (ISO 14040 1997). The Goal and Scope Definition in ISO 14041 defines the purpose of carrying out and the extent of the study. This is an important phase since the system boundary of the study is defined in this place. The Life Cycle Inventory (LCI) (ISO 14041 1998) focuses on quantifying mass and energy fluxes within the system boundary. The results of LCI is a compilation of the inputs (resources) and the outputs (environmental impacts) of a system within its studies boundary. The Life Cycle Impact Assessment (LCIA) is presented in ISO 14042 that is to understand and evaluate the magnitude and significance of environmental impacts of the studied system (Ryding 1999). Finally, the Interpretation is described in the ISO 14043 by using the results of the previous phases to evaluate outcomes related to the described goal and scope to reach conclusions and recommendations (Lecouls 1999).

In recent studies, many authors presented distinctions between two types of LCA: attributional and consequential LCA (Rebitzer et al. 2004). Rebitzer et al. (2004) and Finnveden et al. (2009) argued that the distinction and choice between two types of LCA are very important, and will influence system boundaries and choice of calculation methods in LCI for individual LCA studies. Attributional LCA emphasizes on a description of system regarding the environment-related flows to and from its subsystems and the whole life cycle. In contrast, consequential LCA focuses on describing how environment-related flows will change in response to possible decisions (Finnveden et al. 2009).

The literature has shown a lot of debate regarding the selection of appropriate LCA. As argued by several authors (Lundie, Ciroth and Huppes (2007); Weidema (2003)), consequential LCA should be used because it is more relevant for decision making. However, since the LCA is unable to give an appropriate decision, the authors suggested using attributional LCA because it is a traditional method and more broadly applied. Consequential LCA, according to Weidema (2003), was more helpful in understanding the chain of product and identify the processes and relations that need to improve. On the other hand, Ekvall, Tillman and Molander (2005) and Sandén and Karlström (2007) stated that attributional and consequential LCA might be used concurrently for the purpose of decision making. To illustrate, consequential LCA may help assess environmental influences of individual decisions on the system, whereas attributional LCA is valuable for the purpose of identifying and avoiding large environmental impacts (Ekvall, Tillman & Molander 2005). The combination of LCA approaches is more meaningful rather than separate approaches. Recent studies have used both LCA types on the same product to examine their applicability (Finnveden et al. 2009).

2.2.2 LCA and solid waste management

There is vast evidence on the connection between waste management and LCA drawn from different countries worldwide. Since the 1990s, Heijungs et al. (1992), (Vigon et al. 1993), and Sundqvist et al. (1999) studied methods to estimate GHG emissions from landfilled materials, including LCA. However, these works utilized concise descriptions of LCA, and life cycle assessment of landfill materials produced a theoretical foundation, without practical applications (Heijungs et al. (1992); Vigon et al. (1993)).

An increasing number of research undertaking LCA for specific waste system elements have been completed. (Allegrini et al. 2015) reviewed and assesed environment-related impacts of the incineration of MSW by using assessment of life cycle. In their research, vital aspects of the system were identified providing an improved basis to address environmental assessment of waste-to-energy systems. Tang et al. (2013) adopted LCA to evaluate the total life cycle of a MSW incineration power plant. They analysed sensitivity of each stage of the life cycle to recognize the most significant impact source. The study implemented by Turconi et al. (2011) provided a quantitative evaluation of environmental performance of a MSW incinerator in Italy and Denmark by using two LCA modelling tools, including SimaPro and EASEWASTE. Their LCA results were evaluated based on the important differences in the waste composition, the operation of the power plant, the management of residues and the substitution of energy.

There has been growing interest in evaluating landfill sites by using LCA. In the publications of Fourie and Morris (2004) and Börjesson, Sundh and Svensson (2004), the detailed process of GHG generation from landfill sites was described through LCA. Their results revealed two stages of life in a landfill, including the operating stage where MSW is disposed and the closing stage where storage capacity is reached. Other findings showed that CH_4 emissions from the operating stage of are larger compared to the closing stage because the greatest amount of degradation occurs for the first few years and the emission rate decreases with time. The process keeps emitting GHG following closure and possibly lasts for hundreds of years.

Wilson (2002) and Ménard et al. (2004) conducted similar studies. They adopted the LCA approach to evaluate and compare traditional landfill sites (bioreactors) with alternative waste management scenarios. Obersteiner et al. (2007) provided empirical LCA data for a range of landfill life stages and locations in Central Europe. They discussed several of the key issues in LCA of landfill site in terms of site-specific influence, multi-input process, and time dependency. Further, they found two issues concerning the reliability of results in life cycle inventory regarding the timeframe and the availability and quality of data for LCI.

Some peculiar aspects, according to Finnveden (1999) and Ekvall et al. (2007), must be considered in LCA application for evaluating issues related to solid waste management. First, Blengini (2008) claimed that the ‘cradle-to-grave’ scope typically adopted for specific production systems needs adaptation for waste management. Input materials are represented by the waste that may be directed to different treatment area, either to landfill sites or to composting factories. However, the author seems to forget that waste is still a type of material and landfilled waste will have a new life cycle. Finnveden (1999) recommended expanding the system boundaries of the product, including technical factors. However, covering other technical elements (design, operations) within the LCA system boundary raised controversy. The effects of technical factors are limited to a period of 20 or 30 years, whilst LFG emissions may occur over a 100-year period (Guo 2013). The second on-going debate within the LCA community is waste composition or the multi-input. Sundqvist et al. (1999) revealed that solid waste is a mixture of various materials, which leads to different emissions when waste is buried. Therefore, MSW is characterised as a multi-input and multi-output processes, causing several emissions at different times. This is consistent with earlier work by Finnveden (1999) where the fraction of metal emitted is infinite, while the decay time of organic waste is very short. Hence, the method is provisional and requires further development.

There is a broad consensus within the scientific community, particularly Heijungs et al. (1992), Vigon et al. (1993), Sundqvist et al. (1999), Fourie and Morris (2004) and Börjesson, Sundh and Svensson (2004), Allegrini et al. (2015), Turconi et al. (2011) and Tang et al. (2013), that the LCA is a technique to assess the potential impacts of a system on environment by evaluating its entire life cycle. Life Cycle Assessment is accepted and appreciated worldwide as it allows an objective evaluation of all effects of a system related to environmental aspects. Life Cycle Assessment represents an integrated approach that balances environmental impacts. It exposes each and all impacts associated with all stages of a holistic process. Life Cycle Assessment not only provides an environmental outlook but also compiles an inventory of energy and material input and output to evaluate potential impacts associated with the system.

2.3 Emission inventory models

The Life Cycle Inventory (LCI) is the second phase of the LCA that involves quantification of inputs and outputs of a system through its life cycle. As regulation in ISO 14041, inventory process is characterized by data collection, accounting models, and calculation procedures (ISO 14041 1998).

The quality of the inventory procedure, coupled with concordance of the inventory methods, directly addresses the quality of LCA. However, treatment and management of solid waste is a complex chain of processes, depending on the geography, the characteristics of the waste source, and waste management policy and strategy. Therefore, the Guideline does not provide specific calculation procedures for an individual system because of the difference in characteristics and databases available (Thanh & Matsui 2013). Gentil, Christensen and Aoustin (2009) argued that GHG inventory methods are selected for specific study areas, depending on the scope, the study context and the availability of data. Vietnam, as with other developing countries, has lacked available data and appropriate calculation methods for quantifying impacts of GHG emissions associated with solid waste management. This is an essential requirement for research and adoption of appropriate methods for individual case studies.

Earlier attempts to model LFG formation were undertaken in the 1980s. Methane emissions were not recognized as a potential problem. However, it was believed that LFG was the energetic potential source. Therefore, the first models simulating LFG production were developed in order to determine the size of GHG emissions from landfill site for gas recovery projects for resource use (Oonk 2010). In the mid 1990s the emphasis of modelling shifted to quantification of CH_4 emissions, in advance of the obligation to report GHG emissions to United Nations Framework Convention on Climate Change (UNFCCC). This leads to improved accuracy and the desire to benchmark emissions resulted in development of a number of emission models (Oonk 2010). Many models have been consistently developed and examined to quantify the LFG generation for emission inventory, such as mathematical models, empirical models, and biochemical models. These models differ in terms of kinetic expression and input parameters, which makes them differ when applying to specific contexts (NEERI 2002, cited in Jigar, Bairu & Gesessew 2014, p. 53).

Landfill gas generation can often be simulated by mathematical models, consisting of zero-order, first-order and second-order models (Kittipongvises & Polprasert 2016).

All models are characterized by two parts, including the description of the potential total emissions generated during the life-time of a landfill; and a function (f(t)) that presents how this potential of emissions is released over time (Oonk 2010). The function is in most first-order decay models and its variation. Zero-order models were suggested because they are considered the simplest method. However, they only reflect the first stage in modelling. Based on the principle of mass balance, these lowest-order models assume all the potential of emissions to be released in the year of the calculation and do not simulate the processes of biological LFG generation over time (Amini, Reinhart & Mackie 2012). For a practical application, according to Oonk (2010), these descriptions do not suffice. Therefore, higher-order models are used to enable calculation of CH_4 generation in a specific year from landfilled waste (Oonk 2010).

There have been many attempts to evaluate LFG accounting models. It is believed that the higher-order models produce more accurate results when compared to measured data (Amini, Reinhart and Mackie (2012); Oonk (2010)). In a study performed by Oonk and Boom (1995) for landfill sites in the Netherlands, the results revealed that mean relative errors of both first and second-order models are low in contrast to zero-order models. Also, Scharff and Jacobs (2006) make a comparison between various models for the quantification of CH_4 emissions from landfill sites and they concluded that the decay of waste and the production of CH_4 are best simulated by first-order models including both single-phase and multi-phase. They pointed out the advantages of multi-phase models, such as GasSim and Afvalzorg model, were that they take into account typical waste composition, and each biodegradable fraction of waste is calculated separately, depending on different fractions of organic matters in different types of waste. By contrast, Fredenslund et al. (2007) compared four models, including IPCC-models, Landgem, GasSim and the Afvalzorg-model used to simulate a landfill site in Denmark, and on the basis of this comparison, the authors doubted whether these models are reliable. The authors pointed out that huge differences between models are observed. Landfill gas emissions in various models are highly dependent on specific assumptions, particularly with the highest generation for LandGem and the lowest generation for GasSim and Afvalzorg models. As such, lower-order models were preferred compared with the higher-order models because they were less complicated and input data was short-term.

A number of models have become available and widely adopted. Among them, in order to give a guidance to national authorities on GHG emissions inventory generated from the solid waste sector, IPCC developed quantifying models so-called Tier 1, 2 and 3. Based on the equations of mass balance, the IPCC Default model (Zero-order model or Tier 1) is considered the simplest and is commonly applied to a majority of countries. It provides default parameters to nations with little available data (Friedrich 2013). The model assumes the total amount of CH_4 released from landfill site in the same year, but does not reflect the true pattern of the degradation with time (Paustian, Ravindranath & van Amstel 2006). Meanwhile, based on equations of first-order reaction, Tier 2 and 3 simulate a time-dependent emission process. Tier 2 provides default parameters defined by the IPCC, while Tier 3 requires measured parameters developed by a nation, highlighting the degradable organic component of the waste (Gentil, Christensen & Aoustin 2009). Both models take into account long-term historical data and the operating life of a landfill site for several decades, which presents significant challenges in many countries, including Vietnam.

Other models are based on first-order equations or their variation that include single-phase models (IPCC First-Order Decay, LandGEM, and Triangular model) and multi-phase models (GasSim and Afvalzorg multiphase model). The single-phase model, LandGEM, was developed for and made available by the US. Environmental Protection

Agency (Faour, Reinhart & You 2007). The model requires inputs for only a single waste stream, therefore, a disadvantage of LandGEM is considering all waste to be one type, which does not allow a difference in organic matter content (Scharff and Jacobs (2006); Oonk (2010)). Like Tier 2 and 3 of IPCC, LandGEM model requires long-term historical data, over several decades. In addition, GasSim, developed by Golder Associates for the Environment Agency of England and Wales, is the multi-phase model. The model serves to quantify gas emissions and evaluate all problems related to LFG emissions, for example the effects of LFG on local air quality, and LFG migration via the subsoil (Gregory, Gillett and Bradley (2003); (Oonk 2010)). The model uses two approaches to calculate CH_4 emissions from landfill sites, by using a multi-phase equation and applying the LandGEM model. The highlight in GasSim is incorporation of multi-waste streams, which reflect the rate constant of biodegradation (k) for different waste types (Gregory, Gillett & Bradley 2003). However, GasSim is a complicated model because it does not provide a complete set of equations. The model not only requires the amount of waste input but also the specific breakdown during the years of disposal (Scharff & Jacobs 2006).

The most considerable difficulty in adopting higher-order models is the requirement of long-term historical data on quantity, composition and disposal practice of solid waste. However, many countries in the absence of detailed data need the development of a realistic method, but simulating the time-frame of the emission process (Kumar et al. 2004a); Kumar (2016)). Therefore, based on First-order decay, a modified model is proposed. In the Triangular model, the LFG emissions is presented in a triangular form with the area of the triangle being equivalent to the total amount of gas computed using the IPCC Default model, and the shape of the triangle presents the GHG emission production over time (Kumar et al. 2004a). A modified Triangular model has been adopted by some studies (Kumar et al. 2004a); Mor et al. (2006) and Chakraborty et al. (2011)).

In the Triangular model, most attention is paid to the half-life time of LFG generation, $t_{1/2}$ (or the rate constant of biodegradation, k) and the peak gas production (Q) wherein the default k constant is proposed by IPCC. According to IPCC in 2006 (Eggleston et al. 2006), the value of k is different, depending on the characteristics of solid waste and the climatic conditions of the studied locations, thus the IPCC accommodates default k-value for four climate regions (dry boreal or temperate; wet boreal or temperate; and wet tropical and dry tropical) (Oonk 2010). This is important in emission inventory for countries that lack a detailed data.

2.4 Conclusion

Life Cycle Assessment is embraced as an appropriate technique to assess potential environmental impacts by taking into account all environmental aspects associated with a system through the examination of the whole life cycle. The strength which makes the LCA approach to be accepted and appreciated worldwide is that it can explore a diversity of potential impacts and the nature of the impacts as well. This helps to disclose potential influences associated with all stages of a holistic process. Life Cycle Assessment also compiles an inventory of energy and material input and output of the system to serve the quantification process of impacts.

The gaps concerning use of LCA are (1) lack of country-specific key parameters, and (2) the improper application of methodologies or models for GHG estimation that leads to overestimation of CH_4 yield. This occurs in countries with an absence of specific data, including Vietnam. Each inventory method of GHG emissions for landfill site has its own advantages and disadvantages, especially when standing and applying alone. Taking into account the limitation of waste data available in the case study, two methods of the IPCC Default and the Triangular model are recommended to apply conjointly rather than

Independently to minimize their limitation of the models. Without long-term historic data, the combined methods still satisfy two parts in the main characteristic of modelling LFG production. Further, the integration offers valuable results for holistic estimation within LCA of landfill site. Very little work is available on estimating GHG emissions from landfill site in Vietnam using a combination of IPCC Default and Triangular models, except a few reports on the application of IPCC default only. Therefore, this present research is the first of its kind in Vietnam to be applied in order to estimate GHG emissions from landfill sites.

CHAPTER 3 METHODOLOGY AND MATERIALS

This chapter presents four sub-parts: (1) research methodology, (2) research methods that will identify the scope of the research and define the system boundary, (3) Emission scenarios, and (4) Emission inventory models.

3.1 Research methodology

The aim of this section is to present an overview of the methodology that is presented in Figure 3.1. The research consists of three stages. The first stage is the situation analysis that identifies knowledge gaps in the study area pointed out in the Introduction chapter. Objectives and scope definition of the research will be detailed to clarify the subject and predicted outcomes of the research.

Life Cycle Assessment is suggested as the key research method to adopt in the study presented in Stage 2. Based on the framework of LCA, the goal and scope of the study will be redefined. Also, predictive scenarios will be designed, and emission inventory methods will be selected. The aim of Stage 3 is to collect detailed and specific data, and quantify CH_4 emissions by using two mathematical accounting models: IPCC default; and Triangular model. The calculation results for each scenario will be then assessed and compared to find out the best MSW management for Hanoi regarding GHG emissions reduction.

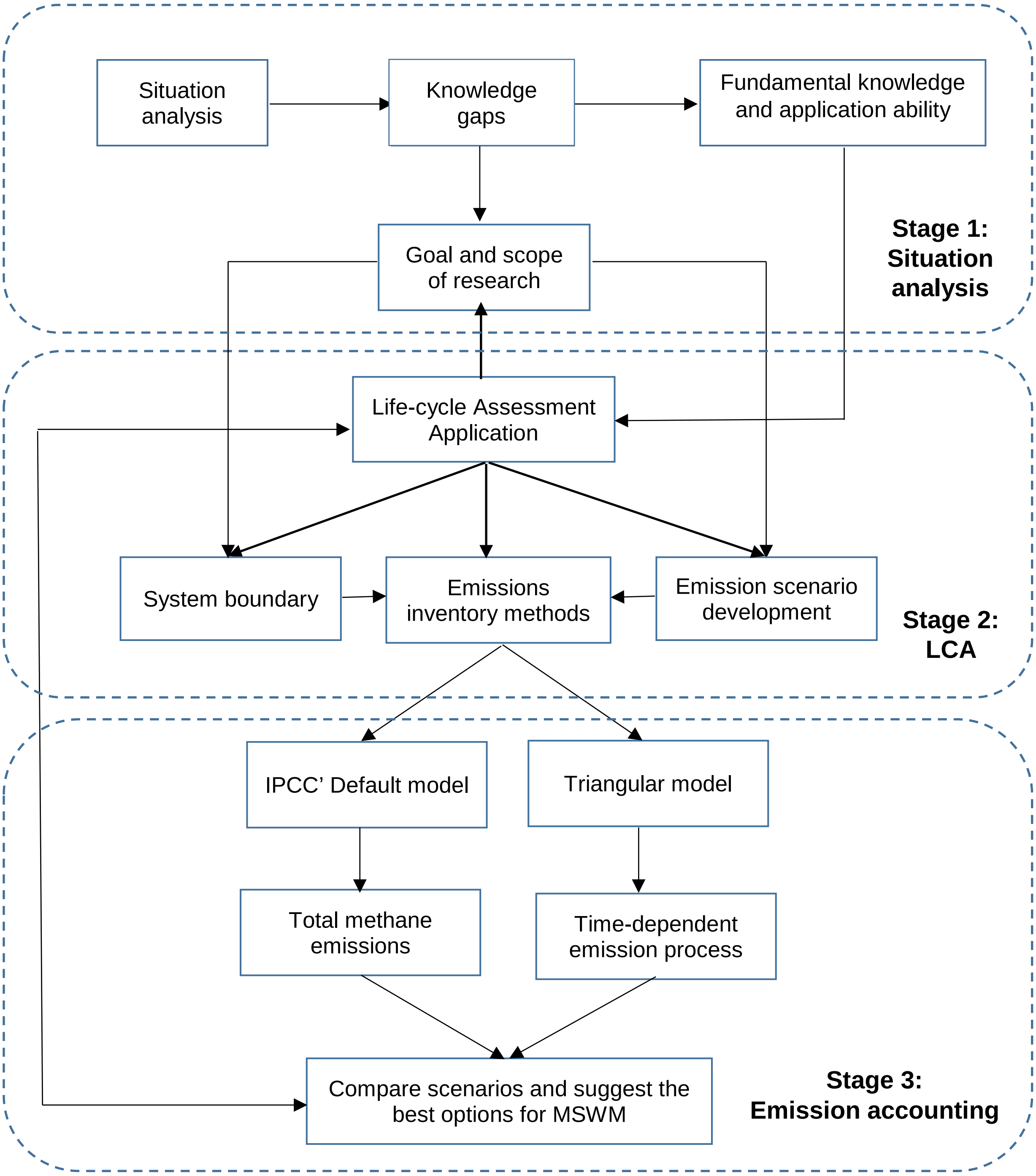


Figure 3. 1 Flow diagram of the research methodology

3.2 Life Cycle Assessment method

Life Cycle assessment is used to estimate the potential influences of CH_4 emissions from landfill site. The LCA is described in Chapter 2. The aim of this section is to identify the scope, and to define the system boundary and scenario development.

3.2.1 Scope of research

The study is to assess the life cycle of the Nam Son Landfill site in Hanoi, Vietnam regarding GHG emissions where the entire life of the landfill site is assessed, from opening, operation to after closure and its environmental implications. In this study, the main processes considered in the LCA are on-site operations of landfill and gas collection, and final cover for the landfill facility. Emissions from leachate treatment and the transport of waste to the landfill are not included. The environmental performance of landfill options were analysed since the opening of the Nam Son Landfill site in 2000. The function of the site is to bury municipal solid waste. The functional unit was one tonne (wet weight) of buried MSW as unit of input and one m^3 of CH_4 emission as unit of output.

In order to evaluate the contribution of alternative solutions, five different waste management options are defined as emission scenarios with one current and four alternative scenarios investigated and compared within the scope of the LCA assessment. It is assumed that the change in amount of MSW will not be investigated because it is assumed to be the same for all scenarios.

3.2.2 System boundaries

Flows of material and energy in an LCA study is confined within the system boundaries. The system boundary determines which unit processes are included, and their interrelationships is presented in a process flow diagram (Figure 3.2) (Eriksson et al. 2002). Eriksson et al. (2002) argued that defining the system boundary is partly based on subjective choices that are made in the Goal and Scope Definition phase. As regulated in ISO 14041 (1998), determination of the system boundary in the initial steps is important in describing the whole system where each of the unit processes is defined, where the unit process begins and ends, and the nature of the transformations and operations occurring within the unit process. This determines which input and output data are needed.

The system boundaries are built for different scenarios. In each scenario, the entire system is prescribed and included the relevant unit processes.

In this study, Figure 3.2 presents relevant processes within the boundary of the MSW management system in Hanoi. The upstream boundary starts with MSW being dumped in landfill site. In order to avoid double counting emissions, the process of collection and transport is not included in the system stream for all scenarios. It is because it is difficult to distinguish and separate the GHG emissions generated from the collection and the transportation that may be delivered to either landfilling or other treatment sites. Unit processes included in the emissions scenarios are summarized as: (1) infrastructure of landfill, such as sanitation landfill and installation of LFG capture system; (2) Integrated composting to landfill; (3) integrated recycling to landfill. Determining the unit processes and segregating every single unit process from the main system help to evaluate their role and environmental impacts within the system. Any change will lead to changes in the original system. This will be a valuable foundation to develop alternative scenarios.

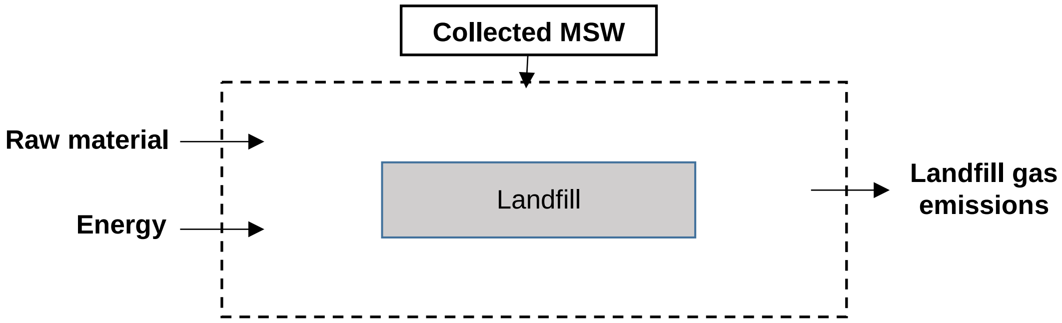


Figure 3. 2 Landfill system boundary

3.2.3 Scenario development in LCA

In this section, scenarios are defined and created for analysis in LCA. The ideal scenario number and time-period for the scenario are also identified. The description of specific emission scenarios in detail will be represented in section 4.2 of Chapter 4.

The development of alternative future scenarios are frequently mentioned in the literature on LCA. The scenario framework is defined in the Goal and Scope Definition phase (ISO 14041 1998). It has significant influences on the subsequent phases, typically on quantifying models in the Life Cycle Inventory (LCI) to assess scenarios. Further, the setting of scenarios will provide the framework for the modelling and as a result, accounting models follow (Pesonen et al. 2000).

A scenario in the LCA framework is defined by the European LCA Working Group of The Society of Environmental Toxicology and Chemistry (SETAC): *"a scenario is a description of a possible future situation relevant for specific LCA applications, based on specific assumptions about the future, and also including the presentation of the development from the present to the future."* (Pesonen et al. 2000, p. 23). According to the definition, a scenario includes a short description and specific assumptions of the scenario.

There are three different categories of scenario (Börjeson et al. 2006). There is a predictive scenario which answers the question “what will happen?”, an explorative scenario answering “what can happen?”, and a normative scenario answering the question “how can a specific target be reached?” (Börjeson et al. 2006). According to Höjer et al. (2008), these sorts of scenarios might be considered in combination. For example in energy systems, predictive scenarios are helpful for background processes in LCAs. Meanwhile explorative scenarios may be useful to include since the time period is longer, which might cause increasing uncertainty in forecasts. As a result, a combination will be of interest to describe possible future developments of the systems (Finnveden 2008). Börjeson et al. (2006) argued that the process of scenario construction consists of three phases: (1) generating ideas and gathering data, (2) integrating elements or combining elements into the whole, and (3) examining the consistency of scenarios.

The “what-if” scenario and the “cornerstone” scenario, are proposed by The European LCA Working Group ”Scenario Development in LCA” of The Society of Environmental Toxicology and Chemistry (SETAC) (Pesonen et al. 2000). The “what-if” scenario is the most used method for LCA studies. It is used to define a hypotheses based on an existing data source. In the “what-if” scenario, a quantitative comparison of selected options is often made to estimate how specific changes may affect environmental impacts existing within the present system. By contrast, scenarios developed by the “cornerstone” approach express how changes affect specifically environmental impacts (Pesonen et al. 2000). Pesonen et al. (2000) argued the results of the “what-if” scenario are often for short-term or medium-term decision-making situations. The results of the “cornerstone” scenarios are not made by quantitative comparison, and serve as a “cornerstone” for further research. Scenarios present possible situations of the future, and each scenario may contain one or more alternative products to be studied within the scope of LCA.

In this study, scenarios are developed using the “what-if” approach with the baseline scenario presenting the current situation of the MSW management in Hanoi, Vietnam. Alternative scenarios are designed and compared, reflecting the situation of future MSW management options. The choice of scenarios is intended to meet the objectives of the environmental plans and strategies of Vietnam and suitable in terms of technology at the landfill site and integrating other treatments (recycling recyclable materials and composting organic waste) prior to delivery to landfill. This could help explore the recycling and composting capacity and examine the Vietnamese plans on solid waste management as well. The comparison between the alternative options are significant in selecting the best scenarios to improve the existing MSW management. The scenarios investigated in this study are based on MSW that does not include industrial, medical and agricultural solid waste. Second, CH_4 emissions from transportation and collection are not taken into account. Finally, the scenarios use unchanged volume of MSW as inputs.

The number of scenarios in LCA studies is of interest to many scientists. Braunschwei and Jahn' study in 1998 (Cited in Pesonen et al. 2000, p. 24) stated that under both the "what-if" and "cornerstone" approach, the LCA study includes at least one base scenario that should be explicitly defined. The ideal number of scenarios in a LCA study was suggested by Wack in 1985 (Cited in Pesonen et al. 2000, p. 24) to be one plus two. He explained that the appropriate number should not be over four because, otherwise, the decision-making will become more complicated and unmanageable for national authorities in decision making.

The number of scenarios depends on the goal and scope of the study (Pesonen et al. (2000), Tascione and Raggi (2012)). According to Pesonen et al. (2000), the suggestions of Wack in 1985 and von Reibnitz in 1991 are only applicable to the "Cornerstone" scenarios, but the "What-if" scenarios will serve a larger number of alternative options to be necessary to study. As defined in the Goal and Scope Definition phase, scenarios include the possible situations of the future, and each scenario might contain one or more alternative options to be studied.

The number of scenarios developed for this study is five (outlined in Chapter 4), including one baseline scenario and four alternative scenarios, which is consistent with the scope of the study, the objectives of Vietnamese national environmental strategies and suitable for the local context. The time horizon of the scenarios, according to Pesonen et al. (2000), should be consistent with the goal of the study. The aim of the paper is investigating and assessing the emission process of landfill, thus the timeframe is examined by modelling emission process.

3.3 Emission inventory models

The second phase of the LCA, the Life Cycle Inventory (LCI), involves data collection and inventory procedure to quantify environmental impacts of a product. Depending on the goals and scope of the research, selection of a calculation method and collection of relevant input data will be given. The input data collection is associated with calculation process. In some instances, since data is collected, helping learn more about the system, as a result, new data requirements or limitations may be identified which, in turn, require a change in the procedure of data collection to achieve the goal set out in the research (ISO 14041 1998).

The combination of two mathematical accounting models: IPCC Default model and the Triangular model is used in this study to estimate CH_4 emission from Nam Son Landfill site in Hanoi, Vietnam. Historic and current data on the MSW quantity and composition, and the operation and management of the landfill site are required for the accounting models. The data selection for the inventory analysis should be consistent with not only the accounting methods but also the scenario framework. The scenario construction, according to Pesonen et al. (2000), often make data needs more complex, as there is a wide range of data types that serve for every single scenario (Pesonen et al. 2000).

3.3.1 The IPCC Default model

The IPCC Default model, in both Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories (Houghton et al. 1997) and 2006 IPCC Guidelines for National Greenhouse Gas Inventories (Paustian, Ravindranath & van Amstel 2006), is based on the principle of mass balance or theoretical gas yield. The model assumes that all potential of CH_4 emissions would be generated from a landfill site in the same year when the waste is disposed. However, this model does not reflect and simulate the degradation of solid waste over time.

The Default model requires the MSW quantity and composition ending up at a landfill site and information on the existing operation of the site. In addition, the CH_4 generation depends on factors, including oxidation factor, a CH_4 generation potential (L0), and CH_4 recovery (R) (if any). The potential of CH_4 generation that could be emitted from a unit of waste is the product of a set of CH_4 correction factors which account for the degree of anaerobic degradation of waste. The set includes the content of the degradable organic carbon (DOC) in MSW determined by composition of waste, and the content of CH_4 in LFG. The IPCC Default model is based on the mass balance equation that is presented in Appendix A (Houghton et al. 1997).

The primary inputs to the Default model are parameters such as the total quantity of MWS buried, the MSW composition, and other parameters used to calculate the CH_4 generation potential (L0), including methane correction factor (MCF), degradable organic carbon (DOC), and fraction of DOC decomposing under anaerobic conditions (DOCf). The value of these parameters, under the 2006 IPCC guidelines, depends on the studied region and national data, for example, climate characteristics (dry temperate, wet temperate, dry tropical, and moist and wet tropical). The required parameters and their default values proposed by IPCC in 2006 IPCC Guidelines for National Greenhouse Gas Inventories are presented in detail in Table A.1 in Appendix A (Paustian, Ravindranath & van Amstel 2006).

3.3.2 Triangular model

Based on the First Order Decay, the Triangular method is modelling time-dependent generation of CH_4. In the model, the process of CH_4 generation is divided into two phases. It is assumed that in the first phase, the degradation of waste begins after one year of waste deposition and the production has an assumed linear growth until it reaches a peak (Q). This is followed by the second phase with a linear decrease from peak (Q) to zero.

The area of the triangle represents the total amount of CH_4 emissions produced from total quantity of MSW to be placed in a landfill (Figure 3.3). The total CH_4 emissions used as inputs for the model is calculated by the IPCC Default model (Kumar and Sharma (2014); Kumar et al. (2004a); and Mor et al. (2006)).

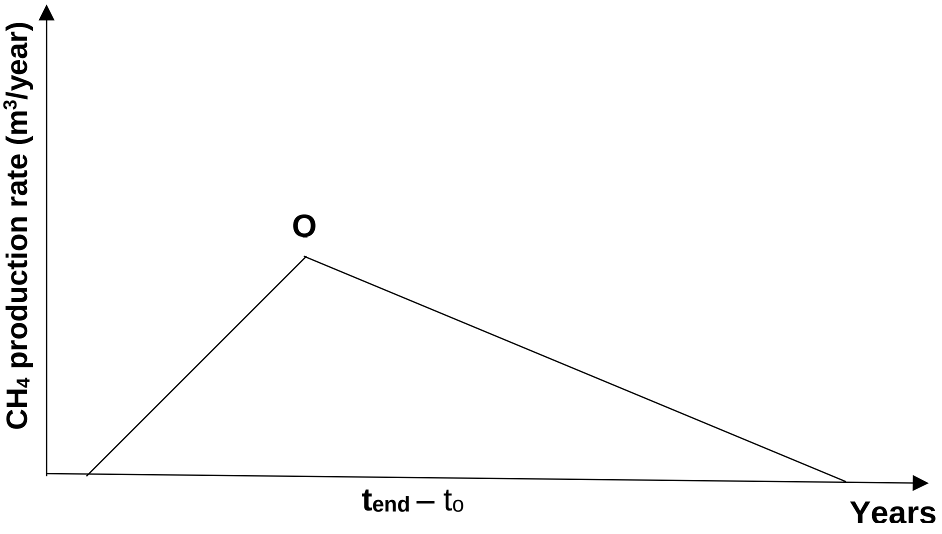


Figure 3. 3 Emission process in the Triangular model

In the Triangular model, the organic waste is divided into two types: rapidly and slowly biodegradable organics. Rapidly biodegradable waste is food waste and garden and park waste (leaves and grass trimmings), paper and cardboard that are decomposed in a few days after being buried in a landfill site and may take up to five years to complete decomposition. Textile, leather, rubber, and wood are the slowly biodegradable organics, begining the decomposition about five years after being placed in the landfill and may last up to 50 years to complete (Tchobanoglous 1993). This is charactered in the reaction constant (k) that describes the rate of the degradation process.

The IPCC accommodates the default k-value for four different climate regions (Oonk 2010). The value of k is affected by waste composition, landfill site conditions and regional climate (Pelt et al. 1998). A very wide range of values given for k is between

0.005 and 0.4 that is presented by IPCC for specific climate zones in 2006 IPCC Guidelines for National Greenhouse Gas Inventories (see Appendix B for further information) (Paustian, Ravindranath & van Amstel 2006). However, the IPCC suggests countries developing specific half-life or k values that is more appropriate for the local context. Due to the difference in climates and geography, US EPA (2004) introduced using the following equation to calculate the constant k for a specific site that is $k = 3.2 \times 10^{-5} \times$ (annual mean rainfall) + 0.01. Further, $k = \ln(2)/t_{1/2}$ ($t_{1/2} = 0,693/k$), where $t_{1/2}$ is the average time for the degradation in waste to decay to half its initial mass. The values of k and the corresponding half-lives in 2006 IPCC Guidelines for the moist and wet tropical climate zone are presented Table B.1 in Appendix B (Paustian, Ravindranath & van Amstel 2006).

Another consideration is identification of the delay time for the emissions process. At most landfill sites, their operation is continuous with solid waste being deposited throughout the year. The process of CH_4 production, however, does not begin immediately after the waste is deposited in landfill site, but occurs through four sequential phases (Berger and Mann (2001); Kumar et al. (2004b)). The CH_4 production starts from Phase III, after the aerobic decomposition and the acidification stage. The two first stages are chemically complex and involves successive microbial reactions and probably vary berween different landfill sites, depending on waste composition and climatic conditions. As a result, the time period from deposition of the waste to starting the production of CH_4 may last for several months, even up to one year. Therefore, the delay time estimates are uncertain and different with a default value of six months provided by both 2006 and 1997 IPCC Guidelines (Houghton et al. (1997); Paustian, Ravindranath and van Amstel (2006)) and the value of one year proposed by Gregory, Gillett and Bradley (2003), Barlaz (2004), and Kumar (2016).

3.3.3 Limitations and delimitations in calculation

The operation of the Nam Son Landfill site is very complicated with operation of a number of cells, including nine burial cells. However, these cells were not used at the same time, but separately and at different periods of time. The construction and operation of the Nam Son Landfill site was divided into two phases. The first phase (Phase 1) included three cells and finished by 2001. So far, three cells in Phase 1 has been filled and closed. Phase 2 includes six cells and started with cell 4 and 5 from 2001 to 2003, followed by cell 6 and 7 operating for two years from 2004 to 2006. Cell 8 operated from 2007 to 2008 with the height of this cell being 20 m at the time of it closing.

However, all cells in Phase 1 and Phase 2 have been filled up to 15m and temporarilly closed. As such, after completing the work on cell 8, from 2008 the rest of cells in Phase 1 and Phase 2 from 1 to 7 have continued to work again until attaining the height of 39m. This will help extend the operation time of Nam Son Landfill site to 2020. However, in the study, to eliminate this complexity, calculations will only be made for cell 8 where the burial process occurred from 2007 and the cell closed in 2008 at a height of 20m. The reason for choosing cell 8 for the calculations is that the cell 8 operates independently and continuously without interruption, whilst others operated in a pair and underwent two separate stages in time.

CHAPTER 4 CURRENT SITUATION AND SCENARIOS FOR MUNICIPAL SOLID WASTE MANAGEMENT IN HANOI, VIETNAM

This section consists of two main parts: (1) municipal solid waste management in Hanoi and (2) scenario development. Wherein the former will clarify the management system of solid waste in Hanoi, and the latter will describe how the scenarios are designed and the specific scenarios in the research.

4.1 Municipal Solid Waste Management in Hanoi, Vietnam

4.1.1 Solid Waste Generation, composition and characteristics

The average total volume of solid waste generated in Hanoi between 2010 and 2015 was approximately 10,000 tonnes per day, of which 6,300 tonnes was domestic waste (accounting for around 64%) (DONRE 2015). Industrial solid waste was approximately 7.9%; solid waste from construction activity was 28%, and medical waste was smallest at 0.1% (Table 4.1). The quantity of MSW in Hanoi increases on average by 10% per year, and in urban areas, the increase is by 15% per year (DONRE 2015). Dividing the total solid waste generated in Hanoi by its total population, about 1.2 kg MSW is generated by each person per day, the figure is higher than 1.02 kg per person per day in Ho Chi Minh City and is the highest compared to the country average of 0.61 kg per person per day (Thai 2014) (Table 4.2).

Table 4. 1 Quantity of MSW generation by years

Type of waste	**Amount of solid waste generation (Tonnes/day)**					**Average amount**
	2010	**2012**	**2013**	**2014**	**2015**	
Domestic waste	5,500	6,366	6,422	6,400	6,819	**6,301**
Industrial waste	850	750	750	750	799	**780**
Medical waste	-	9.5	9.6	9.8	10.44	**10**
Construction waste	1,500	3,200	3,000	3,000	3,196.50	**2,779**
Total	7,850	10,326	10,182	10,160	10,825	**9,868**

Source: DONRE (2015)

Growth of waste production is due to an increase in population. A larger population may result in more product consumption and greater waste generation. Table 4.2 reveals that largest cities with populations >= 20 million, such as Jakarta (Indonesia), and Beijing and Shanghai (China) generate the largest amount of MSW with over 20,000 tonnes per day. By contrast, the total amount of MSW generated per day from the cities with a smaller population with populations < 3 million, including Phnom Penh (Cambodia) and Quezon City (Philipines) is less than 2,000 tonnes.

The increase in per capita waste generation is highly dependent on socio-economic factors of a nation (Pariatamby & Fauziah 2014). Increase in income level, as a result of social economic growth, will generally lead to greater per capita rate of waste generation and also influence the waste composition. Probably, an increase in the standard of living may lead the higher consumption of products, and potential greater waste generation.

Table 4.2 illustrates that among selected countries in the Asia Region, Singapore with the highest income level (46,570 GDP per capita) has the largest rate of waste generation per capita (1.49 kg/capita/day), followed by Beijing and Shanghai, two cities in china. The rate of per capita production in low income cities, like Phnom Penh (Cambodia) and Delhi

(India) is under 1 kg. However, in Hanoi, although the income level of the city is lower compared to other cities (Jakarta, Quezon City, Bankok, Ho Chi Minh City, Beijing, and Shanghai), its per capita waste generation (1.2 kg) is higher than that of those cities, just behind Singapore. This partly reveals the weakness in solid waste management in Hanoi. An opposite trend is seen in Singapore. Although the GDP index of Singapore (Table 4.2) is 24 times higher than Hanoi (Table 4.2), the amount of solid waste generated per capita is not much higher, just 1.2 times. This may be explained by a stronger national economy that offers sufficient financial and technical support for improvements of solid waste management strategies and technologies (Zhang 2012).

Table 4. 2 Quantity of MSW in various cities

The city	Population (thousand)	GDP per capita (USA)	Income level (a)	MSW quantity (kg/capita/day)	References
Phnom Penh (Cambodia)	1,504	785	Low	0.8	Sethy, Sothun and Wildblood (2014)
Jakarta (Indonesia)	27,900	2,977	Lower middle	0.9	Damanhuri, Handoko and Padmi (2014)
Quezon City (Philipines)	2,762	2,147	Lower middle	0.67	Guerrero, Maas and Hogland (2013)
Singapore	5,077	46,570	High	1.49	Pariatamby and Fauziah (2014)
Bankok (Thailand)	6,711	5,071	Uper middle	1.1	Guerrero, Maas and Hogland (2013)
Hanoi (Vietnam)	6,562	1,911	Lower	1.2	DONRE (2015)
Ho Chi Minh (Vietnam)	7,397	2,800	Lower	1.02	Verma, Borongan and Memon (2016)
Delhi (India)	16,300	1,752	Lower	0.47	Kaushal, Varghese and Chabukdhara (2012)
Beijing (China)	19,612	12,447	High	1.1	Lianghu et al. (2014)
Shanghai (China)	23,019	12,784	High	1.03	

(a) World Bank 2012: low (<$876), Lower mid. ($876-3465), Uper Mid. ($3466-10725), High (>$10725)

Table 4. 3 Composition of MSW in various cities

The city	MSW quantity (tonnes/day)	Composition (% in weight)						References
		Organic	Paper	Plastic	Glass	Metal	Others	
Phnom Penh (Cambodia)	1,203	55	3	10	8	7	17	Shekdar (2009)
Jakarta (Indonesia)	25,110	74	10	8	2	2	4	
Quezon City (Philipines)	1,851	41.6	19.5	13.8	2.5	4.8	18	
Singapore	7,565	44.4	28.3	11.8	4.1	4.8	7	
Bankok (Thailand)	7,382	48.6	14.6	13.9	5.1	3.6	14	
Hanoi (Vietnam)	7,850	53.8	6.5	13.6	1.9	0.9	23	Leroy and Vuong (2016)
Ho Chi Minh (Vietnam)	7,545	69	3	16	1.6	0.2	10	Verma, Borongan and Memon (2016)
Delhi (India)	7,661	42	6	4	2	2	44	Kaushal, Varghese and Chabukdhara (2012)
Beijing (China)	21,573	66	11	12.3	1	0.3	9	Wang and Wang (2013)
Shanghai (China)	23,710	70	6.7	11.8	4.1	0.8	6.6	Liu and Wu (2011)

Table 4.3 shows the waste composition of some selected countries, highlighting the components in the waste stream. This information enable the ability to select appropriate treatments, including recycling, composting, incineration and landfill. All cities have a similar trend in the waste stream, with the largest proportion being the organic fraction which is over 50% of solid waste amount. This organic waste is considered a biological source to produce fertilizers by composting. Also, the table indicates the high potential of recycling possibilities in all cities due to a high percentage of recyclable materials (paper, plastic, glass and metal) in the MSW stream. Based on the characteristics of MWS, in

2001, the Singapore Government launched a National Recycling Programme that encouraged the public separating their waste at source by removing recyclable items from the daily garbage over 14 consecutive days. The programme helped reduce the average daily municipal wastes. In 2008, 48 % of paper, 9 % plastic waste, 94 % metal and 18 % glass were recycled in Singapore (Pariatamby & Fauziah 2014). Meanwhile, over 90% of the quantity of domestic waste in Hanoi was treated by landfilling (DONRE 2015), in which only 26.5% of the total area of landfill are sanitary landfills (Leroy & Vuong 2016).

4.1.2 MSW management system

In Hanoi, solid waste is managed by three levels: city, district and ward levels. The people committee of city, the highest administrative body, is responsible for implementation of regulations and legislation issued by the state level. However, some departments within the city level are responsible for management of solid waste directly and indirectly. At the district level, the people committee implements regulations issued by higher levels in their area. They also address solid waste management and environmental problems in the city. The ward level is an institutional level closest to citizens. Their role is to execute orders of the district relating to solid waste management (DONRE 2015).

According to environmental protection law of Vietnam, only industrial and medical waste are required to be separated at the source from ordinary and hazardous waste. Industrial waste is well sorted in industrial zones or big factories; however, it is only partly sorted in small factories and craft villages. The remaining solid waste is mixed with domestic waste and then collected. Only 50% of healthcare waste is properly sorted at the source following regulations by 90% hospitals in the area of Hanoi city. Most domestic waste in Hanoi is not separated at the source. Only some households, institutions or facilities sort waste to take advantage of recyclable and reusable materials or sell them to informal private collectors (DONRE 2015).

Domestic garbage from households is collected daily by public or private operators. Waste will be put in public collection points or bins, then collected and transported by trucks to disposal sites. Hanoi is facing problems of lack of temporary collection points. Ordinary and hazardous industrial waste are required to be collected and treated separately. DONRE reported that there is approximately 646 tonnes of ordinary industrial waste generated daily in Hanoi of which 85-90% of this amount is collected by operators. Collection rate of hazardous industrial garbage is only 60-70% (equivalent to 62-73 tonnes) (DONRE 2015).

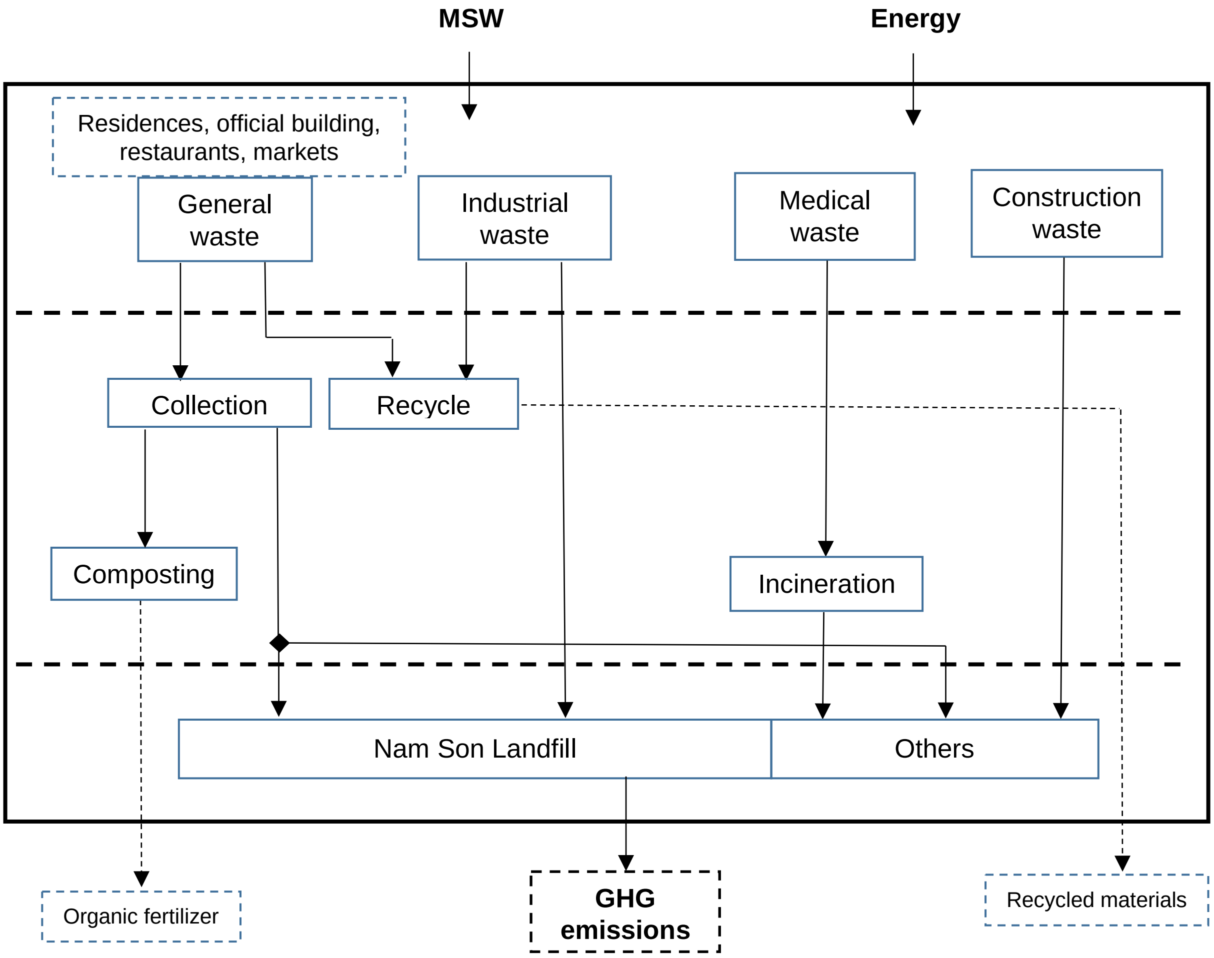


Figure 4. 1 Flow diagram of MSW management in Hanoi

Non-hazardous medical waste is carried out by sanitation companies, before they are treated with domestic waste in some landfills. Some hazardous waste is treated in the field by some medical waste disposal system. Construction waste is temporarily dumped at rural areas then transported by sanitation operators to landfill sites. Sludge taken from urban areas of Hanoi will be buried at Yen So Landfill site, while sludge from rural areas will be buried in domestic waste landfill sites of districts (DONRE 2015).

Across Vietnam, the most common methods for solid waste disposal are landfill, composting and incineration. For example, industrial waste is incinerated or stored in cellars or safe landfills. Medical waste is eliminated either on-site or off-site with a medical treatment system. Construction waste is mainly disposed into open pits created by clay exploitation or in some natural or artificial lakes. It is also used to fill in ground in construction sites. Before dumping in landfill, sludge is normally stored in tanks to dewater. Wastewater from septic sludge is treated before releasing into the environment (DONRE 2015).

4.2 Scenarios for MSW management in Hanoi

Currently, MSW in Hanoi is collected without classification at the source and then directly delivered to landfill sites. Existing landfill sites, however, are reaching their capacity. Therefore, government policies and national strategies on improving MSW management systems were approved. Notably, with the high rate of organic and recyclable components in MSW, separating organic and inorganic waste at sources to be treated by composting and recycling, instead of landfill. The scenario development in this study intends to explore the potential reduction of the environmental effects as result of composting and recycling associated with potential in the reduction of CH_4 emissions.

This study proposes five scenarios. The baseline scenario (S0) represents the existing MSW management system, and the subsequent scenarios reflect alternative options. The brief description and system boundary of scenarios are presented in Table 4.4 and Figure 4.2.

Table 4. 4 Description of scenarios used in this study

Scenarios		Description
S0	Current ‘Business as usual’	Landfilling of 80% of collected MSW
S1	Upgrade of Landfill gas capture	Installing landfill gas capture system with flaring (70% of CH_4 emissions)
S2	Composting of organic waste	Composting 50% of organic waste
S3	Recycling prior to landfill	Recycling 30% of recyclable materials
S4	Integration of capture, recycling and composting	- Installing landfill gas capture system, - Composting of organic waste, and - Recycling of recyclable materials

The study assumes the same amount of waste with its unchanged composition buried in the landfill from opening to closing, which is applied as inputs during calculation. Based on the assumptions for the scenarios, change in the waste material flow of each scenario is presented in Table 4.5. For Scenarios S2, S3, and S4, the increase in recycling and composting of MSW reduces the total amount of solid waste sent to the landfill site. This corresponds to a new percentage composition of waste.

For the current “Business as usual” scenario, the MSW in Hanoi contains a high proportion of organic waste, accounting for over the half (53.81%) in the landfilled waste amount. The similar trend is witnessed in scenario S3 with 59.36% of organic waste. By contrast, the scenario S2 and S4 have a lower proportion of organic waste (36.81% and 42.24% respectively), they also have the highest percentage of slowly degrading waste (paper, textile, plastic, glass and metal). This leads to differing potential of CH_4 emissions and age of the landfill in each scenarios.

Table 4. 5 Waste material flow of scenarios

Scenarios	**Amount of waste (Tonnes)**	**Percentage of different landfilled waste (%)**							
		Organic	paper	Textile	Wood	Plastic	Glass	metal	others
S0 and S1	2,173,904	53.81	6.53	5.82	2.51	13.57	1.87	0.87	15.02
S2	1,589,015	36.81	8.93	7.96	3.43	18.56	2.56	1.19	20.55
S3	1,969,644	59.36	5.04	4.49	1.94	10.48	1.44	0.67	16.57
S4	1,384,755	42.24	7.18	6.39	2.76	14.91	2.05	0.96	23.56

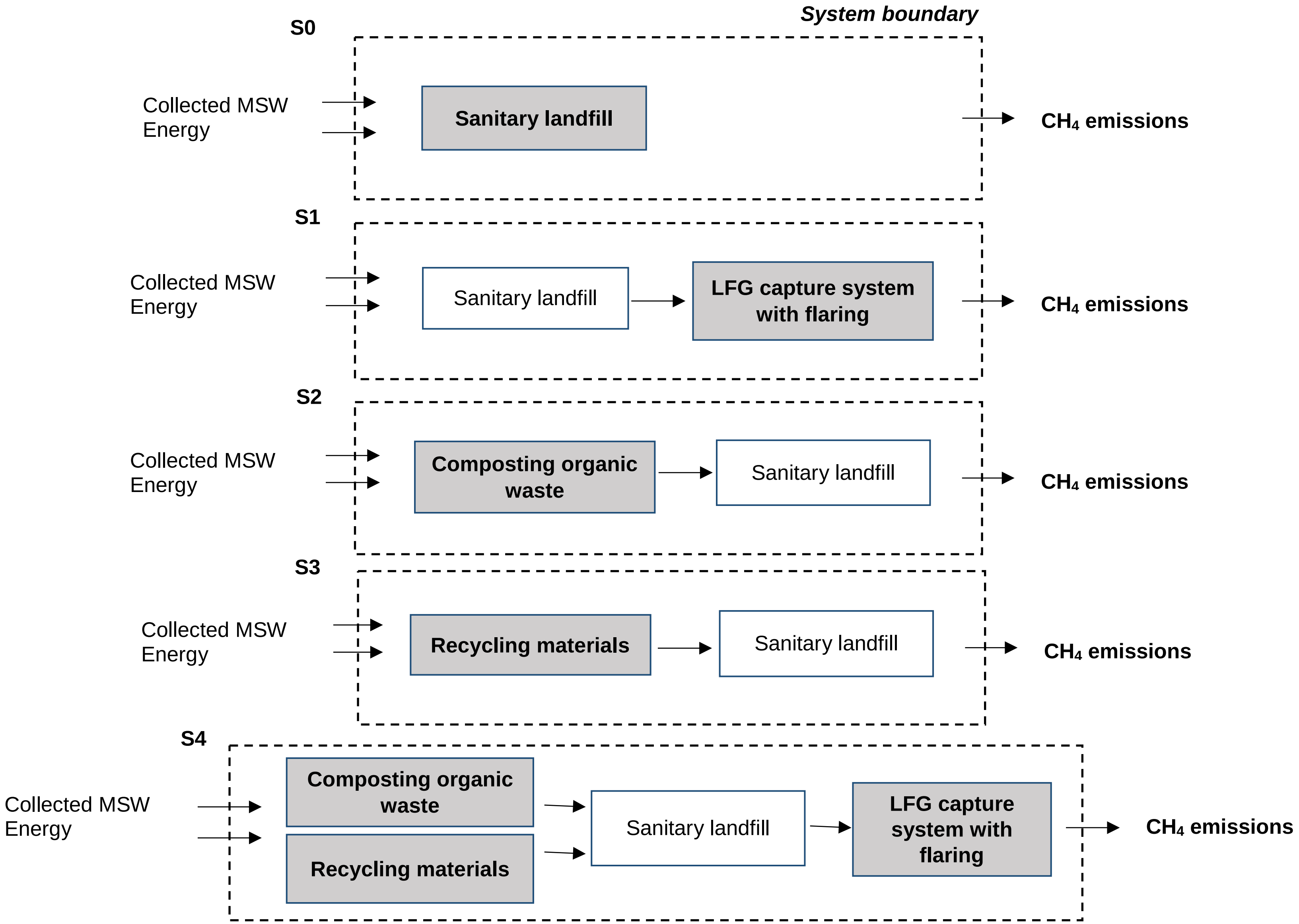


Figure 4. 2 System boundaries for scenarios

4.2.1 Current ‘Business as usual’ (S0)

The baseline scenario (S0) “Business as usual” corresponds to the current MSW management in Hanoi. According to statistical data, National Report on Environment of Ministry of Natural Resources and Environment (MONRE 2011), MSW is not separated at the source and approximately 3,468 tonnes of waste per day are disposed of in the Nam Son Landfill site without any further treatment. The Nam Son Landfill site is designed as a sanitary landfill site, without a recovery system or a LFG capture system. The composition of MSW going to the Nam Son Landfill site includes 53.81% of organic waste, 6.53% of paper, 13.57% of plastic, 1.87% of glass, 0.87% of metal, 2.51% of wood, 5.82% of textile and 15% of the residual waste (Leroy & Vuong 2016).

4.2.2 Upgrade of Landfill gas capture (S1)

Compared to S0, the landfill site has the gas capture system installed with the efficiency of the collection being 70% of generated gas. However, the collected LFG is flared regardless of energy recovery. Except for 70% of CH_4 gas being collected (R=0.7), other parameters in the scenario are the same as S0. The value of the model parameters chosen for scenario S1 is presented in Table 5.1.

4.2.3 Composting of organic waste (S2)

The basis of this scenario is used as the plan for solid waste management in Hanoi. In S2, Composting of organic waste, 50% of organic waste, from 80% of total waste quantity landfilled, is assumed to be separated, collected and composted to make fertilizer. Using the assumption that the same amount of MSW, with the same composition as S0, is used as input data, 50% of organic waste is equivalent to 584,889 tonnes within 1,169,778 tonnes of organic waste to be composted before disposing to landfill site. As such, the new composition of MSW consists of 36.81% of organic waste, 8.93% of paper, 3.43% of wood, and 7.96% of textile (Table 4.5).

4.2.4 Recycling prior to landfill (S3)

This scenario explores the potential reduction of GHG emissions, resulting from the recycling of source-segregated waste materials. It is assumed that several recyclable materials will be collected and treated in a material recycling facility to produce secondary materials. Based on the national strategy on MSW management, the scenario assumes that 30% of MSW fractions from the amount of buried MSW, including paper, metals, glass, plastic, wood and textile is separated at the source and recycled. Also, it is assumed that the same amount of MSW, with the same composition as in S0 is buried. The change in the waste quantity and percentage of the waste component for scenario S3 are presented in Table 4.5.

4.2.5 Integration of capture, recycling and composting (S4)

This scenario explores the potential to reduce CH_4 emissions through integrating the MSW management system. Firstly, 50% of organic waste from landfilled MSW will be collected and treated by composting to make fertilizer. In addition, recyclable materials, such as paper, metals, glass, plastic, wood and textile will be recycled at a 30% rate in the material recycling facility. Finally, 70% of CH_4 emissions will be collected and recovered. The same amount of MSW, with the same composition inS0, is delivered and treated at the burial site.

CHAPTER 5 RESULTS AND DISCUSSION

This chapter includes two main sub-parts: (1) input parameters for accounting models and (2) methane emissions from the Nam Son Landfill site. The CH_4 emissions from Nam Son Landfill site will be analysed and discussed under the potential of CH_4 emissions and time-variation in CH_4 production.

5.1 Input parameters for accounting models

Based on the current MSW management in Hanoi, along with its landfill features, the moist and wet tropical climate, the values of all factors used of the accounting models is presented in detail in Table 5.1.

For the IPCC default model, the value of methane correction factor (MCF) reflects the status of management of the site. To accommodate different types of landfill sites, the IPCC recommends default MCF values, ranging from 0.4 to 1. This corresponds to a range of unmanaged to well-managed landfill site. In Nam Son Landfill site, the burial areas of MSW in Phase 2 is well managed with a top cover of soil, supposing that the value of MCF and oxidation factor (OX) is 1 and 0.1 respectively, and is applied for all scenarios.

Defining degradable organic carbon (DOC) depends on the amount and the component of waste. Applying statistical data on waste composition in the Nam Son Landfill site, the percentage of DOC in MSW is 13.2%. This figure is for scenarios S0 and S1. In comparison to S0 and S1, the values of DOC applied to the rest of the scenarios are lower with 12.6% for S2, 12.9% for S3 and 12% for S4 (Table 5.1). This shows that CH_4 emissions from scenarios S2, S3 and S4 is smaller than that of the current scenario.

Defining fraction of DOC decomposing under anaerobic conditions (DOCf) was also carried out depending on the component of waste. This factor defaulted by IPCC varies from 0.42 at 10^{o}C to 0.98 at 50^{o}C. Landfill sites surveyed with a height more than 20 m, the temperature inside the landfill is approximately 50^{o}C. According to measured data, the height of the chosen cell in the Nam Son Landfill site is 20 m and its average temperature of an anaerobic zone is 40^{o}C. Therefore, the value of DOCf calculated is 0.84 (Table 5.1). It is assumed that the landfill condition is unchanged, therefore this value is used in all scenarios.

Table 5. 1 Input parameters used in calculation for scenarios

Input parameters	**MCF$^{(1)}$**	**DOC$^{(2)}$ (%)**	**DOCf$^{(3)}$**	**F$^{(4)}$**	**R$^{(5)}$**	**OX$^{(6)}$**
S0	1	13.2	0.84	0.5	0	0.1
S1		13.2			0.7	
S2		12.6			0	
S3		12.9			0	
S4		12.0			0.7	

(1) methane correction factor; (2) degradable organic carbon; (3) fraction of DOC decomposing under anaerobic conditions; (4)fraction of methane in landfill gas (volume fraction); (5) methane recovered; (6) oxidation factor

In the triangular gas production model, MSW is classified into rapidly, moderately and slowly degradable organics. Rapidly biodegradable organics (food waste) starts decomposing a few days after waste is placed in the landfill and take up to five years to complete decomposition. Moderately degradable organic (garden and park waste, leaves, grass trimmings) start the degradation process after a few months and finish after seven to ten years of burial. Paper, textile, leather, rubber, and wood are slow to biodegrade and begin decomposing about five years after they are buried in a landfill site and might take up to 50 years to complete the process (Tchobanoglous (1993), Paustian, Ravindranath and van Amstel (2006)).

Coefficient k reflects the rate of CH_4 generation. The value of k is affected by the component of waste, the condition of the landfill site and the local climate. If the proportion of easily digested organic waste is high and the landfill site is under warm climate conditions, the k value will be larger. As a result, the time of digestion will be shorter. Conversely, if the rate of easily digested organic waste is low and the landfill site is under cold climate conditions, the value of k will be small, which makes waste digestion difficult, and time of digestion longer.

In this study, the consideration of value k depends on the climate condition at the Nam Son Landfill site, the waste component and reference of IPCC default k values. Nam Son landfill site is located in Hanoi under a warm humid tropical climate with precipitation being around 1,690 mm per year and the annual average temperature being about 23.4°C. Therefore, default values of k and the corresponding half-lives are referenced in 2006 IPCC Guidelines for a tropical climate zone with mean annual temperature over 20^{o}C and mean annual precipitation over 1,000 mm (See Table B.1 in Appendix B). According to the equation of US EPA (2004), the calculated value of k is 0.06 and corresponding $t_{1/2}$ is 10 years. The value is only applied for mixed MSW due to lack of detailed data on percentages of organic fractions. Provided by the Triangular model, it is assumed that the organic waste (food waste or garden and park waste) needs 10 years for completion of decomposition and the average value of k and the corresponding half-life is 0.07 and 2 years. Slowly degrading waste requires 50 years to complete and the value of k and the corresponding $t_{1/2}$ assumed is 0.07 and 10 years (See Table B.1 in Appendix B). In addition, one year of delay time is used in the calculation.

5.2 Methane emissions from Nam Son landfill site

This section reviews the calculation of emissions of each scenario.

5.2.1 Potential methane emissions

The potential emissions of CH_4 from the Nam Son Landfill site differs between the five scenarios (Table 5.2). Scenario S0 -"Business as usual" shows that the total amount of CH_4 emitted is extremely high at 201,986 thousand m^3. However, if a gas recovery system is installed, it would capture 70% of CH_4 emissions for electricity generation as described in Scenario S2, and reduce CH_4 emissions by 141,396 thousand m^3. This brings with it environmental benefits and accompanying energy generation and associated economic benefits.

Table 5. 2 The total emissions of each scenario using IPCC default model

Scenario	Amount of waste (thousand tonnes)	CH_4 emissions (thousand m^3)	Emission reduction	
			Thousand m^3	%
S0 (Landfill only)	2174	201,986	0	0
S1 (Gas capture)	2174	60,596	141,390	70
S2 (Landfill/Compost)	1589	140,315	61,670	31
S3 (Landfill/recycle)	1970	178,392	23,594	12
S4 (upgraded system)	1385	35,017	166,969	83

The benefits of composting and recycling are seen in Scenarios S2 (Composting of organic waste) and S3 (Recycling prior to landfill) where refined products are separated and retained for usage to produce future products, offsetting the emissions from processing virgin materials. The findings for S2 and S3 indicate that composting results in a greater CH_4 emissions reduction compared to recycling with 31% and 12% of CH_4 emissions reduction respectively. This might be because the percentage of organic waste in garbage in Hanoi (53.81%) is much higher than recyclable materials. Composting in scenario S2 decreases CH_4 emissions by 61,670 thousand m^3. In scenario S3, only some of the recycled materials are decomposed to produce CH_4, for example, paper, wood, textile and rubber. The reduction of 23,594 thousand m^3 CH_4 from the 30% recycling materials is a significant number. The most significant reduction of CH_4 emissions is seen in scenario S4 where composting 50% of organic waste, recycling 30% of recyclable material is accompanied with landfill gas capture for flaring. The scenario decreases by 83% of emitted gas, which is equivalent to CH_4 emissions of 166,969 thousand m^3.

5.2.2 Variation in methane production with time

The process of CH_4 emissions over time in Nam Son landfill site is presented in Figure 5.1 and 5.2. Figure 5.1 exhibits the annual landfill gas production rates for mixed MSW once the data on waste composition is excluded, using $k = 0.06$ and $t_{1/2} = 10$ years. The results show that the emission process for all scenarios are similar to the model assuming that there is no CH_4 production in the first year of 2008. The production starts from 2009 with a dramatic increase and peak at 100,993 thousand m^3 for S0; 70,158 thousand m^3 for S2; 89,196 thousand m^3 for S3; and 17,508 thousand m^3 for S4 after ten years by 2018, followed by a significant reduction over the next 20 years. Over the first 30 years, approximately 80% of total CH_4 will be generated. The CH_4 generation from 2040 remains gradual over a long period of time until 2100. As such, the lifespan of the landfill site is around 100 years and the most suitable time to operate a CH_4 capture system is from 2009 to 2038 (Figure 5.1).

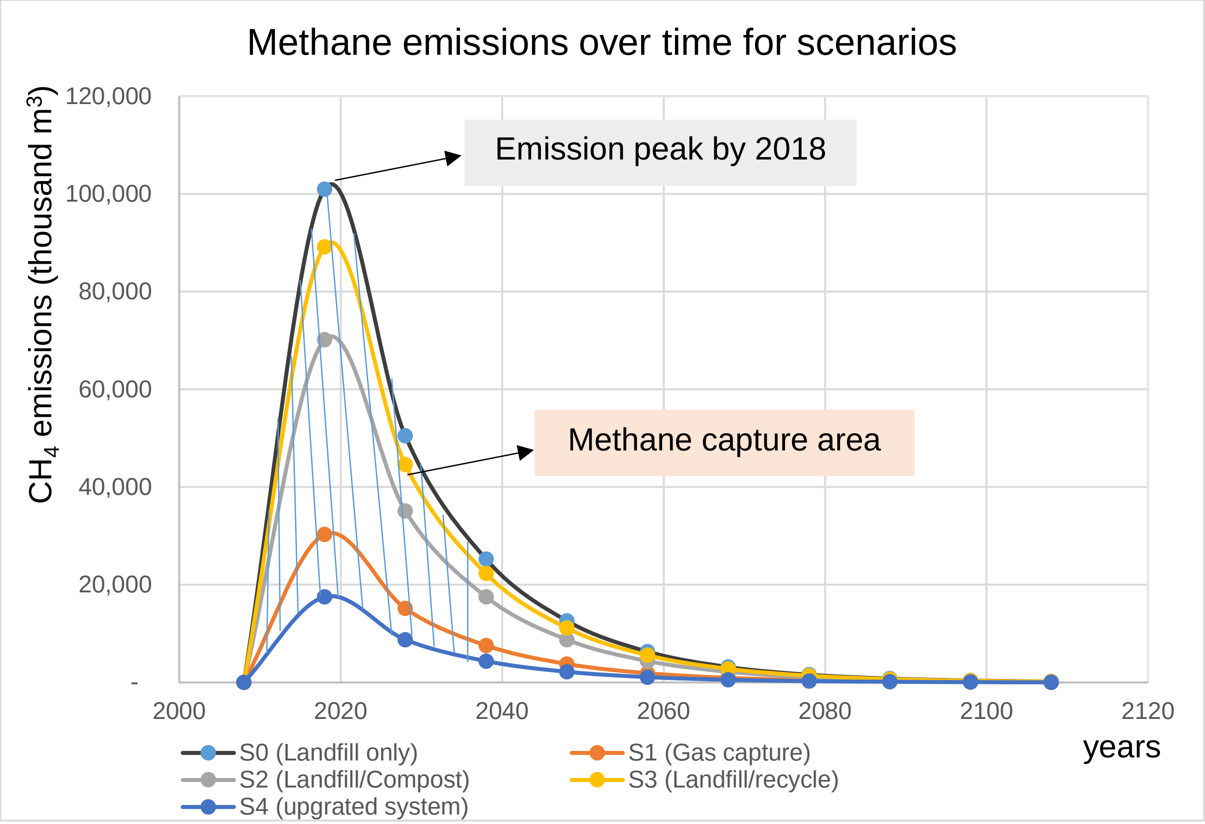


Figure 5. 1 Methane emissions in Nam Son landfill site over time for scenarios

Annual CH_4 production provided by the Triangular model at the Nam Son landfill site is presented in Figure 5.2. The amount of CH_4 emissions calculated by the Triangular model is far lower than the IPCC model because only decomposable materials which produce CH_4 (organic waste, paper, wood, textile, rubber and leather) are taken into account in the model. The model simulations show that rapidly and moderately biodegradable organic wastes are decomposed a few days after being placed in the landfill. The processes of emissions reach peak after 2 years in 2009 and finish after 10 years in 2017. Meanwhile, the process of slowly biodegradable fractions begin decomposing about 5 years after burial and reach a peak by 2017, 10 years after landfilling. This means that once decomposition of organic waste is nearly completed, slowly decomposable material will begin and reach maximum by 2017. The generation of CH_4 in the Nam Son Landfill site continues and lasts 50 years to 2057 (Figure 5.3).

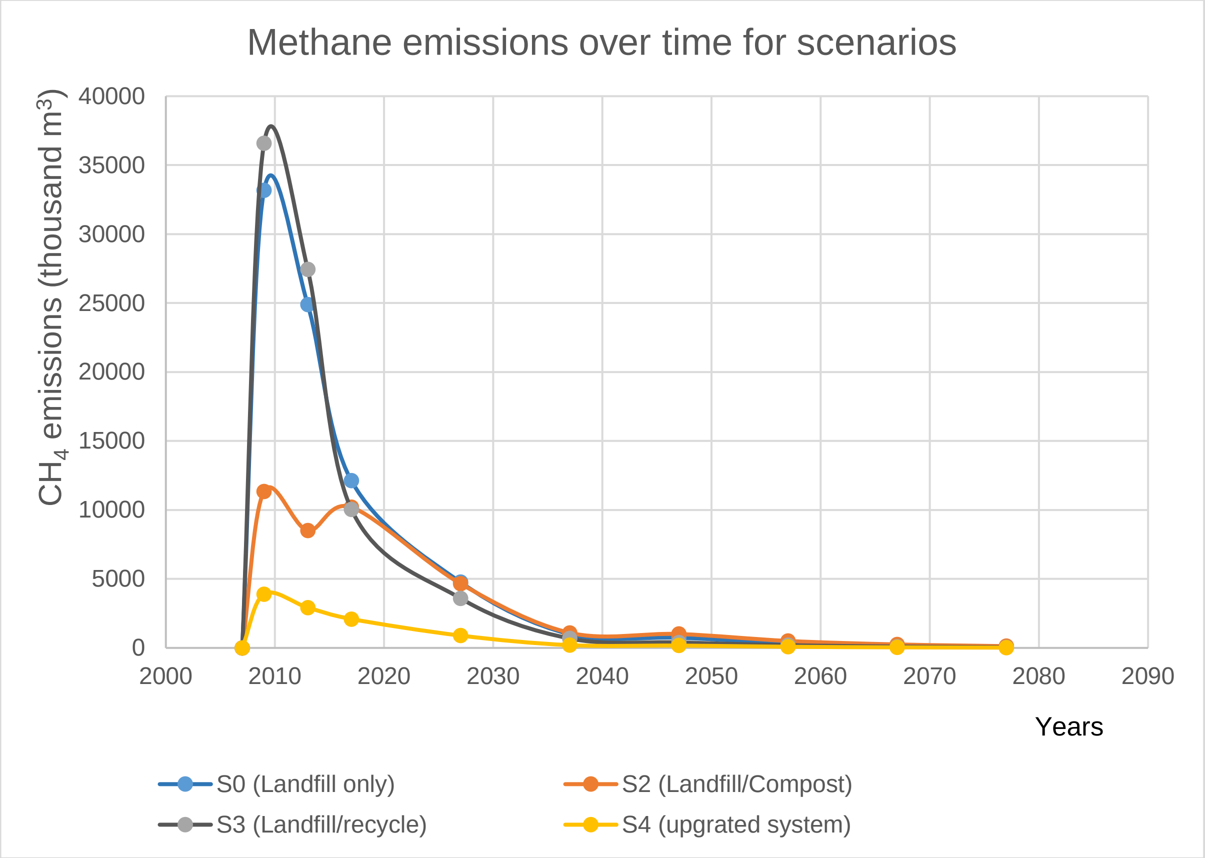


Figure 5. 2 Methane emissions over time for scenarios

The results show that scenarios S4 and S2 reduce a significant amount of CH_4 emissions. The emissions in scenarios S4 and S2 reach a peak in 2009, however the CH_4 generation lasts until 2030, 30 years after burial. This shows that the composting method plays an important role in improving the MSW management system. Scenario S3 has the lowest reduction of CH_4 emissions compared to other scenarios, the emissions during 2017 to 2037 is lower than that of S0 and even S2 due to the decrease in recyclable materials.

CHAPTER 6 CONCLUSION

The research used Life-cycle Assessment (LCA) as a key method. The research has provided a comprehensive, transparent, and scientific understanding potential environmental impacts of solid waste management regarding GHG emissions by taking into account all environmental aspects associated with the MSW landfill. The research has been valuable by identifying the gaps of using LCA in Vietnam. There is an absence of country-specific key parameters, and the lack of the appropriate methods or models in estimation of GHG emissions.

The study has combined two accounting models for inventory of CH_4 emissions from landfill in phase of Life Cycle Inventory (LCI): IPCC Default and Triangular models that is to reflect a comprehensive process of CH_4 emissions over time despite the limitation of available data. Based on the principle of mass balance, the IPCC default model has gained popularity due to its simple assumptions of all potential CH_4 emitted from a landfill site. The Triangular model, a modified model of the First Order Decay that was developed and applied in the absence of available data, described the true pattern of degradation by simulating CH_4 generation over time. The calculation was carried out in Nam Son Landfill site.

Thousands of tonnes of MSW generated daily is an inevitable consequence of the economic growth and rapid urbanization and industrialization of Hanoi. The average total volume of MSW generated in Hanoi between 2010 and 2015 was approximately 6,300 tonnes per day. The quantity of MSW is projected to increase 10% per year creating many challenges in the solid waste management facing Hanoi. The rate of waste generation in Hanoi is 1.2 kg per person per day, being highest compared to the country average of 0.61 kg per person per day in Vietnam, and even higher in comparison of other countries, especially Delhi in India, and Beijing and Shanghai in China. The limitation of appropriate treatment methods, the lack of suitable facilities for the collection and the separation at source are other gaps in the MSW management.

The research developed five scenarios; wherein Scenario S0 is “business as usual” and four alternative scenarios describe options for the MWS management in Hanoi. These scenarios serve to explore the potential of CH_4 emission reduction from capturing gas with flaring (S1 – 70% of CH_4 captured with flaring), composting (S2 – 50% of organic waste composted), recycling (S3 – 30% of recyclable materials recycled). The integration of composting and recycling and gas capturing is central to S4.

The results show that CH_4 emissions are extremely high at 201,986 thousand m^3 for scenario S0 - “Business as usual”. A significant reduction of 70% of CH_4 emissions coinciding with flaring of LFG is achieved in scenario 1. However, the greatest reduction in CH_4 emissions occurs in scenario S4 with 83% of reduction of CH_4 emissions. The findings for S2 and S3 present the benefits of composting and recycling with the composting scenario contributes a greater emission reduction compared to recycling, 31% and 12% of emission reduction respectively.

All scenarios reach peak of CH_4 emissions in 2009 that may be explained by the higher rate of organic waste in garbage component in Nam Son landfill site. However, the year that ends the process of CH_4 emissions is different for various scenarios. Scenario S0 – “business as usual” and S3, the generation of CH_4 in the Nam Son landfill lasts around 50 years from 2009 to 2057. Meanwhile, for scenarios S4 and S2, the CH_4 generations last until 2030, 30 years after burying.

The integration of composting, recycling and gas capture in Scenario S4 is the best option for improvement of MSW management in Hanoi and to reduce environmental impacts of

GHG emissions. This option may be a valuable solution that supports decision-making of solid waste management involved at a local authority level, as well as policy-makers of the national level to improve MSW management and reduce GHGs emissions to combat climate change.

APPENDIXES

Appendix A. The IPCC default model

The IPCC default model is based on the mass balance equation as follows:

$$\mathrm{CH}_{4,\mathrm{emitted}} = \left[\left(\mathrm{MSW}_{\mathrm{input}} \times \mathrm{L}_0\right) - \mathrm{R}\right] \times (1 - \mathrm{OX}) \qquad (1)$$

Where:

$CH_{4emitted}$: total CH_4 emitted from landfill (tonnes/yr)

MSW_{input}: total amount MSW disposed to landfill (tonnes/yr)

L_0 = CH_4 generation potential (tonnes CH_4/tonnes waste)

R: methane recovered (tonnes/yr)

OX: oxidation factor

CH_4 generation potential (L_0) is calculated by equation (2) below:

$$\mathrm{L}_0 = \mathrm{MCF} \times \mathrm{DOC} \times \mathrm{DOCf} \times \mathrm{F} \times \frac{16}{12} \qquad (2)$$

Where:

MCF: methane correction factor (fraction)

DOC: degradable organic carbon (kg C/ kg MSW)

DOC_f: fraction of DOC decomposing under anaerobic conditions (fraction)

F: fraction of methane in landfill gas (volume fraction)

16/12: molecular weight ratio CH_4/C

Table A. 1 The default values used for IPCC application

Factor	Derivation method	Default value
MCF	MCF value reflects the status management of the site. IPCC recommended default MCF values for different types of landfill.	Managed - anaerobic: 1 Managed - semi-aerobic: 0.5 Unmanaged (>5m waste): 0.8 Unmanaged (<5m waste): 0.4 Uncategorised: 0.6
DOC	DOC is the content of the organic carbon that is accessible to biochemical decomposition. DOC values is based on national MSW composition and calculated from a weighted average of the carbon content of various components of the wet waste stream by equation: DOC= (A*0.15) + (B*0.4) + (C*0.43) + (D*0.24) + (E*0.39)	A: % of organic waste B: % of paper C: % of wood D: % of textile E: % of rubber and leather
DOC_f	DOCF is an estimate of the fraction of carbon that is ultimately degraded and reflects some organic carbon not degrading, or degrading very slowly, when deposited in landfill. DOC_f depends on the temperature of landfill and is calculated by the theoretical equation (Tabasaran 1981): $DOC_f = 0.014*T + 0.28$ Where: T is the temperature.	The IPCC default value is 0.77, however, based on a review of recent literature, it appears that this default value may be an overestimate. An IPCC workshop in Washington in 1995 recommended the use of 0.5 as a new default factor on the basis of several experimental studies.
F	Landfill gas consists mainly of CH_4 and carbon dioxide (CO_2). The CH_4 fraction F is usually taken to be 0.5, but can vary between 0.4 and 0.6, depending on several factors including waste composition (e.g. carbohydrate and cellulose).	0.5
R	R value will be changed based on methane recovery technology applied in landfill site	0
OX	OX value reflects the amount of CH4 from landfill that is oxidised in the soil or other material covering the waste.	Managed with top cover: 0.1 Managed or unmanaged without top cover: 0

Appendix B. The Triangular model

The triangular model is based the following equation:

$$\mathrm{CH}_{4,\mathrm{emitted,i}} = \frac{1}{2}\left(\mathrm{t}_{\mathrm{end,i}} - \mathrm{t}_{\mathrm{o,i}}\right) \times \mathrm{Q}_{\mathrm{emission,max,i}} \tag{3}$$

Where:

$CH_{4,emitted,i}$: total amount of CH_4 emitted from landfill at year i (tonnes/yr)

$t_{end,i}$: the time during which gas production take place at year i (year)

$t_{o,i}$: the time at which LFG production starts from the waste at year i (year)

$Q_{emission, max,i}$: the maximum gas production rate (tonnes/year)

Table B. 1 Recommended default values of CH_4 generation rate k and half-life ($t_{1/2}$)

Type of Waste		***k***		**$t_{1/2}$**	
		Range	**Default**	**Range**	**Default**
Slowly degrading waste	paper/textiles	0.06-0.085	**0.07**	8 - 12	**10**
	Wood/straw	0.03-0.05	**0.035**	14-23	**20**
Moderately degrading waste	Other (non-food) organic putrescible/ Garden and park waste	0.15-0.2	**0.17**	3-5	**4**
Rapidly degrading waste	Food waste	0.17-0.7	**0.4**	1-4	**2**

REFERENCES

Allegrini, E, Vadenbo, C, Boldrin, A & Astrup, TF 2015, 'Life cycle assessment of resource recovery from municipal solid waste incineration bottom ash', *Journal of Environmental Management*, vol. 151, no. Supplement C, pp. 132-143.

Amini, HR, Reinhart, DR & Mackie, KR 2012, 'Determination of first-order landfill gas modeling parameters and uncertainties', *Waste Management*, vol. 32, no. 2, pp. 305-316.

Atabi, F, Ehyaei, MA & Ahmadi, MH 2014, 'Calculation of CH_4 and CO_2 Emission Rate in Kahrizak Landfill Site with Land GEM Mathematical Model', paper presented to the 4th World Sustainability Forum 2014, 1-30 November.

Barlaz, MA 2004, *Critical review of forest products decomposition in municipal solid waste landfills*, National Council for Air and Stream Improvement, North Carolina.

Berger, S & Mann, J 2001, 'Landfill gas Primer-An overview for environmental health professionals', *Agency for Toxic Substances and Disease Registry (ATSDR), Department of Health and Human Services, Agency for Toxic Substances and Disease Registry, Division of Health Assessment and Consultation.*

Blengini, GA 2008, 'Applying LCA to organic waste management in Piedmont, Italy', *Management of Environmental Quality: An International Journal*, vol. 19, no. 5, pp. 533-549.

Bogner, J & Matthews, E 2003, 'Global methane emissions from landfills: new methodology and annual estimates 1980–1996', *Global Biogeochemical Cycles*, vol. 17, no. 2, pp. 18: 34.

Börjeson, L, Höjer, M, Dreborg, KH, Ekvall, T & Finnveden, G 2006, 'Scenario types and techniques: towards a user's guide', *Futures*, vol. 38, no. 7, pp. 723-739.

Börjesson, G, Sundh, I & Svensson, B 2004, 'Microbial oxidation of CH_4 at different temperatures in landfill cover soils', *FEMS Microbiology Ecology*, vol. 48, no. 3, pp. 305-312.

Chakraborty, M, Sharma, C, Pandey, J, Singh, N & Gupta, PK 2011, 'Methane emission estimation from landfills in Delhi: A comparative assessment of different methodologies', *Atmospheric Environment*, vol. 45, no. 39, pp. 7135-42.

Cook, J, Oreskes, N, Doran, PT, Anderegg, WR, Verheggen, B, Maibach, EW, Carlton, JS, Lewandowsky, S, Skuce, AG & Green, SA 2016, 'Consensus on consensus: a synthesis of consensus estimates on human-caused global warming', *Environmental Research Letters*, vol. 11, no. 4, p. 048002.

Damanhuri, E, Handoko, W & Padmi, T 2014, 'Municipal Solid Waste Management in Indonesia', in *Municipal Solid Waste Management in Asia and the Pacific Islands*, Springer, pp. 139-55.

Del Borghi, A, Gallo, M & Del Borghi, M 2009, 'A survey of life cycle approaches in waste management', *The International Journal of Life Cycle Assessment*, vol. 14, no. 7, pp. 597-610.

Dhokhikah, Y & Trihadiningrum, Y 2012, 'Solid waste management in Asian developing countries: challenges and opportunities', *Journal of Applied Environmental and Biological Sciences,* vol. 2, no. 7, pp. 329-335.

Department of Natural Resources and Environment (DONRE) 2015, *Environmental Situation Report in Hanoi city*, Department of Natural Resources and Environment, Hanoi, Vietnam.

Eggleston, H, Buendia, L, Miwa, K, Ngara, T & Tanabe, K 2006, 'IPCC guidelines for national greenhouse gas inventories', *Institute for Global Environmental Strategies, Hayama, Japan*, vol. 2, pp. 48-56.

Ekvall, T, Assefa, G, Björklund, A, Eriksson, O & Finnveden, G 2007, 'What life-cycle assessment does and does not do in assessments of waste management', *Waste Management*, vol. 27, no. 8, pp. 989-996.

Ekvall, T, Tillman, AM & Molander, S 2005, 'Normative ethics and methodology for life cycle assessment', *Journal of Cleaner Production*, vol. 13, no. 13, pp. 1225-1234.

Eriksson, O, Frostell, B, Björklund, A, Assefa, G, Sundqvist, JO, Granath, J, Carlsson, M, Baky, A & Thyselius, L 2002, 'ORWARE—a simulation tool for waste management', *Resources, Conservation and Recycling*, vol. 36, no. 4, pp. 287-307.

Faour, AA, Reinhart, DR & You, H 2007, 'First-order kinetic gas generation model parameters for wet landfills', *Waste Management*, vol. 27, no. 7, pp. 946-953.

Finnveden, G 1999, 'Methodological aspects of life cycle assessment of integrated solid waste management systems', *Resources, Conservation and Recycling*, vol. 26, no. 3, pp. 173-187.

Finnveden, G 2008, 'A world with CO_2 caps', *The International Journal of Life Cycle Assessment*, vol. 13, no. 5, p. 365.

Finnveden, G, Hauschild, MZ, Ekvall, T, Guinée, J, Heijungs, R, Hellweg, S, Koehler, A, Pennington, D & Suh, S 2009, 'Recent developments in life cycle assessment', *Journal of Environmental Management*, vol. 91, no. 1, pp. 1-21.

Finnveden, G & Moberg, Å 2005, 'Environmental systems analysis tools - an overview', *Journal of Cleaner Production*, vol. 13, no. 12, pp. 1165-1173.

Fourie, A & Morris, J 2004, 'Measured gas emissions from four landfills in South Africa and some implications for landfill design and methane recovery in semi-arid climates', *Waste Management* & Research, vol. 22, no. 6, pp. 440-253.

Fredenslund, A, Kjeldsen, P, Scheutz, C & Lemming, G 2007, 'Biocover–reduction of greenhouse gas emissions from landfills by use of engineered bio-covers', *Kalmar ECO-Tech, Kalmar, Sweden*.

Fredenslund, AM 2010, ‘Reduction of greenhouse gas emissions from landfills by use of engineered biocovers: full scale studies’, PhD thesis, Technical University of Denmark, Department of Environmental Engineering, Denmark.

Friedrich, E 2013, 'An Investigation Into the Emissions of Greenhouse Gases Associated with the Disposal of Solid Waste in the EThekwini Municipality', PhD thesis, University of KwaZulu-Natal, Durban, South Africa.

Gentil, E, Christensen, TH & Aoustin, E 2009, 'Greenhouse gas accounting and waste management', *Waste Management & Research*, vol. 27, no. 8, pp. 696-706.

Gregory, R, Gillett, A & Bradley, D 2003, *Methane emissions from landfill sites in the UK*, Land Quality Management Limited, the UK.

Guerrero, LA, Maas, G & Hogland, W 2013, 'Solid waste management challenges for cities in developing countries', *Waste Management*, vol. 33, no. 1, pp. 220-232.

Guinee, JB, Heijungs, R, Huppes, G, Zamagni, A, Masoni, P, Buonamici, R, Ekvall, T & Rydberg, T 2010, ‘Life cycle assessment: past, present, and future’, *Environmental Science and Technology*, vol. 45, no. 1, pp. 90-96.

Guo, M 2013, *Life cycle assessment (LCA) of light-weight eco-composites*, PhD thesis, Imperial College London, London, UK.

Heijungs, R, Guinée, JB, Huppes, G, Lankreijer, RM, Udo de Haes, HA, Wegener Sleeswijk, A, Ansems, A, Eggels, P, Duin, Rv & De Goede, H 1992, *Environmental life cycle assessment of products: guide and backgrounds (part 1)*, Netherlands Agency for Energy and the Environment, The Netherlands.

Höjer, M, Ahlroth, S, Dreborg, KH, Ekvall, T, Finnveden, G, Hjelm, O, Hochschorner, E, Nilsson, M & Palm, V 2008, 'Scenarios in selected tools for environmental systems analysis', *Journal of Cleaner Production*, vol. 16, no. 18, pp. 1958-1970.

Houghton, J, Meira Filho, L, Lim, B, Treanton, K & Mamaty, I 1997, 'Revised 1996 IPCC guidelines for national greenhouse gas inventories. v.1: Greenhouse gas inventory reporting instructions. v.2: Greenhouse gas inventory workbook. v.3: Greenhouse gas inventory reference manual', IPCC.

Intergovernmental Panel on Climate Change (IPCC) 2015, *Climate change 2014: mitigation of climate change*, vol. 3, Cambridge University Press.

International Organization for Standardization (ISO) 14040 1997, *Environmental management - Life cycle Assessment - Principles and framework*, Technical Committee ISO, Switzerland.

International Organization for Standardization (ISO) 14041 1998, *Environmental management - Life Cycle Assessment - Goal and scope definition and inventory analysis*, Technical Committee ISO, Switzerland.

Jigar, E, Bairu, A & Gesessew, A 2014, 'Application of IPCC model for estimation of methane from municipal solid waste landfill', *Journal of Environmental Science and Water Resources*, vol. 3, no.4, pp. 52-58.

Kaushal, RK, Varghese, GK & Chabukdhara, M 2012, 'Municipal solid waste management in India-current state and future challenges: a review', *International Journal of Engineering Science and Technology*, vol. 4, no. 4, pp. 1473-89.

Kittipongvises, S & Polprasert, C 2016, 'GHGs Emissions and Sustainable Solid Waste Management', in OP Karthikeyan, K Heimann & SS Muthu (eds), *Recycling of Solid Waste for Biofuels and Bio-chemicals*, Springer Singapore, Singapore, pp. 55-85.

Kumar, A & Sharma, M 2014, 'Estimation of GHG emission and energy recovery potential from MSW landfill sites', *Sustainable Energy Technologies and Assessments*, vol. 5, pp. 50-61.

Kumar, S 2016, *Municipal Solid Waste Management in Developing Countries*, CRC Press, US.

Kumar, S, Gaikwad, SA, Shekdar, AV, Kshirsagar, PS & Singh, RN 2004a, 'Estimation method for national methane emission from solid waste landfills', *Atmospheric Environment*, vol. 38, no. 21, pp. 3481-7.

Kumar, S, Mondal, A, Gaikwad, S, Devotta, S & Singh, R 2004b, 'Qualitative assessment of methane emission inventory from municipal solid waste disposal sites: a case study', *Atmospheric Environment*, vol. 38, no. 29, pp. 4921-9.

Lecouls, H 1999, 'ISO 14043: Environmental management· life cycle assessment· life cycle interpretation', *The International Journal of Life Cycle Assessment*, vol. 4, no. 5, pp. 245.

Leroy, M & Vuong, C 2016, *Solid Waste Typology and Management in Hanoi*, Institut des Métiers de la Ville (IMV), Hanoi.

Lianghu, S, Sheng, H, Dongjie, N, Xiaoli, C, Yongfeng, N & Youcai, Z 2014, 'Municipal solid waste management in China', in *Municipal Solid Waste Management in Asia and the Pacific Islands*, Springer, pp. 95-112.

Liu, C & Wu, X-w 2011, 'Factors influencing municipal solid waste generation in China: A multiple statistical analysis study', *Waste Management and Research*, vol. 29, no. 4, pp. 371-378.

Lu, H, Huang, G, Liu, Z & He, L 2008, 'Greenhouse gas mitigation-induced rough-interval programming for municipal solid waste management', *Journal of the Air and Waste Management Association*, vol. 58, no. 12, pp. 1546-1559.

Lundie, S, Ciroth, A & Huppes, G 2007, 'Inventory methods in LCA: towards consistency and improvement (UNEP-SETAC Life Cylce InitiativeLife cycle inventory LCI programmetask force 3: Methodological consistency)', pp. 1-135.

McElwee, P, Le, T, Vu TDH, Nguyen, H, Le, A, Dang, T & Nguyen, T 2010, 'The social dimensions of adaptation to climate change in Vietnam', *World Bank Discussion Paper*.

Ménard, JF, Lesage, P, Deschênes, L & Samson, R 2004, 'Comparative life cycle assessment of two landfill technologies for the treatment of municipal solid waste', *The International Journal of Life Cycle Assessment*, vol. 9, no. 6, pp. 371-378.

Ministry of Natural Resources and Environment (MONRE) 2011, *National state of Environment* 2011 - Solid waste, Ministry of Natural Resources and Environment, Hanoi, Vietnam.

Mor, S, Ravindra, K, De Visscher, A, Dahiya, R & Chandra, A 2006, 'Municipal solid waste characterization and its assessment for potential methane generation: a case study', *Science of the Total Environment*, vol. 371, no. 1, pp. 1-10.

Nabavi-Pelesaraei, A, Bayat, R, Hosseinzadeh-Bandbafha, H, Afrasyabi, H & Chau, K-w 2017, 'Modeling of energy consumption and environmental life cycle assessment for incineration and landfill systems of municipal solid waste management-A case study in Tehran Metropolis of Iran', *Journal of Cleaner Production*, vol. 148, pp. 427-440.

Nguyen, VG & Nguyen, BD 2017, 'Hydrogeophysical approach for contamination assessment in NamSon landfill, Hanoi, Vietnam', *Arabian Journal of Geosciences*, vol. 10, no. 17, p. 12: 377.

Obersteiner, G, Binner, E, Mostbauer, P & Salhofer, S 2007, 'Landfill modelling in LCA–a contribution based on empirical data', *Waste Management*, vol. 27, no. 8, pp. S58-S74.

Oonk, H 2010, 'Literature review: methane from landfills', *Final report for Sustainable landfill foundation*, The Netherlands.

Oonk, H & Boom, T 1995, 'Validation of landfill gas formation models', *Studies in Environmental Science*, vol. 65, pp. 597-602.

Pariatamby, A & Fauziah, S 2014, 'Sustainable 3R practice in the Asia and Pacific Regions: the challenges and issues', in *Municipal Solid Waste Management in Asia and the Pacific Islands*, Springer, pp. 15-40.

Paustian, K, Ravindranath, N & Van Amstel, A 2006, *2006 IPCC Guidelines for National Greenhouse Gas Inventories*.

Pelt, R, White, C, Blackard, A, Bass, RL, Burklin, C, Heaton, RE, Reisdorph, A & Thorneloe, SA 1998, 'User's Manual Landfill Gas Emissions Model', *US Environmental Protection Agency Contract*, Washington, DC.

Pesonen, H-L, Ekvall, T, Fleischer, G, Huppes, G, Jahn, C, Klos, ZS, Rebitzer, G, Sonnemann, GW, Tintinelli, A & Weidema, BP 2000, 'Framework for scenario development in LCA', *The International Journal of Life Cycle Assessment*, vol. 5, no. 1, p. 21-30.

Pikoń, K & Gaska, K 2010, 'Greenhouse gas emission mitigation relevant to changes in municipal solid waste management system', *Journal of the Air & Waste Management Association*, vol. 60, no. 7, pp. 782-788.

Rebitzer, G, Ekvall, T, Frischknecht, R, Hunkeler, D, Norris, G, Rydberg, T, Schmidt, W-P, Suh, S, Weidema, BP & Pennington, DW 2004, 'Life cycle assessment: Part 1: Framework, goal and scope definition, inventory analysis, and applications', *Environment International*, vol. 30, no. 5, pp. 701-720.

Ryding, SO 1999, 'ISO 14042 Environmental management - Life cycle assessment - life cycle impact assessment', *The International Journal of Life Cycle Assessment*, vol. 4, no. 6, pp. 307.

Sandén, BA & Karlström, M 2007, 'Positive and negative feedback in consequential life-cycle assessment', *Journal of Cleaner Production*, vol. 15, no. 15, pp. 1469-1481.

Scharff, H & Jacobs, J 2006, 'Applying guidance for methane emission estimation for landfills', *Waste Management*, vol. 26, no. 4, pp. 417-429.

Scheutz, C, Kjeldsen, P, Bogner, JE, De Visscher, A, Gebert, J, Hilger, HA, Huber-Humer, M & Spokas, K 2009, 'Microbial methane oxidation processes and technologies for mitigation of landfill gas emissions', *Waste Management & Research*, vol. 27, no. 5, pp. 409-455.

Sethy, S, Sothun, C & Wildblood, R 2014, 'Municipal solid waste management in Cambodia', in *Municipal solid waste Management in Asia and the Pacific Islands*, Springer, pp. 77-94.

Shekdar, A 1997, 'A strategy for the development of landfill gas technology in India', *Waste Management and Research*, vol. 15, no. 3, pp. 255-266.

Shekdar, AV 2009, 'Sustainable solid waste management: An integrated approach for Asian countries', *Waste Management*, vol. 29, no. 4, pp. 1438-1448.

Solomon, S, Qin, D, Manning, M, Chen, Z, Marquis, M, Averyt, KB, Tignor, M & Miller, HL 2007, *Contribution of working group I to the fourth assessment report of the Intergovernmental Panel on* Climate Change, 2007, Cambridge University Press, Cambridge.

Spies, S, Pfaff-Simoneit, GW, Entwicklungsbank, K & Eschborn, P 2010, 'SWM GHG Calculator– a Tool for Calculating Greenhouse Gases in Solid Waste Management (SWM)', in *ISWA World Congress*.

Sundqvist, JO, Finnveden, G, Albertsson, A, Karlsson, S, Berendson, J, Eriksson, E & Höglund, L 1999, 'Life cycle assessment and solid waste', *AFR report*, vol. 279.

Tang, Y, Ma, X, Lai, Z & Chen, Y 2013, 'Energy analysis and environmental impacts of a MSW oxy-fuel incineration power plant in China', *Energy Policy*, vol. 60, pp. 132-141.

Tascione, V & Raggi, A 2012, 'Identification and selection of alternative scenarios in LCA studies of integrated waste management systems: a review of main issues and perspectives', *Sustainability*, vol. 4, no. 10, pp. 2430-2442.

Tchobanoglous, G 1993, *Integrated solid waste managementengineering principles and management issues,* McGraw-Hill series in Water Resources and Environmental Engineering, NY.

Thai, NTK 2014, 'Municipal solid waste management in Vietnam challenges and solutions', *Municipal Solid Waste Management in Asia and the Pacific Islands*, Springer, pp. 355-377.

Thanh, NP & Matsui, Y 2013, 'Assessment of potential impacts of municipal solid waste treatment alternatives by using life cycle approach: a case study in Vietnam', *Environmental Monitoring and Assessment*, vol. 185, no. 10, pp. 7993-8004.

Thompson, S & Tanapat, S 2005, 'Modeling waste management options for greenhouse gas reduction', *Journal of Environmental Informatics*, vol. 6, no. 1, pp. 16-24.

Turconi, R, Butera, S, Boldrin, A, Grosso, M, Rigamonti, L & Astrup, T 2011, 'Life cycle assessment of waste incineration in Denmark and Italy using two LCA models', *Waste management & research*, vol. 29, no. 10 Supplement, pp. S78-S90.

US Environmental Protection Agency (USEPA), Ooaqpas 2004, 'Quantification of exposure: Development of the emissions inventory for the inhalation risk assessment (Chapter 7)'.

US Environmental Protection Agency (USEPA) 2006, *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 – 2004*, Environmental Protection Agency, Washington, DC.

Verma, R, Borongan, G & Memon, M 2016, 'Municipal Solid Waste Management in Ho Chi Minh City, Viet Nam, Current Practices and Future Recommendation', *Procedia Environmental Sciences*, vol. 35, pp. 127-139.

Vigon, BW, Tolle, D, Cornaby, B & Latham, H 1993, 'Life-cycle assessment: Inventory guidelines and principles'.

Wang, H & Wang, C 2013, 'Municipal solid waste management in Beijing: characteristics and challenges', *Waste Management and Research*, vol. 31, no. 1, pp. 67-72.

Wangyao, K, Towprayoon, S, Chiemchaisri, C, Gheewala, SH & Nopharatana, A 2010, 'Application of the IPCC Waste Model to solid waste disposal sites in tropical countries: case study of Thailand', *Environmental Monitoring and Assessment*, vol. 164, no. 1, pp. 249-261.

Weidema, BP 2003, *Market information in life cycle assessment*, vol. 863, Miljøstyrelsen.

Wilson, E 2002, 'Life cycle inventory for Municipal Solid Waste management Part 2: MSW management scenarios and modeling', *Waste Management and Research*, vol. 20, no. 1, pp. 23-36.

Wittmaier, M, Langer, S & Sawilla, B 2009, 'Possibilities and limitations of life cycle assessment (LCA) in the development of waste utilization systems–Applied examples for a region in Northern Germany', *Waste Management*, vol. 29, no. 5, pp. 1732-1738.

Wreford, K 1996, 'An analysis of the factors affecting landfill gas composition and production and leachate characteristics at the Vancouver Landfill Site at Burns Bog', Master thesis, University of British Columbia.

Zhang, C 2012, 'Assessing greenhouse gas emission from waste management in EU countries', Ms Thesis, *University of Jyväskylä.*