Energy recovery from municipal solid waste landfill for a sustainable circular economy in Danang City, Vietnam

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Abstract. Sustainable development of Danang City in the direction of circular economy (CE) and a zero-waste city is an urgent solution because the impacts of local municipal solid waste (MSW) generation in the city’s districts are increasingly causing serious pressure for MSW management and treatment. Segregation of waste at source, reuse, recycling, and energy recovery from landfill gas (LFG) generated is considered as one of the keys to solving the dilemma of sustainable waste management. This study analyzed and evaluated the generation of greenhouse gases (GHGs), mainly CH₄ and CO₂ gases from the Khanh Son landfill based on the application of the EnLandFill software and assessed the potential of energy recovery, clean electricity generation, as well as GHG emission reduction in the period of 2021–2050 based on the CE-oriented scenario of the city government. With the potential to recover LFGs in the period of 2021–2050 could reach 136.9 million m³ (with efficiency E = 90%), the total annual potential value of electricity generation is estimated at 420.767 million kWh, equivalent to the total potential for GHGs emission reduction (GWP) about 271.25 thousand tCO₂-eq. At the same time, this will be a baseline study to serve as the basis for extensive assessments and to suggest the most appropriate waste management strategies and policies create a circular economy in the future.

1. Introduction
Danang City is the fourth largest city in Vietnam after Ho Chi Minh City, Hanoi Capital, and Hai Phong City in terms of urbanization and socio-economic development. Located on the Eastern Sea coast with the estuary of the Han River, Danang is one of the Port cities with a strategic location in Central Vietnam and one of five municipalities directly under the Central Government. The total area of the city is 1,284.88 km² [1]. The population of Danang City has reached 1,134,310 people in 2019 [1]. This place has a rapid urbanization rate, people's lives are increasingly improved, the demand for material life and resource use is increasing, leading to an increase in the amount of solid waste in general and the amount of municipal solid waste (MSW) in particular is increasing [1]. In this context, currently, Danang City has been aiming to build a zero-waste city with a sustainable circular economy.

The term of CE first appeared in a study by Pearce and Turner [2] referring to the link between the environment and economic activities that have attracted considerable attention from many different target groups worldwide in recent years [3]. However, the boundary of CE definition is not defined, there are variations based on many factors and different perspectives [4]; typically, a variety of principles and recommendations have emerged over the past decades, including “regenerative design” [5], “performance
economy” [6], “Cradle-to-Cradle” [7] and “industrial ecology” [8]. But in general, the goal of CE models is towards a better alternative to the traditional economic development model, called “take, make and dispose” [9–11]. Currently, CE has been recognized as a guiding principle for policy in many countries and has approached implementation in a variety of ways [12]. In the European Union (EU), CE has become a central aspect of development strategies and policies and is seen as part of the Circular Economy Action Plan [13]. On a global scale, countries including Germany, Japan, China, and the EU are recognized as having developed legal systems for the implementation of CE principles [4], [14]. China has particularly considered CE as the central goal of the 11th and 12th Five-Year Plans on National Economic and Social Development [14], and also in 2009 officially promulgated the “Circular Economy Promotion Law”, in which CE is defined as a general term for actions to reduce, reuse and recycle in production, circulation, and consumption [4]. Especially, China's CE approach is a top-down solution, which is quite different from other countries that have developed CE policies with a bottom-up approach [3]. The basic CE models have contributed to the formation of a new set-up system to optimize the use of materials and bring value throughout lifecycle phases as well as minimize emissions [15–17]. This is also considered as one of the typical management strategies to transit to a low-carbon and less polluting economy [18].

The adaptation of circular solutions in environmental management is worldwide recognition from academic institutions to governmental and non-governmental organizations due to the issues of depletion of natural resources as well as the adverse effects of climate change [18]. Although there is increasing interest in implementing recovery solutions such as reuse and recycling, but it is inefficient waste management solutions that most of the waste is only buried or dumped without applying environmental protection measures [16], [20]. When not being handled properly (especially in open-dumping sites), landfill MSW can form hazards from toxic substances generated from decomposition and direct permeation into soil, mainly as chlorinated solvents, heavy metals, Aromatic Hydrocarbons or Vinyl Chlorides [21], [22]. On the other hand, when MSW is properly collected and disposed of in sanitary landfills, anaerobic biodegradation also generates significant emissions lead to global warming, most notably, CH₄ contributes up to 15% of the total emissions of GHGs and is also the main contributor to GHG emissions from the waste sector [16], [20]. This study was carried out with the goal of analyzing and evaluating the evolution of LFG emissions (CH₄ and CO₂ gases) for the period of 2021 – 2050 from the Khanh Son landfill site with analysis of uncertainty factors by the EnLandfill software. The study also conducts an assessment of the potential for energy recovery based on CE policies applied to meet various objectives, consisting of energy conversion and electricity generation for urban areas, as well as achieving the national common interest related to GHGs control in order to reduce the impacts of climate change. Based on comparative evaluations with similar policies and solutions from other regions and countries showing the effectiveness of CE-oriented sustainable MSW management, with the ultimate goal of the study is to provide policy makers and relevant agencies/organizations with information on the diversification of energy sources for urban and surrounding areas, along with the benefits achieved from reducing the contribution of GHG emissions from the waste sector and promoting renewable energy production in Danang City, Vietnam.

2. Study area and methods

2.1. Study area

In Danang City, the need to handle the entire amount of waste generated up to the present and in the future is also extremely urgent and requires a timely solution to ensure the complete treatment of generated waste along with the socio-economic development of the city. Currently, most of the MSW in Danang City has been collected, transported, and treated [1]. The main method of domestic waste treatment in the city is still burial, this activity takes place at the Khanh Son landfill (Figure 1). After nearly 20 years of existence, the Khanh Son landfill is facing the problem of overcrowding, which is a dilemma for the city when the amount of MSW is increasing, whilst the alternative is currently in the process of being completed and has not kept pace with the city's waste generation progress, at least in the next few years.
Figure 1 presents description of the study area, specifying the scope of the MSW treatment area in the Khanh Son landfill. The landfill with a total existing area of 32.4 ha located in Hoa Khanh Nam ward, Lien Chieu district, Danang city [1]. The landfill area is mainly low hills located in the West of Danang city, the terrain is relatively rough and steep, the altitude varies from 13.5 m to 19.0 m that the traffic is relatively convenient [1]. Currently, the treated MSW volume has been up to 1,132 tonnes/day in the Khanh Son landfill, specifically domestic waste is 1,056 tonnes/day, non-hazardous industrial waste is 50 tonnes/day, non-hazardous medical solid waste is 17 tonnes/day, and sewage sludge is 9 tonnes/day [1].

![Map of the Study Area in the Khanh Son Landfill Site](image)

**Figure 1.** Description of the Khanh Son landfill site in Danang City, Vietnam

The current position of non-hazardous waste burial cells is located to the West – Southwest of the landfill area, including five existing garbage cells (landfill cells 1, 2, 3, 4, 5) and one planned expansion (cell 6) [1]. The total area of these cells is about 13.83 ha, as shown in Table 1. The existing non-hazardous MSW treatment areas have been operated since 2007, particularly the cell 1 received MSW from 2007 with the highest elevation about 38.74m; the cell 2 operated from July 2012 to June 2017 and covered 0.3m of soil layer with the highest elevation about 43.93m. Whilst the cells 4 and 5 landfilled MSW from September 2015 to June 2017 with the highest elevation roughly 43.93m and June 2017 to current with the highest elevation around 40.50m, respectively. Furthermore, the hazardous waste treatment area has a total area of roughly 1 ha that the hazardous waste treatment subdivision has an area of 6,500 m² and the treated hazardous waste cell has an area of 5,000 m² [1]. In addition, in the Khanh Son Complex Zone area, there are other facilities including an operating office, weighing station, truck wash station, leachate treatment plant, and operating roads.

| Order | Subdivision          | Area (ha) | Ratio (%) |
|-------|----------------------|-----------|-----------|
| 1     | Trash box 1 (Cell 1) | 2.27      | 7.0       |
| 2     | Trash box 2 (Cell 2) | 2.73      | 8.4       |
| 3     | Trash box 3 (Cell 3) | 2.61      | 8.1       |
| 4     | Trash box 4 (Cell 4) | 2.85      | 8.8       |
| 5     | Trash box 5 (Cell 5) | 3.37      | 10.4      |
| 6     | Hazardous waste burial box | 0.50 | 1.5 |
| 7     | Hazardous waste treatment area | 0.65 | 2.0 |

Table 1. The status of landfill cells in the Khanh Son landfill, Danang City
2.2. Analysis of LFGs emissions contribution

The EnLandFill software (Environmental Information – Model Integrated System for Air Emission and Dispersion Estimation from Landfill) is the name of an integrated system of environmental information and mathematical model was built to allow calculation of potential gas emissions CH₄ (Lₒ) and determination of the optimal CH₄ (k) gas generation rate constant for a landfill [23], [24]. The model block are considered as an essential component in the EnLandFill with three integrated mathematical models [23], including the model (1) calculates the potential to generate CH₄ (Lₒ) based on the theory of first-order decomposition (FOD) model of Pipatti et al. (2006) [25] (the equation Eq. [1], Eq. [2] and Eq. [3]); the model (2) estimates emissions of LFGs based on the LandGEM model theory of Alexander et al. (2005) [26] (the equation Eq. [4] and Eq. [5]); and the model (3) simulates pollutant dispersion from landfills. Figure 2 shows the steps flowchart of the implementation for this research.

\[
L_0 = \text{DDOC}_m \times \frac{16/12}{12} \times F, \tag{1}
\]

where \((16/12)\) is the molecular weight ratio of CH₄/C (ratio), F is the fraction of CH₄ by volume in the generated landfill gas (the value range recommended by the IPCC is 0.5 – 0.55), \(\text{DDOC}_m\) is the mass of the decomposable degradable organic carbon (DOC) deposited into the landfill in year T (tonne/year). \(\text{DDOC}_m\) can be estimated as shown in Eq. (2) below.

\[
\text{DDOC}_m = W_T \times \text{DOC} \times \text{DOC}_F \times \text{MCF,} \tag{2}
\]

where \(W_T\) is the mass of solid waste deposited into the landfill in year T (tonne/year), and \(W_T = 1\) is selected to determine the \(\text{DDOC}_m\) value of 1 tonne of MSW in the landfill; \(\text{DOC}_T\) is the fraction of DOC that can decompose (fraction) (the value recommended by the IPCC is 0.5); MCF is the CH₄ correction factor for aerobic decomposition in the year of deposition (fraction) (MCF = 0.6) based on actual conditions of landfill [25], DOC is the DOC in the year of deposition (fraction, tonne C/tonne waste). The DOC value represents the volume of organic carbon in waste and depends on the waste composition ratios in various components of the waste stream. The DOC can be estimated as follow Eq. (3):

\[
\text{DOC} = \sum_{i=1}^{n} \text{DOC}_i \times W_i, \tag{3}
\]

where \(\text{DOC}_i\) is the fraction of the DOC in waste type \(i\) (%), and \(W_i\) is the fraction of waste type \(i\) by waste category (%); \(W_i\) is the fraction of mass of waste type \(i\) and deposition (%). The value \(L_0\) is the input data of model (2) to simulate emissions of LFGs.

\[
Q_{\text{CH}_4} = \sum_{i=1}^{n} \sum_{j=0}^{1} k_l \frac{M_i}{10} e^{-k_l t_j}, \tag{4}
\]

\[
Q_{\text{CO}_2,\text{sum}} = Q_{\text{CH}_4} \times \left(\frac{100}{F} - 1\right) \times D_{\text{CO}_2}, \tag{5}
\]

where \(i\) is the step index in year which ranges from 1 to \(n\) (year); \(n\) is the difference (year of the calculation) – (initial year of waste acceptance); \(j\) is is equal to 0,1 time increment in year; \(M_i\) is is the disposed waste mass in year \(i\) in tonne; \(t_j\) is the age of the \(j\) portion of the waste \(M_i\) in year \(i\) within the operation year (year as a decimal number); \(L_0\) is the optimal CH₄ generation potential (m³/tonne waste); and \(k\) is the optimal rate of CH₄ generation (year⁻¹). Moreover, \(D_{\text{CO}_2}\) and \(D_{\text{CH}_4}\) are the value of the specific gravity of the CO₂ and CH₄ gases (tonne/m³) and \(F\) is the percentage of CH₄ in the total generated landfill gas (%). However, considering the circumstances of biogas collection system installation assumed that not all the volume of CH₄ produced in landfills can be captured for electricity generation potential [27]. A fraction of CH₄ generated emission is able to release directly into the atmosphere as a type of tracer gas, oxidation, or accumulation [27]. Therefore, a coefficient of landfill CH₄ collection efficiency \((E, \%)\) is added in Eq. (6) below to estimate CH₄ emission from landfills with regard to biogas recovery [23].
\[
Q_{CH_4_{\text{tot}}} = (1-E) \times \sum_{i=1}^{n} \sum_{j=0.1}^{1} k_i L_0 \left[ \frac{M_i}{10} \right] e^{-k_0} \times D_{CH_4},
\]

(6)

2.3. Analysis of power generation potential from LFGs

The electricity generation potential of MSW landfills depends on the total volume of \(CH_4\) recovered from landfill gas collection systems [28], [29]. The FOD model in the EnLandFill software can be used to determine LFG emissions for each year in this research area. The total generated \(CH_4\) gas volume from landfill captured to produce energy can be estimated as Eq. (7) according to Bui & Nguyen [30]:

\[
CAP_{CH_4_{\text{tot}}} = E \times \sum_{i=1}^{n} \sum_{j=0.1}^{1} k_i L_0 \left[ \frac{M_i}{10} \right] e^{-k_0} \times D_{CH_4},
\]

(7)

The electricity generation potential, \(EP_{LFG,\text{year}}\) (unit: kWh/year) from the total captured \(CH_4\) gas volume estimated for each operating year can be obtained as Eq. (2) [30–32]:

\[
EP_{LFG,\text{year}} = \frac{CAP_{CH_4_{\text{tot}}} \times LHV_{CH_4} \times \delta \times \varepsilon}{\phi},
\]

(8)

where \(LHV_{CH_4}\) is the Lower Heating Value (LHV) of \(CH_4\) gas (unit: MJ/m\(^3\)), and the \(LHV_{CH_4}\) value is about from 35 MJ/m\(^3\) to 37.2 MJ/m\(^3\) [28], [33], [34]; \(\delta\) is the capacity factor of the entire recovered \(CH_4\) combustion process to generate energy source, the common \(\delta\) value is roughly 85% [28], [35]; \(\varepsilon\) is the electricity generation efficiency of the gas turbine engine, and is given a range of 30 – 35% [32], [36]; \(\phi\) is the conversion factor from MJ to kWh, and \(\phi\) value is taken as 3.6 [28], [29]. The energy plant size from captured \(CH_4\) gas of landfill (LFGTE\(_{\text{size}}\)) assuming it is able to operate throughout the year is calculated in kW or MW as Eq. (9) below [9], [23], [30]:

\[
LFGTE_{\text{size}} = \frac{EP_{LFG,\text{year}}}{D_{hr} \times \gamma},
\]

(9)

where \(D_{hr}\) is the number of hours in a day (unit: hours), and \(\gamma\) is the number of days that power plant is worked in a year (unit: days).

2.4. Analysis of GHG emissions reduction potential

The Global Warming Potential (GWP) can be understood as a certain amount of GHG, released into the atmosphere causes a warming effect on the Earth [37] over a given period of time (normally 100 years) [38], [39]. The GWP values used to convert the GHG emissions from different units to homogeneous unit called CO\(_2\) equivalent or CO\(_2\)-eq and estimated based on Eq. (10) follows [38], [39]:

\[
Emission_{GHG,CO_2-equiv} = Emission_{GHG_i} \times GWP_{index,i},
\]

(10)

where \(Emission_{GHG,CO_2-equiv}\) is the emission of GHG i converted to the unit of CO\(_2\)-eq; \(Emission_{GHG_i}\) is the emission of GHG i estimated in the unit of tonne or kg, and \(GWP_{index,i}\) is the Global Warming Potential of GHG i. To calculate the total value of GHG emission reduction potential generated from landfills for each year based on the computing scenario plan having biogas recovery to produce power generation can be shown in Eq. (11) [30], [40], [41].

\[
\sum RE_{GHG_i,\text{year}} = Q'_{CH_4_{\text{year}}} \times GWP_{CH_4} + Q'_{CO_2_{\text{year}}} \times GWP_{CO_2}
\]

(11)
where $\sum RE_{GHGs, yeari}$ is the total GHGs emission reduction potential of the year $i$ (unit: tCO$_2$-eq/year); $Q'_{CH_4, yeari}$ and $Q'_{CO_2, yeari}$ is the emissions of CH$_4$ and CO$_2$ gases generated from landfill in the year $i$ can be decreased; $GWP_{CH_4}$ and $GWP_{CO_2}$ is the GWP values of CH$_4$ and CO$_2$ gases.

2.5. Scenario analysis
According to the analysis for the current state of facilities to meet the treatment, the collection and MSW treatment, the potential for MSW generation, as well as the waste management orientations of Danang City. A detailed computing scenario is set up to assess the effectiveness of each planned MSW treatment option (Table 2 and Figure 3), which proposes to implement a systematic separation of waste at the source with all MSW generated are collected and treated at the Complex; in which 10% of waste including paper, plastic, plastic bags, metal is treated at recycling subdivisions; the remaining waste components are buried at Khanh Son landfill (in the expanded treatment area). At the same time, It proceeds to install the LFGs collection system generated from the landfill cells of the Khanh Son landfill to burn and serve for electricity generation (with efficiency, $E_\%$ between 90% and 95%). The entire amount of electricity generated from the LFGs recovery type will be used for the operation of the Complex and several households in Lien Chieu District, Danang City. Theoretically, the treatment efficiency from the developed scenario contributes to clearly reflect the “Zero Waste City” goal that the city government is aiming for 100% MSW collected and treated; in which about 90 – 95% of the waste is recycled, reused, energy recovered or composted in the period of 2025 – 2050 and the landfill volume is reduced by 15 – 20% [42]. This is also a contribution to the common national goals in the period of 2020 – 2030 aiming to energy recovery, control and the reduction of CH$_4$ emissions in the waste sector [24].

Figure 2. The flowchart presenting the steps of the methodology
Table 2. Summary of the analyzed scenario to forecast the LFGs emission

| Period       | Approaches of treatment                                                                                                                                 |
|--------------|-------------------------------------------------------------------------------------------------------------------------------------------------------|
| 2007 – 2012  | About 90% of MSW in Danang City collected to the Khanh Son landfill; MSW landfilled in trash boxes 1 and 2 (Cell 1 and 2).                               |
| 2012 – 2015  | About 90% of MSW in Danang City collected to the Khanh Son landfill; MSW landfilled the trash box 3 (Cell 3).                                              |
| 2015 – 2017  | About 90% of MSW in Danang City collected to the Khanh Son landfill; MSW landfilled in trash box 4 (Cell 4).                                               |
| 2017 – 2020  | About 95% of MSW in Danang City collected to the Khanh Son landfill; MSW landfilled in trash box 5 (Cell 5).                                             |
| 2021 – 2050  | Total MSW in Danang City collected to the Khanh Son landfill; About 10% of waste including paper, plastic, metal treated in recycling area; From 70 to 75% of MSW used for composting generation; Installing and capturing the LFG emissions to create the clean energy; From 15 to 20% of MSW landfilled in the trash boxes 5 and 6 (Cell 5 and 6). |

Figure 3. The CE diagram of the Khanh Son landfill in MSW management in Danang City, Vietnam

3. Results and discussion

3.1. Assessment of the MSW management status in Danang City

MSW management has become one of the main challenges for the government of Danang City, mainly due to the rapid pace of urbanization, especially the development of local tourism along with the rapid generation of different types of solid waste in urban areas. This is clearly illustrated in the relationship between Gross domestic product (GDP) per capita value and generated MSW volume in Danang City in the period of 2010 – 2020; in specific, the GDP per capita values rose significantly from 31.21 million VND to 103.61 million VND per person, which was relative with the increase of MSW volume from 279,014.3 tonnes up to 356,813.6 in the 2010 – 2020 period [43] (Figure 4).
Figure 4. Relationship between generated MSW volume and GDP per capita in Danang City in the period 2010–2020

In addition, the results are clearly reflected given that the total volume of collected MSW increased by 17.3% between 2010 and 2013 from 223,521 tonnes/yr to 262,182 tonnes/yr [44]; by 2017 the collected volume reached 314,565 tonnes/yr [42], and estimated to increase of 40.7% and 20.0% respectively for the years 2009, 2013 and by 2019 the collected volume reached about 401,500 tonnes/yr [43], an increase of 27.6% compared to 2017 with the collection rate of the whole period at 92–95% [42]. Figure 5 presents MSW generation levels of all districts in 2019, and Table 3 shows annual MSW volume treated from 2007 to 2020 in the Khanh Son landfill site. Similarly, the city’s MSW generation index has also increased year over year from 0.675 kg.person\(^{-1}.d\(^{-1}\) [44] to 0.97 kg.person\(^{-1}.d\(^{-1}\) [43] in the period 2010–2019. With all pressure above, the operation of Da Nang Urban Environment Company, public service unit responsible for the collection, transportation and processing waste under the coordination and management of the Provincial People’s Committee as well as the Department of Natural Resources and Environment [45] (Figure 6), has arisen many problems. When at 6 in 11 transfer stations and some gathering points are always overloaded with waste transshipment capacity only reaching 7% [42], the backlog problems of MSW continuously persists, causing bad odors and serious urban environmental pollution [43].

Figure 5. The map of solid waste generation levels of Danang City in the year 2019
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Table 3. Annual treated MSW volume between 2007 and 2020 in the Khanh Son landfill (Unit: kg/day)

| Year | Cam Le District | Hoa Vang District | Hai Chau District | Lien Chieu District | Ngu Hanh Son District | Son Tra District | Thanh Khe District | Total |
|------|-----------------|-------------------|------------------|---------------------|-----------------------|-----------------|-------------------|-------|
| 2007 | 67,389          | 88,554            | 153,064          | 109,652             | 49,726                | 100,672         | 137,632           | 706,690 |
| 2008 | 70,939          | 90,857            | 157,043          | 112,502             | 51,019                | 103,290         | 141,210           | 726,861 |
| 2009 | 72,784          | 93,219            | 161,127          | 115,518             | 52,346                | 105,976         | 144,882           | 745,851 |
| 2010 | 74,596          | 95,540            | 165,139          | 118,394             | 53,649                | 108,615         | 148,490           | 764,423 |
| 2011 | 76,453          | 97,919            | 169,251          | 121,342             | 54,985                | 111,319         | 152,187           | 783,457 |
| 2012 | 78,357          | 100,358           | 173,465          | 124,364             | 56,354                | 114,091         | 155,977           | 802,965 |
| 2013 | 80,308          | 102,856           | 177,784          | 127,460             | 57,757                | 116,932         | 159,861           | 822,959 |
| 2014 | 82,308          | 105,418           | 182,211          | 130,634             | 59,195                | 119,844         | 163,841           | 843,451 |
| 2015 | 84,357          | 108,042           | 186,748          | 133,887             | 60,669                | 122,828         | 167,921           | 864,453 |
| 2016 | 86,458          | 110,733           | 191,398          | 137,220             | 62,180                | 125,886         | 172,102           | 885,977 |
| 2017 | 88,610          | 113,490           | 196,164          | 140,637             | 63,728                | 129,021         | 176,387           | 908,038 |
| 2018 | 90,817          | 116,316           | 201,049          | 144,139             | 65,315                | 132,233         | 180,779           | 930,648 |
| 2019 | 93,078          | 119,212           | 206,055          | 147,728             | 66,941                | 135,526         | 185,281           | 953,822 |
| 2020 | 95,396          | 122,180           | 211,186          | 151,407             | 68,608                | 138,901         | 189,894           | 977,572 |

In order to enhance the recycling rate (mainly for paper, plastic, metal) and waste management efficiency, the action plan No. 1577/KH-UBND vision to 2025 for waste segregation at source has been widely implemented from the ward/commune level [43]. Until June 2018, positive transformation from the results showed that over 80% of residential areas have implemented waste separation at source according to the collection process, and three in six districts of Da Nang have apply 3R activities (Reduce, Reuse and Recycle) [43].

Figure 6. The processes of MSW collection and treatment in Danang City, Vietnam

3.2. Prediction of the GHGs (CH\textsubscript{4} and CO\textsubscript{2}) emission potential in the Khanh Son landfill site

The Khanh Son landfill site is located in the area of Danang City – Central Vietnam. The climate here is hot and arid. The CH\textsubscript{4} generation potential (L\textsubscript{0}) and CH\textsubscript{4} gas generation rate constant (k) mainly depend on the climatic conditions of each area. It can be shown that the values of k and L\textsubscript{0} determine most of the gas emission load at the landfill. In general, the composition of solid wastes in the Khanh Son landfill,
unchanged significantly over the years and has continued to remain with an assumption for the next period from 2021 – 2050 (Table 4 and Figure 7).

Along with the coefficient DOC$f = 0.5$; coefficients $MCF_{KhanhSon} = 1$ [26], $F$ is estimated in the value range of 50 – 55% to create corresponding potential $CH_4$ generation capacity ($L_0$) values being $138.5 \text{ m}^3/\text{tonne}$, $141.3 \text{ m}^3/\text{tonne}$, $144.0 \text{ m}^3/\text{tonne}$, $146.8 \text{ m}^3/\text{tonne}$, $149.6 \text{ m}^3/\text{tonne}$, and $152.3 \text{ m}^3/\text{tonne}$ respectively.

**Figure 7.** The main MSW components in the Khanh Son landfill, Danang City, Vietnam

**Table 4.** Synthesis of buried MSW components of the Khanh Son landfill, Danang City

| MSW components     | $W_i$ mean (%) | Range of DOC$_i$ (%) | DOC$_i$ mean (%) | $W_i \times$ DOC$_i$ |
|--------------------|----------------|----------------------|-----------------|---------------------|
| Paper/Carton       | 3.98           | 40 - 50              | 42.97172        | 0.017103            |
| Textiles           | 2.53           | 25 - 50              | 46.98571        | 0.011887            |
| Organic matter (Food) | 70.68            | 20 - 50              | 31.43181        | 0.222160            |
| Wood               | 1.39           | 46 - 54              | 57.24273        | 0.007957            |
| Rubber             | 1.18           | 47                   | 47              | 0.005546            |
| Other waste        | 20.24          | -                    | -               | -                   |
| **Total**          | **100.00**     | -                    | -               | **0.264653**        |

In general, the $CH_4$ emission load tends to increase gradually from 2008 to 2021 and then tends to decrease rapidly in the period of 2021 – 2050. The $CH_4$ emission load value peaks in 2021 at around 32,500 tonnes/yr and these cumulative emission values reach about 342,000 tonnes between 2008 and 2021. However, with selecting the value of $L_0$ through the sensitivity to each $k$ value that this value is determined by the solid waste composition at the landfill and a number of other factors. Solid waste composition changes over time (hourly, day by day), not fixed, it is recommended to test with $L_0$ which is suitable to the climatic conditions of the area and make comparisons for testing, choose the best value. The optimal input $CH_4$ ($k_{opt}$) generated rate constant for the LFG emission load forecasting model is determined by the experimental method based on the initial range of $k$ values. The result of running calculation iterations determines the load, the concentration of the contaminant at the measuring locations have been compared and verified to have determined the optimal $k_{opt}$ value for landfill $k_{opt} = 0.4$. It would be the most obvious in the difference in value $L_0$ of $CH_4$ over the years. The following Figure 8 is the result of the $L_0$ values at optimal $k$ ($k_{opt} = 0.4$ year$^{-1}$).
Figure 8. The difference in $L_0$ values of CH$_4$ (A) and CO$_2$ (B) generation with the optimal $k$ value

The result estimates CH$_4$ emissions from 2008 according to the trend of CH$_4$ ($k$) emission rate constant, specifically looking at the graph, it is possible to give an accurate assessment about the difference between the $L_0$ values. It means $k_{opt} = 0.4$ year$^{-1}$ considered as being the most suitable coefficient for the climate conditions in Vietnam in general and the Khanh Son landfill of Danang City in particular, as well as with simulating cases using the EnLandfill software. With selecting value $k$ through sensitivity for each value $L_0$ fixed that this value commonly depends on the climatic characteristics of the area under consideration. In Vietnam-specific conditions, the value of coefficient $k$ is established in the range $0.4 - 0.7$ [23]. The emission simulation for each value of each LFG in the period of 2008 – 2050 is conducted to compare and choose the most suitable $k$ for the EnLandfill model. For each $L_0$ value, the model is run and exported output results with four different $k$ values. The Figure 9 below shows the results respectively with $L_0 = 138.5$ (m$^3$/tonne) corresponding to $F = 50\%$ (Fig. 9-A1, B1); $L_0 = 141.3$ (m$^3$/tonne) corresponding to $F = 51\%$ (Fig. 9-A2, B2); $L_0 = 144$ (m$^3$/tonne) corresponding to $F = 52\%$ (Fig. 9-A3, B3); $L_0 = 146.8$ (m$^3$/tonne) corresponding to $F = 53\%$ (Fig. 9-A4, B4); $L_0 = 149.6$ (m$^3$/tonne) corresponding to $F = 54\%$ (Fig. 9-A5, B5); and $L_0 = 152.3$ (m$^3$/tonne) corresponding to $F = 55\%$ (Fig. 9-A6, B6).
Figure 9. The difference in $k$ values of CH₄ (A1, A2, A3, A4, A5, A6) and CO₂ (B1, B2, B3, B4, B5, B6) gases generation with the fixed $L_0$ values
Whilst visualizing to compare emission values, a couple of coefficients give quite many different values. Because of the complete difference of these $L_0$ values, it can be seen that there is an error and it is not suitable to run the model. To be able to find an optimal $L_0$ value, the estimation of pollutant dispersion needs to carry out in order to compare the model and measured substance concentrations with NASH statistical index above 0.75 [23], [24] (Table 5). After calibration and validation, the optimal $L_0$ value is determined at about 138.5 m$^3$/tonne and looking at the chart comparing the sensitivity to $L_0$ of the $k$ values, which is not significantly different in CH$_4$ emissions between the different $k$ values over the years. Hence, the potential of CH$_4$ gas generation ($L_0$) is more difficult to determine the emissions of gases than the CH$_4$ generation rate constant ($k$). Figure 10 below shows the spatial distribution map of average CH$_4$ emissions in the years 2017, 2018, and 2019, which can be seen that with the optimal $L_{0,\text{opt}} = 138.5$ and $k_{\text{opt}} = 0.4$ year$^{-1}$, CH$_4$ emission load values are quite high. It reached 16,136.43 mg/s; 16,621.66 mg/s; 17,091.47 mg/s respectively in the years 2017, 2018 and 2019. Furthermore, CH$_4$ emissions generate focus on the Northern areas of 1, 3, 4, 5 borders the existing hazardous waste treatment area.

Table 5. Validation results of CH$_4$ concentration between observed and simulated values using the EnLandFill software

| Time        | Type   | KK01(1) | KK02(2) | KK03(3) | KK04(4) |
|-------------|--------|---------|---------|---------|---------|
| 20/03/2015  | Observation | 0.005   | 0.007   | 0.026   | 0.800   |
|             | Simulation | 0.006   | 0.007   | 0.070   | 1.005   |
| 16/06/2015  | Observation | 0.006   | 0.008   | 0.028   | 0.670   |
|             | Simulation | 0.006   | 0.100   | 0.080   | 0.672   |
| 24/09/2015  | Observation | 0.004   | 0.007   | 0.026   | 0.810   |
|             | Simulation | 0.005   | 0.005   | 0.026   | 0.816   |
| 30/12/2015  | Observation | 0.005   | 0.008   | 0.018   | 0.820   |
|             | Simulation | 0.005   | 0.101   | 0.100   | 0.940   |
| 07/04/2016  | Observation | 0.001   | 0.008   | 0.001   | 0.140   |
|             | Simulation | 0.100   | 0.006   | 0.100   | 0.143   |
| 16/06/2016  | Observation | 0.001   | 0.091   | 0.001   | 0.100   |
|             | Simulation | 0.003   | 0.120   | 0.100   | 0.237   |
| 27/09/2016  | Observation | 0.350   | 0.300   | 0.730   | 0.420   |
|             | Simulation | 0.346   | 0.306   | 0.800   | 0.429   |
| 07/12/2016  | Observation | 0.310   | 0.290   | 0.690   | 0.400   |
|             | Simulation | 0.322   | 0.292   | 0.522   | 0.600   |
| 28/03/2017  | Observation | 0.160   | 0.190   | 0.740   | 0.420   |
|             | Simulation | 0.140   | 0.250   | 0.811   | 0.422   |
| 15/06/2017  | Observation | 0.100   | 0.110   | 0.420   | 0.310   |
|             | Simulation | 0.200   | 0.210   | 0.560   | 0.320   |
| 12/09/2017  | Observation | 0.160   | 0.190   | 0.740   | 0.370   |
|             | Simulation | 0.270   | 0.191   | 0.636   | 0.471   |

NASH index $0.808$ $0.764$ $0.918$ $0.815$

$R^2$ $0.871$ $0.864$ $0.932$ $0.916$

(1) KK01 ($X = 16.046391^\circ; Y = 108.146622^\circ$): at residential area in the head of the main wind direction;
(2) KK02 ($X = 16.041588^\circ; Y = 108.134399^\circ$): at residential area at the end of the main wind direction;
(3) KK03 ($X = 16.044896^\circ; Y = 108.144302^\circ$): at hazardous waste burial trash box;
(4) KK04 ($X = 16.041863^\circ; Y = 108.141857^\circ$): at non-hazardous waste burial trash box.
3.3. Assessment of the energy recovery potential and GHGs reduction from the Khanh Son landfill

Based on the estimated results of the total amount of CH$_4$ emissions recovered from the collection system with the recovery efficiency $E = 90\%$ in the period of 2021 – 2050 according to the analysis scenarios (according to the optimal parameters of $L_0$ and $k_{opt}$), the annual value of electricity generation potential $EP_{\text{LFGYear}_i}$ (kWh/year) has been estimated according to the formula Eq. (8) is shown in Figure 11. From the construction scenario orientation to the analysis, it is found that the potential for annual electricity generation in the period 2021 – 2050 is highest in 2021, with a total estimated value of about 138,717 million kWh/year. In general, the potential for electricity generation tends to decrease gradually during the forecast period from 138,717 million kWh/year to 3.79 million kWh/year in the period of 2021 – 2030 and almost no potential for energy recovery from 2040 to 2050 (approximately 0.001 million kWh/year in 2050). Moreover, it could be seen that the electricity generation potential directly related to the amount of captured CH$_4$ emissions estimated on the basis of the determined optimal factors $L_0$, $k_{opt}$ and increased rapidly from 2008 – 2021, peaked in 2021, and then reduced significantly by 2050. Thus, the recovery potential of CH$_4$ gas to generate clean energy is merely suitable in the 2021 – 2030 period. From there, the power station size ($\text{LFGTE}_{\text{size}}$) can be determined according to the formula Eq. (9) from CH$_4$ gas of the Khanh Son landfill site with the assumption that the generating station is capable of operating throughout the year with $D_{hr} = 24$ hours/day and the number of days the generating station operates in a year with $\gamma = 365$ days. Thus, with the above assumption, in the analysis scenario, the size of the power station will gradually increase from 15,835.26 kW in the year 2021 and then gradually decrease to about 432.68 kW in the year 2030 and by the year 2040, it will almost no longer be able to generate electricity for usage demands (Figure 11).
Figure 11. The potential forecast for annual generated electricity changes (million kWh/yr) in Khanh Son landfill

Figure 12. The comparison of potential to reduce GHGs emissions for the period of 2021 – 2050 in the Khanh Son landfill site, Danang City

In order to assess the potential to reduce emissions of GHGs, including CH₄ and CO₂, the GWP index is considered as a general level of conversion that has been calculated in CO₂-eq units based on based on the results of the “5th Assessment Report” (AR5) of IPCC 2014 [39] according to the formulas Eq. (10) and Eq. (11). The estimated results are detailed in Figure 12. With the analysis scenario, the potential to reduce GHG emissions is calculated for the period 2021 – 2050 with the recovery efficiency E = 90% due to the installation of the generated LFGs recovery system. The total estimated mitigation potential
\[ \sum \text{RE}_{\text{GHG, eq}} = 271.25 \text{ thousand tCO}_2\text{-eq} \text{ compared to before having the LFG gas recovery system is} \]
\[ \sum \text{RE}_{\text{GHG, no-re}} = 2,712.49 \text{ thousand tCO}_2\text{-eq}, \text{ decreasing gradually from 2021} – 2030 \text{ with 89.42 thousand} \]
to 24.43 thousand tCO\text{-eq}/year; and by 2050, only about 0.8 tCO\text{-eq} will remain per year.

3.4. Discussion

In general, the coefficient of MSW generation in Danang City ranges from 0.8 – 0.9 kg/person/day, averaging about 0.838 kg/person/day. The volume of MSW generated by districts varies, depending on economic development and living standards. In particular, Lien Chieu District has the highest MSW generation rate (around 0.9 kg/person/day) because it is home to many entertainment and food service areas; many markets are sold and people's living standards are improved. Whilst Hoa Vang is the district with the lowest MSW generation coefficient of only about 0.8 kg/person/day, owing to it is a suburban district far from the center; the majority of households work in the agricultural sector and the standard of living is low. Moreover, the CH\textsubscript{4} generation potential (L\textsubscript{0}) is more difficult to determine the emissions of gases than the CH\textsubscript{4} (k) generation rate factor. When compared with the case studies at South Binh Duong landfill in Binh Duong province [46] and Tan Lap 1 landfill in Tien Giang province [30], belonging to the Southern Key Economic Zone, Vietnam showed that the optimal CH\textsubscript{4} generation potential value, L\textsubscript{0, opt(x)} was all significantly higher, particularly L\textsubscript{0, opt,SouthBinhDuong} = 81 < L\textsubscript{0, opt,TanLap1} = 110 < L\textsubscript{0, opt,KhanhSon} = 138 m\textsuperscript{3}/tonne. Nevertheless, this optimal value, L\textsubscript{0, opt,KhanhSon} was still lower than the recommended default values of IPCC [25], [40]. This can be explained by the fact that the MSW receiving sources from the Tan Lap 1 landfill have been smaller in scale and had much less diverse waste components than in the Khanh Son landfill, and in the case of the South Binh Duong landfill, organic matter components have commonly accounted for only 45%, since roughly 55% of the organic wastes have sorted and treated at the composting areas [46]. Furthermore, according to the trend of CH\textsubscript{4} emission rate constant, k in the range 0.4 – 0.5 year\textsuperscript{-1} is the most suitable for the climate conditions in the Khanh Son landfill site. Similarly, the optimal CH\textsubscript{4} gas generation rate constant value (k\textsubscript{opt}) in all three areas had certain similarities with k\textsubscript{opt,SouthBinhDuong} = 0.355 years\textsuperscript{-1}, k\textsubscript{opt,TanLap1} = 0.23 years\textsuperscript{-1}, and k\textsubscript{opt,KhanhSon} = 0.40 years\textsuperscript{-1} reflecting the considerable influence of general characteristics of geographical location and climate on decomposition conditions at landfill sites, and were also within the recommended value range of IPCC [25], [40] with k = 0.15 – 0.70 years\textsuperscript{-1} for medium and rapid decomposition landfills in hot, humid tropical regions with average annual rainfall over 1,000 mm.

4. Conclusions

This study evaluated the effectiveness of solid waste management planning in Danang City following the direction of a CE with a focus on analyzing the potential of creating clean energy from the recovered LFGs and reducing the contribution of GHG emissions, which is considered one of the highlights in the research. The assessment was carried out at Khanh Son landfill area with the goal of forecasting the amount of CH\textsubscript{4} and CO\textsubscript{2} gases generated by the EnLandFill software in the period of 2021 – 2050, as a basis for setting up an analysis scenario for estimation of energy recovery and power generation from LFGs following the trend of building a sustainable CE and zero-waste city orientation of Danang City, Vietnam. The results of estimating the potential value of CH\textsubscript{4} gas generation is from 8,015.7 – 11,967.28 tonnes/year and that of CO\textsubscript{2} gas generation are from 21,993.3 – 87,706.98 tonnes/year from 2008 to 2021 with an optimal L\textsubscript{0} = 138.5 m\textsuperscript{3}/tonne of waste. The optimal input CH\textsubscript{4} (k\textsubscript{opt}) generated rate constant for the LFG emission load value forecasting model is determined by the experimental method based on the initial range of k values. The result of running calculation iterations determines the load, the concentration of the contagion at the measuring locations have been compared and verified to has determined the optimal k\textsubscript{opt} value for landfill is k\textsubscript{opt} = 0.4 year\textsuperscript{-1}. The trend of CH\textsubscript{4} and CO\textsubscript{2} generation has increased over the period from 2008 to 2020. It has reached the peak of 119,672.8 tonnes/year (CH\textsubscript{4}) and 87,706.98 tonnes/year (CO\textsubscript{2}) in 2021. The potential value of CH\textsubscript{4} and CO\textsubscript{2} gas generation has a tendency to plummet in the next 29 years to 2050. It will have been 0.293 tonnes/year (CH\textsubscript{4}) and 0.804 tonnes/year (CO\textsubscript{2}) in 2050. At the
same time, the obtained results also reported that in the period from 2021 – 2050, the total potential for energy recovery from CH$_4$ gas of the Khanh Son landfill is estimated at about 420,767 million kWh, equivalent to the total potential for GHGs emission reduction (GWP) about 271.25 thousand tCO$_2$-eq. Therefore, the exploitation of energy recovery from landfill gas can not only help to reduce GHGs emissions, but also provide a locally satisfying energy source for operating subdivisions in the Complex or other neighborhood areas.

**Author contribution statement:** P.H.N: Methodology, Models, Formal analysis, Writing – Original draft, Writing – Review & Editing. Q.K.N.C: Data curation, Data Formal analysis, Formal analysis, Validation, GIS. L.T.B: Conceptualization, Funding acquisition, Investigation, Project administration, Resources, and Supervision.

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**References**

[1] Da Nang City People’s Committee, “Report on environmental impact assessment of the project of upgrading and renovating several items at Khanh Son landfill in 2019,” Danang City, 2019.

[2] D. W. Pearce and R. K. Turner, “Economics of Natural Resources and the Environment,” *Balt. MD Johns Hopkins Univ. Press*, p. 378, 1990, doi: https://doi.org/10.2307/1242904.

[3] P. Ghisellini, C. Cialani, and S. Ulgiati, “A review on circular economy: The expected transition to a balanced interplay of environmental and economic systems,” *J. Clean. Prod.* 114, 11–32, 2016, doi: 10.1016/j.jclepro.2015.09.007.

[4] R. Merli, M. Preziosi, and A. Acampora, “How do scholars approach the circular economy? A systematic literature review,” *J. Clean. Prod.* 178, 703–722, 2018, doi: 10.1016/j.jclepro.2017.12.112.

[5] J. Motloch, “Regenerative design for sustainable development,” *Landsc. Urban Plan.* 32, 3, 198–201, 1995, doi: 10.1016/0169-2046(95)90009-8.

[6] W. R. Stahel, “The Performance Economy: Business Models for the Functional Service Economy,” in *Handbook of Performability Engineering*, K. B. Misra, Ed. London: Springer London, 2008, pp. 127–138.

[7] M. Braungart, W. McDonough, and A. Bollinger, “Cradle-to-cradle design: creating healthy emissions – a strategy for eco-effective product and system design,” *J. Clean. Prod.* 15, 13, 1337–1348, 2007, doi: https://doi.org/10.1016/j.jclepro.2006.08.003.

[8] S. Erkman, “Industrial ecology: An historical view,” *J. Clean. Prod.* 5, 1, 1–10, 1997, doi: https://doi.org/10.1016/S0959-6526(97)00003-6.

[9] D. Ness, “Sustainable urban infrastructure in China: Towards a Factor 10 improvement in resource productivity through integrated infrastructure systems,” *Int. J. Sustain. Dev. \& World Ecol.* 15, 4, 288–301, 2008, doi: 10.3843/SusDev.15.4:2a.

[10] Y. Geng and B. Doberstein, “Developing the circular economy in China: Challenges and opportunities for achieving ‘leapfrog development,’” *Int. J. Sustain. Dev. \& World Ecol.* 15, 3, 231–239, 2008, doi: 10.3843/SusDev.15.3:6.

[11] H. Salmenperä, K. Pitkänen, P. Kauto, and L. Saikku, “Critical factors for enhancing the circular economy in waste management,” *J. Clean. Prod.*, 280, 2021, doi: 10.1016/j.jclepro.2020.124339.

[12] D. A. R. George, B. C. Lin, and Y. Chen, “A circular economy model of economic growth,” *Environ. Model. Softw.* 73, 60–63, 2015, doi: https://doi.org/10.1016/j.envsoft.2015.06.014.

[13] R. Hughes, “The EU Circular Economy Package - Life Cycle Thinking to Life Cycle Law?,” *Procedia CIRP* 61, 10–16, 2017, doi: 10.1016/j.procir.2016.12.006.

[14] B. Su, A. Heshmati, Y. Geng, and X. Yu, “A review of the circular economy in China: Moving
from rhetoric to implementation,” *J. Clean. Prod.* **42**, 215–227, 2013, doi: 10.1016/j.jclepro.2012.11.020.

[15] N. M. P. Bocken, I. de Pauw, C. Bakker, and B. van der Grinten, “Product design and business model strategies for a circular economy,” *J. Ind. Prod. Eng.* **33**, 5, 308–320, 2016, doi: 10.1080/21681015.2016.1172124.

[16] M. R. Esa, A. Halog, and L. Rigamonti, “Developing strategies for managing construction and demolition wastes in Malaysia based on the concept of circular economy,” *J. Mater. Cycles Waste Manag.* **19**, 3, 1144–1154, 2017, doi: 10.1007/s10163-016-0516-x.

[17] P. Brown, N. Bocken, and R. Balkenende, “Why do companies pursue collaborative circular oriented innovation?,” *Sustain.* **11**, 3, 1–23, 2019, doi: 10.3390/su11030635.

[18] P. Priyadarshini and P. C. Abhilash, “Circular economy practices within energy and waste management sectors of India: A meta-analysis,” *Bioresour. Technol.* **304**, November 2019, p. 123018, 2020, doi: 10.1016/j.biortech.2020.123018.

[19] L. A. López Ruiz, X. Roca Ramón, and S. Gassó Domingo, “The circular economy in the construction and demolition waste sector – A review and an integrative model approach,” *J. Clean. Prod.* **248**, 2020, doi: 10.1016/j.jclepro.2019.119238.

[20] S. Suárez, X. Roca, and S. Gasso, “Product-specific life cycle assessment of recycled gypsum as a replacement for natural gypsum in ordinary Portland cement: application to the Spanish context,” *J. Clean. Prod.* **117**, 150–159, 2016, doi: https://doi.org/10.1016/j.jclepro.2016.01.044.

[21] C. Ludwig, S. Hellweg, and S. Stucki, *Municipal Solid Waste Management.* Villigen PSI, Switzerland, 2003.

[22] S. M. Ali, A. Pervaiz, B. Afzal, N. Hamid, and A. Yasmin, “Open dumping of municipal solid waste and its hazardous impacts on soil and vegetation diversity at waste dumping sites of Islamabad city,” *J. King Saud Univ. Sci.* **26**, 1, 59–65, 2014, doi: 10.1016/j.jksus.2013.08.003.

[23] B. T. Long and N. H. Phong, “Integrated model for methane emission and dispersion assessment from landfills: A case study of Ho Chi Minh City, Vietnam,” *Sci. Total Environ.* **738**, 139865, 2020, doi: 10.1016/j.scitotenv.2020.139865.

[24] P. H. Nguyen, D. C. M. Nguyen, and L. T. Bui, “Potential of methane emission reduction and energy recovery from the municipal solid waste landfills - a case study of Binh Duong province, Vietnam,” in *The National Conference on Geography Information System 2020 (GIS Conference) - GIS for smart cities towaurs sustainable development*, 2020, pp. 381–393.

[25] R. Pipatti et al., “Chapter 3: Solid Waste Disposal,” in *2006 IPCC Guidelines for National Greenhouse Gas Inventories*, IPCC, Ed. 2006, pp. 1–40.

[26] A. Alexander, C. Burklin, and A. Singleton, “Landfill Gas Emissions Model (LandGEM) Version 3.02 User’s Guide,” no. May, p. 56, 2005.

[27] J. Bogner and K. Spokas, “Landfill CH4: Rates, fates, and role in global carbon cycle,” *Chemosphere* **26**, 1–4, 369–386, 1993, doi: 10.1016/0045-6535(93)90432-5.

[28] D. Cudjoe and M. S. Han, “Economic and environmental assessment of landfill gas electricity generation in urban districts of Beijing municipality,” *Sustain. Prod. Consum.* **23**, 128–137, 2020, doi: 10.1016/j.spc.2020.04.010.

[29] D. Cudjoe, M. S. Han, and W. Chen, “Power generation from municipal solid waste landfill in the Beijing-Tianjin-Hebei region,” *Energy* **217**, 2021, doi: 10.1016/j.energy.2020.119393.

[30] L. T. Bui and P. H. Nguyen, “Prediction of potential for greenhouse gas mitigation and power recovery from a municipal solid waste landfill case in Tien Giang province , Vietnam,” *Vietnam J. Hydrometeorol.* **2021**, 7, 32–52, 2021, doi: 10.36335/VNJHM.2021(7).32-52.

[31] D. Cudjoe, M. S. Han, and A. P. Nandwardhana, “Electricity generation using biogas from organic fraction of municipal solid waste generated in provinces of China: Techno-economic and environmental impact analysis,” *Fuel Process. Technol.* **203**, March, 106381, 2020, doi: 10.1016/j.fuproc.2020.106381.

[32] P. Ghosh et al., “Assessment of methane emissions and energy recovery potential from the municipal solid waste landfills of Delhi, India,” *Bioresour. Technol.*, 611–615, 2019, doi:
[33] N. Scarlat, V. Motola, J. F. Dallemend, F. Monforti-Ferrario, and L. Mofor, “Evaluation of energy potential of Municipal Solid Waste from African urban areas,” Renew. Sustain. Energy Rev. 50, 1269–1286, 2015, doi: 10.1016/j.rser.2015.05.067.

[34] T. R. Ayodele, A. S. O. Ogunjuyigbe, and E. E. Ekoh, “Outlook of Agricultural Sector in the Face of Changing Global Climate: The Case of Nigeria,” Agric. Res. Technol. Open Access J. 5, 3, 68–71, 2017, doi: 10.19080/artoaj.2017.05.555664.

[35] A. S. O. Ogunjuyigbe, T. R. Ayodele, and M. A. Alao, “Electricity generation from municipal solid waste in some selected cities of Nigeria: An assessment of feasibility, potential and technologies,” Renew. Sustain. Energy Rev. 80, May, 149–162, 2017, doi: 10.1016/j.rser.2017.05.177.

[36] T. R. Ayodele, A. S. O. Ogunjuyigbe, and M. A. Alao, “Economic and environmental assessment of electricity generation using biogas from organic fraction of municipal solid waste for the city of Ibadan, Nigeria,” J. Clean. Prod. 203, 718–735, 2018, doi: 10.1016/j.jclepro.2018.08.282.

[37] Climate Leadership Group - C40 Cities, “Workshop on developing city-level greenhouse gas inventory activities - Technical manual for participating experts,” Ho Chi Minh City, 2018.

[38] M. Brander, “Greenhouse Gases, CO₂, CO₂e, and Carbon: What Do All These Terms Mean?,” Ecometrica, no. August, p. 3, 2012.

[39] Green House Protocol, “Global Warming Potential Values,” 2015.

[40] IPCC, “CH4 Emissions from Solid Waste Disposal,” IPCC Good Pract. Guid. Uncertain. Manag. Natl. Greenh. Gas Invent., pp. 419–439, 2006.

[41] C. Yaman, I. Anil, and O. Alagha, “Potential for greenhouse gas reduction and energy recovery from MSW through different waste management technologies,” J. Clean. Prod. 264, 121432, 2020, doi: 10.1016/j.jclepro.2020.121432.

[42] Da Nang City People’s Committee, “Report on domestic solid waste management in Da Nang city,” Danang City, 2018.

[43] MONRE, “Vietnam National Environmental Report 2019: Waste Management,” Ha Noi Capital, 2020.

[44] Da Nang City Environmental Protection Department, “Assessment of solid waste management status in Danang City,” Danang City, 2019.

[45] MONRE, “Vietnam National Environmental Report 2011: Waste Management,” Ha Noi Capital, 2012.

[46] L. H. Anh et al., “Site-specific determination of methane generation potential and estimation of landfill gas emissions from municipal solid waste landfill: a case study in Nam Binh Duong, Vietnam,” Biomass Convers. Biorefinery, March, 2021, doi: 10.1007/s13399-020-01192-0.