EEET ECOLOGICAL ENGINEERING & ENVIRONMENTAL TECHNOLOGY

Ecological Engineering & Environmental Technology 2023, 24(8), 311–320
https://doi.org/10.12912/27197050/172852
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Received: 2023.08.15
Accepted: 2023.09.23
Published: 2023.10.16

Landfill Gas Prospect as a Renewable Energy Source at Talang Gulo Jambi City, Indonesia

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ABSTRACT

The landfill is a place used for landfill that can have a negative impact on the environment such as, causing greenhouse gas emissions, soil contamination, and groundwater pollution. Landfill gas content of CH_4, CO_2 and non-methane organic compounds (NMOC) is the cause of the greenhouse effect and Global warming potential (GWP). The concentration of CH_4 in landfill gas is relatively low, but CH_4 causes a greenhouse effect 21 times greater than CO_2. The research was conducted at the Talang Gulo landfill in Jambi City. The purpose of this study is to measure and analyze the production and amount of CH_4 gas concentration emitted into the atmosphere and assess methane gas emissions as an energy source. The Application to estimate gas using models was with LandGEM-v302 software. The results of LandGEM-v302 simulation of landfill gas show a peak in 2023 of $3{,}194\times10^4$ Mg·year^{-1} for total landfill gas, methane emissions A6 ($8{,}530\times10^3$ Mg·year^{-1}), carbon dioxide ($2{,}341\times10^4$ Mg year^{-1}) and NMOC ($3{,}667\times10^2$ Mg·year^{-1}). The potential of methane gas as a source of fuel energy is 11,403,693.84 kg·year^{-1} and electrical energy is 182,862.08 kWh.

Keywords: landfill, gas, renewable, energy, Indonesia, pollution, emission.

INTRODUCTION

Population growth and urbanization continue to increase followed by more and more municipal solid waste (MSW) generated every year around the world. According to the World Bank, 2.01 billion tons of MSW were generated in 2016, and up to 3.40 billion tons will be generated by 2050 under a business-of-usually scenario (Kaza et al., 2018; Duan et al., 2021). The population increase in Jambi City since 2018 has been 598,103 people with waste generation in the Talang Gulo landfill of 346,815.70 m^3·year^{-1}, continuing to increase until 2022 of 619,553 people with waste generation in the landfill of 430,562.21 m^3·year^{-1} or an increase of 19.45% (BPS, 2022; DLH, 2022). In 2020, the Talang Gulo landfill has utilized methane gas as a source of thermal energy with a piping system to 50 households around the landfill (DLH, 2022). Talang Gulo landfill accommodates all MSW originating from households, offices, restaurants, industries, and others. Through the process of biodegradation and decomposition, MSW will produce greenhouse gases, such as methane (CH_4), carbon dioxide (CO_2) and nitrogen dioxide (N_2O) (Abanades et al., 2022). The content of landfill gases, namely CH_4 and CO_2, are the cause of the greenhouse effect and global warming (Niskanen et al., 2012). Indonesia as a developing country has set a planning strategy to reduce greenhouse gas emissions by 29% in the waste sector until the 2030 period (Ministry of Environment and Forestry, 2020) which was previously 26% until the 2020 period. Gas sources contained in landfills consist of 50–60% CH4 and 40–50% CO_2 (Mønster et al., 2019). According to Duan et al. (2021) at the CH_4 fermentation stage, hydrogen sulfide, aromatic and aliphatic hydrocarbons are usually found. The gas produced has an impact on climate change. The concentration of CH_4 in landfill gas is relatively low, but CH_4 causes a greenhouse effect 21 times greater than CO_2 (GHG Inventory, Ministry of Energy and Mineral Resources, 2018). According to (Zhou et al., 2017) the release of carbon dioxide, methane and nitrous oxide from the trash can shows that the annual average CO_2, CH_4 and N_2O effluxes in the pre-disposal stage were $(1.6\pm0.9)10^3$, 0.049 ± 0.016 and 0.94 ± 0.54 mg kg^{-1} h^{-1} (dry matter basis). Methane gas is a component of biogas produced from MSW piles in landfills by 55–75% (Fuldauer et al., 2018; Mostbauer et al., 2013) and CH_4 gas is very dangerous because it is explosive, therefore handling methane gas in landfills needs to be done by being used as an energy source.

The MSW sector has the potential to increase global warming (GWP) although it is often underestimated (Budihardjo et al., 2023). Methane gas emissions have a higher GWP than CO_2 during combustion or open combustion practices (Budihardjo et al., 2022). Kaza et al. (2018) found that 5% of global GHG emissions come solely from poor waste management. In addition, municipal waste generation is expected to increase to 3.4 billion tons by 2050. As stated in the Paris Agreement, total emissions in all sectors, including the waste sector, must be reduced by 45% by 2030, and a strong strategy must be determined to achieve this mission (Huang, 2021). Demir et al. (2019)] stated that the most common solution to manage waste and reduce emissions is the prevention or minimization of waste from the source. The appropriate strategy for waste management depends on waste generation and disposal, the level of the economy, and the operation and management of each municipality (Bian et al., 2020).

Given the impact of methane gas on the environment, it is necessary to control gas emissions to reduce methane gas emissions (Kumar et al., 2016). Utilization of methane gas as an energy source as an effort to mitigate climate change (Dace et al., 2014). To maintain the stability of energy needs, the potential for solid waste management as an important renewable energy source in the future that is economically feasible and environmentally friendly (Bajic et al., 2015). In the period of utilization of methane gas as an alternative energy source, it is necessary to measure methane gas contained in the Talang Gulo landfill as an inventory activity that has never been carried out and the prospective potential of waste in the landfill which also means the growth of the potential gas produced and if not utilized can cause disruption to the surrounding environment. Therefore, it needs to be used positively, In order to be optimal, it is necessary to study or analyze how much potential electrical energy produced from CH_4 gas emissions can be utilized by the community. According to Mønster et al. (2019), the waste treatment method in the landfill using sanitary landfill technology will produce more methane gas because the landfill is covered by soil. The concentration of CH_4 gas emitted into the atmosphere needs to be measured. Measurement and prediction of CH_4 gas can use the LandGEM model (Poma et al., 2021). The LandGem model is useful for evaluating landfill gas control measures and improving methane emission estimates useful for greenhouse gas inventories (Foster-Wittig et al., 2015; Evangelisti et al., 2017). Estimates show that each year about 12% of CH_4 produced in global landfills is captured in sanitary landfills (Scheutz and Kjeldsen, 2019), so control of CH_4 emissions from landfills should be prioritized in waste management procedures. Methane emissions from landfill landfills are a significant source of global greenhouse gas emissions into the atmosphere; thus, reducing it would be a beneficial way to mitigate overall greenhouse gas emissions (Li et al., 2020). According to (Utami et al., 2022) Bandar Lampung City can produce around 1.40 million m^3 CH_4 $year^{-1}$, which is equivalent to 1.07 million kg of LPG. Meanwhile, the conversion of biogas from household organic waste is estimated to reduce 21.09 million kg of CO_2-eq $year^{-1}$ GHG emissions. Meanwhile, in Jambi City, the generation of municipal solid waste (MSW) is expected to continue to increase. The increase in MSW was followed by mismanagement, such as lack of 3R (reduce, reuse, recycle) practices, transportation services and inefficient waste collection.

METHOD

The study was conducted at the Talang Gulo landfill in Jambi City, Jambi Province, Indonesia from January to December 2022. The landfill has an area of 31.3 ha consisting of 10 ha of land that is no longer used and 21.3 ha of land specifically for sanitary landfills. MSW production in Jambi City is 1572.83 m^3 day^{-1} and the amount of MSW stockpiled in landfill is around 1179.62 m^3 day^{-1}, the rest is still MSW that has not been transported to landfill. This is due to the limited freight fleet, and the freight capacity is about 3-4 tons for each transport truck. MSW stockpiles in landfill will have an impact on CH_4 gas production. Then the average rainfall in Jambi City is 225.82 per month with 15.42 rainy days per month. The LandGem model (Poma et al., 2021) was used to calculate CH_4 gas. The mathematical model for estimating the production of methane emissions is by the method LandGEM (Landfill Gas Emission Model) i.e. (EPA, 2014):

$$Q_{CH4} = \sum_{i}^{n} \sum_{j=0,1}^{1} k \, Lo \left(\frac{Mi}{10}\right) e^{-k \, tij} \quad (1)$$

where: QCH_4 – annual methane generation in the year of the calculation (m^3 $year^{-1}$), *i* – 1 year time increment, *n* – year of the calculation - (initial year of waste acceptance), *j* – 0.1 year time increment, *k* – methane generation rate (0.05 $year^{-1}$), *Lo* – potential methane generation capacity (170 $m^3 \cdot Mg^{-1}$), *Mi* – mass of waste accepted in the *i* year (Mg), *tij* – age of the–*j* section of waste mass *Mi* accepted in the *i* year.

Determination of methane gas emissions with the LandGEM model based on organic waste in the landfill. The LandGEM model is a useful tool for reliable estimates of greenhouse gas emissions. This model is easier to use for countries that have limited data related to the amount of domestic waste in Landfills. The LandGEM model assumes that waste is considered homogeneous, k and Lo values are constant (Karanjekar, 2012). Based on the Clean Air Act (CAA) regulation as stipulated in AP-42, the values of k, Lo, and non-methane organic compounds (NMOC) concentrations have been determined with the values of: k = 0,05 $year^{-1}$, Lo = 170 m^3 Mg^{-1}, Concentration NMOC = 4000 ppmv hexane.

The use of the LandGEM model will feature more complex emission estimations with methane gas volumes equal to 50% of the total volume of gas produced in landfills. According to Kumar and Samadder (2017) methane gas as an energy source, can be produced from waste. Thus, it can be considered as a potential alternative energy source, which is economically feasible and environmentally friendly.

RESULTS AND DISCUSSION

Landfill Talang Gulo Final Processing Site was established in 1997 and is located on Jalan Lintas (Jalan Talang Gulo), RT.04 Kelurahan Kenali Asam Bawah, Kota Baru District, Jambi City, Jambi Province. The location of the landfill is about 15 Km from the city center, while the coordinates of this location are 1°41'18.6" South Latitude and 103°37'6.54" East Longitude. The elevation of the location is +38.25 m to +49 m above sea level. The location of the Talang Gulo landfill is presented in Figure 1.

Landfill gas generation and methane emissions

Measurement of gas generation in Talang Gulo landfill using LandGem V3.02 model (Alexander 2005) which is a development of the US EPA model (2005). The Talang Gulo landfill began operations in 1997 and has a technical life plan of 25 years. Waste generation data every year is required as input on the LandGem V 3.02 device. Waste generation data is presented in Table 1.

Table 1 shows that in 1997 the waste generation in Jambi City amounted to 87,718.77 tons $year^{-1}$ and the waste transported to landfill amounted to 65,789.08 tons $year^{-1}$. In 2023, waste generation will increase to 159,688.01 tons $year^{-1}$ and waste transported to landfill will be 119,766.01 tons $year^{-1}$. The waste generation data presented in Table 1 is waste that has been buried in landfill from 1997 to 2022. Increase is related to increasing population. Meanwhile, the waste transported to the landfill is less than the waste generation due to composting and sorting activities for recycled waste and waste sorting activities carried out by scavengers.

Waste inputs received from users, user waste in landfills and methane gas emissions from 1997 to 2022 continue to increase. In 1997, when the new landfill opened, it did not produce CH_4 gas emissions. CH_4 gas emissions starting in 1998 amounted to 546,821.90 m^3 $year^{-1}$. User waste receipt inputs and methane emissions are presented in Table 2.

Based on waste data received in 2022 of 119,766 tons year^{-1} resulting in methane emissions of 12,395,319.39 m^3 year^{-1}. Methane emissions come from the biodegradation process of organic matter that produces CH_4, CO_2 and N_2O. Total gas landfills, methane, carbon dioxide, non-methane organic compounds can be seen in Table 3. According to Dewilda et al. (2020), and Kavitha et al. (2020), the municipal solid waste organic fraction (OFMSW) is characterized by

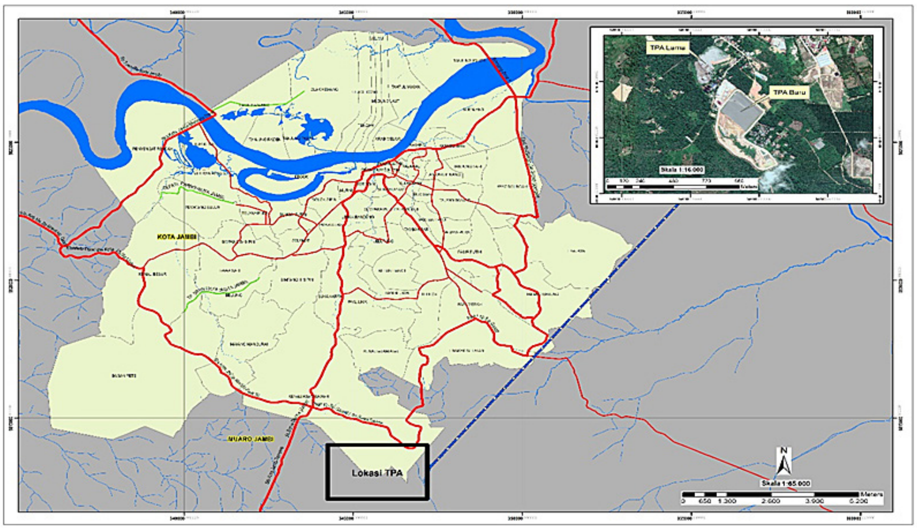

Figure 1. Location of Talang Gulo Landfill, Jambi City

Table 1. Annual waste generation data [SIPSN Data 2022; DLH Jambi City, 2022]

Year	Garbage generation	Garbage entering the Talang Gulo landfill garbage generation	Calculated units
	(ton·year^{-1})	(ton·year^{-1})	(short tons·year^{-1})
1997	87 718.77	65 789.08	72 368
1998	104 272.36	78 204.27	86 025
1999	105 334.99	79 001.24	86 901
2000	106 673.04	80 004.78	88 005
2001	108 304.15	81 228.11	89 351
2002	110 301.65	82 726.24	90 999
2003	111 535.71	83 651.79	92 017
2004	112 889.35	84 667.02	93 134
2005	114 176.31	85 632.23	94 195
2006	115 609.92	86 707.44	95 378
2007	120 315.46	90 236.60	99 260
2008	121 627.71	91 220.78	100 343
2009	133 772.65	100 329.48	110 362
2010	136 151.10	102 113.32	112 325
2011	138 035.92	103 526.94	113 880
2012	142 368.43	106 776.32	117 454
2013	143 128.03	107 346.03	118 081
2014	145 139.84	108 854.88	119 740
2015	147 185.12	110 388.84	121 428
2016	149 080.93	111 810.70	122 992
2017	151 087.37	113 315.53	124 647
2018	152 598.14	114 448.61	125 893
2019	154 557.83	115 918.37	127 510
2020	156 103.40	117 077.55	128 785
2021	158 106.98	118 580.24	130 438
2022	159 688.01	119 766.01	131 743

high humidity and biodegradability due in large part from food waste, kitchen waste and food waste from settlements, restaurants, cafeterias, factory dining rooms and markets. The characteristics of waste entering landfills are important to consider because they are a major source of environmental impacts and risks especially when choosing waste to energy processing technology (Beylot et al., 2013; Jouhara et al., 2017; Zou et al., 2023). The technology of processing waste into energy by carrying out biological processes requires paying attention to the high content of organic waste such as food, vegetables, market waste, green / garden waste with high humidity content and sensitive to pH (Farley et al., 2015). Estimation of gas contained in landfill generation based on waste generation data using bulk-waste every year in landfill (Wahyono, 2014). Then the methane formation parameter (k) is assumed to be 0.05 per year and the methane formation capacity (Lo) is 170 m^3 Mg^{-1}, these two parameters are based on temperature, humidity and rainfall conditions (Mønster et al., 2019). The LandGEM-v302 software calculates that landfill waste begins to produce landfill gas the following year. The Talang Gulo landfill began operations in 1997 and landfill gas production from 1998 to 2022, this is shown in the LandGEM-v302 graph in Figure 2. Simulation of prediction of potential emissions of Talang Gulo landfill with LandGEM-v302 software resulted in total landfill emissions of landfill gas consisting of methane, carbon dioxide and non-methane organic compounds (NMOC) from 1998 to 2069 (Fig. 2). Total landfill gas, methane, carbon dioxide and NMOC continue to increase from 1998 to 2022 and experience *peak* values in 2023 of $3{,}194\times10^4$ Mg $year^{-1}$ for total landfill gas, and methane emissions ($8{,}530\times10^3$ Mg $year^{-1}$), carbon dioxide ($2{,}341\times10^4$ Mg $year^{-1}$) and NMOC ($3{,}667\times10^2$ Mg $year^{-1}$). Emissions increase in proportion to the mass amount of waste entering the Talang Gulo landfill. Furthermore, after 2023 landfill gas will decrease from year to year. In this study, the prediction of landfill gas generation will be carried out until 20 years after the

Table 2. User waste acceptance inputs, user waste-in-place, and methane emissions

Year	User waste acceptance Inputs ($Mg\cdot year^{-1}$)	User waste-in-place (Mg)	Methane emissions ($m^3\cdot year^{-1}$)
1997	65 789	0	0
1998	78 204	65 789	546 821.90
1999	79 001	143 993	1 170 166.84
2000	80 005	222 995	1 769 735.10
2001	81 228	302 999	2 348 403.24
2002	82 726	384 227	2 909 017.41
2003	83 652	466 954	3 454 742.17
2004	84 667	550 606	3 981 544.55
2005	85 632	635 273	4 491 092.81
2006	86 707	720 905	4 983 812.68
2007	90 237	807 612	5 461 439.19
2008	91 221	897 849	5 945 105.05
2009	100 329	989 070	6 413 362.50
2010	102 113	1 089 399	6 934 491.93
2011	103 527	1 191 512	7 445 032.40
2012	106 776	1 295 039	7 942 423.17
2013	107 346	1 401 816	8 442 563.91
2014	108 855	1 509 162	8 923 047.78
2015	110 389	1 618 017	9 392 639.34
2016	111 811	1 728 405	9 852 078.54
2017	113 316	1 840 216	10 300 928.76
2018	114 449	1 953 532	10 740 396.06
2019	115 918	2 067 980	11 167 848.15
2020	117 078	2 183 899	11 586 669.42
2021	118 580	2 300 976	11 994 699.34
2022	119 766	2 419 556	12 395 319.39

Table 3. Total landfill gas, methane, carbon dioxide, and non-methane organic compounds (NMOC)

Year	Total landfill gas (Mg·year^{-1})	Methane (Mg·year^{-1})	Carbon dioxide (Mg·year^{-1})	NMOC (Mg·year^{-1})
1997	0	0	0	0
1998	1 365.77	364.81	1 000.96	15.68
1999	2 922.66	780.67	2 141.99	33.56
2000	4 420.17	1 180.68	3 239.50	50.75
2001	5 865.48	1 566.73	4 298.75	67.34
2002	7 265.70	1 940.75	5 324.95	83.42
2003	8 628.73	2 304.83	6 323.90	99.07
2004	9 944.49	2 656.28	7 288.21	114.17
2005	11 217.17	2 996.23	8 220.94	128.79
2006	12 447.81	3 324.94	9 122.86	142.91
2007	13 640.75	3 643.59	9 997.16	156.61
2008	14 848.77	3 966.27	10 882.51	170.48
2009	16 018.32	4 278.66	11 739.65	183.91
2010	17 319.91	4 626.34	12 693.58	198.85
2011	18 595.06	4 966.94	13 628.12	213.49
2012	19 837.37	5 298.77	14 538.60	227.75
2013	21 086.55	5 632.44	15 454.10	242.10
2014	22 286.63	5 953.00	16 333.63	255.87
2015	23 459.50	6 266.28	17 193.21	269.34
2016	24 607.02	6 572.80	18 034.22	282.52
2017	25 728.09	6 872.25	18 855.84	295.39
2018	26 825.72	7 165.44	19 660.28	307.99
2019	27 893.34	7 450.61	20 442.73	320.25
2020	28 939.41	7 730.03	21 209.38	332.26
2021	29 958.53	8 002.24	21 956.28	343.96
2022	30 959.13	8 269.52	22 689.62	355.44

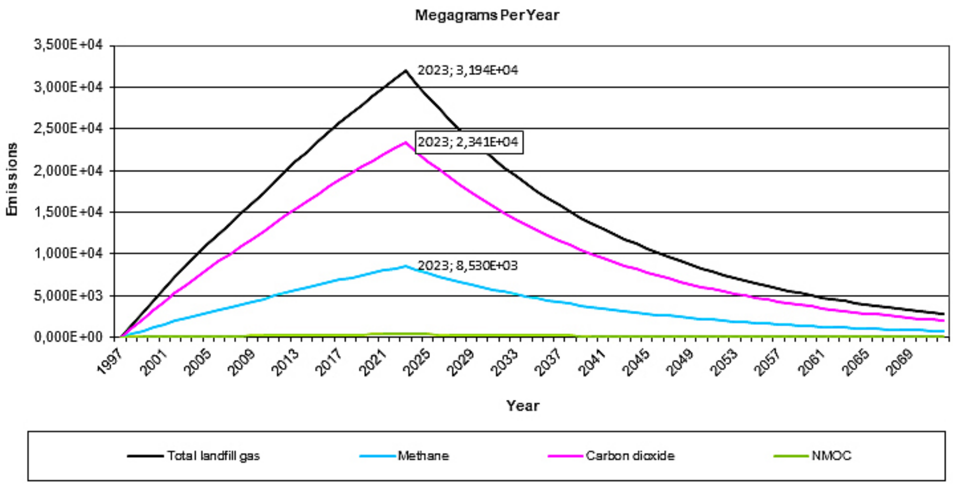

Figure 2. Talang Gulo landfill gas generation [LandGEM-v302, 2023]

landfill stops operating in 2022, so the prediction of landfill gas generation until 2042 is 1,235×10^4 Mg year^{-1} with methane emissions produced at 3,299×10^3 Mg year^{-1}. Norouzi et al. (2018) stated that there will be a decrease in biogas production until the 20th year. By 2030, CH_4 emissions from landfill are expected to be reduced by up to 10% of CH_4 emissions from all sources (EPA, 2014). The emergence of landfill gas is a product of anaerobic decay in organic waste which goes through several stages, starting from the stage of landfill waste to the stage of the waste maturation process after all organic components decompose and decompose into CH_4 and CO_2. According to

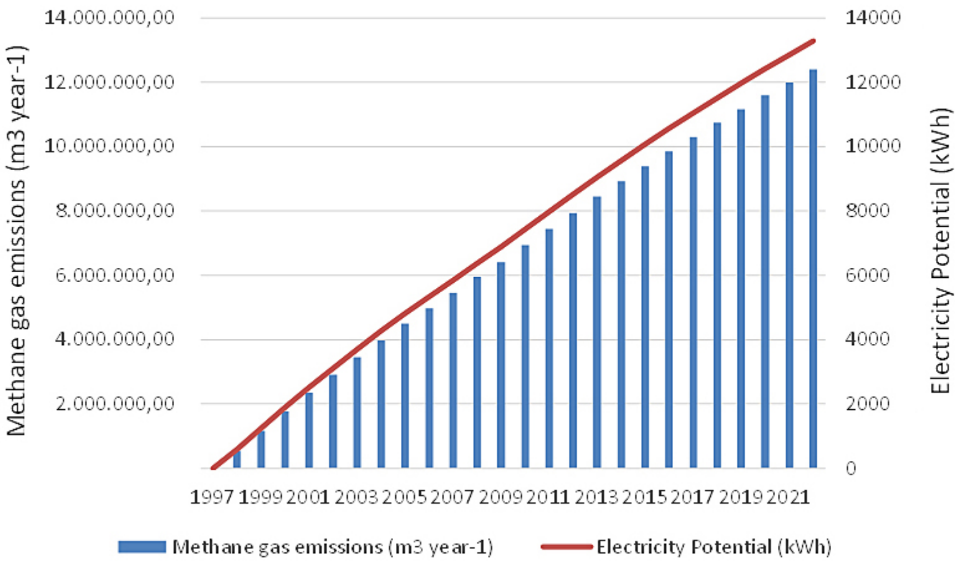

Figure 3. Results of methane gas conversion into electricity

(Abushammala et al., 2016; Aguilar-Virgen et al., 2014; Capellin et al., 2014; Aghdam et al., 2017; Monster et al., 2019) CH_4 (usually in the 45%-60% range), CO_2 (usually in the 40-60% range), and several other compounds. The most important anthropogenic greenhouse gases are CH_4 and CO_2, and the global warming potential of CH_4 is 20-28 times that of CO_2 over a period of 100 years (IPCC, 2013; Mønster et al., 2019).

Methane gas emissions as an energy source

Methane gas produced from waste generation can be converted into electrical energy based on EPA can be seen in Figure 3. The utilization of methane gas can reduce global warming and petroleum energy consumption. The advantage can be used as a substitute for fuel for cooking (Salamah 2015). The potential methane production of Talang Gulo landfill with LandGem-v302 software in 2022 is 8,269.52 Mg year^{-1} or 12,395,319.39 m^3 year^{-1}. Then for the potential production of landfill gas (biogas) of 30,959.13 Mg year^{-1} or 2,317×10^7 m^3 year^{-1} ≈ 24,790,638.77 m^3 year^{-1} in 2022. Mønster et al., (2019) states that landfill gas should be managed by gas collection and energy utilization, by combustion or by other means, such as mitigation that relies on microbial oxidation of methane in overburden soils or biofilters. Based on the equivalence of biogas with energy sources (Aji and Bambang, 2019; Nakashima and Junior, 2021), the equivalence value of 1 m^3 of biogas with Liquid Petrolium Gas (LPG) is 0.46 kg.

$$\textit{Equivalence of biogas with LPG} = \textit{Biogas production year}^{-1} \times 0.46\ \text{kg} = 24{,}790{,}638.77\ \text{m}^3\ \text{year}^{-1} \times 0.46\ \text{kg} = 11{,}403{,}693.84\ \text{kg year}^{-1} \quad (2)$$

From the survey results, it is known that the price of 3 kg of subsidized LPG is IDR 18.000, then the price of 1 kg of LPG = IDR 6.000. So the price of biogas year $^{-1}$ = 11,403,693.84 kg × IDR. 6,000 = IDR. 68,422,163,012. This reflects that an increase in methane gas production will be followed by an increase in revenue from the conversion of methane gas into energy sources. Based on interviews with the community around the Talang Gulo landfill and the Head of UPTD Landfill and his staff, information was obtained as many as 104 households who used methane gas for cooking. Previously, the community used 3 kg of LPG, and the average monthly requirement for use was 3 LPG cylinders head^{-1} of family. So the average needs per year are:

$$3\ \text{LPG cylinders} \times 104\ \text{household} \times \text{LPG} \times 3\ \text{kg} = 936\ \text{kg LPG month}^{-1} \quad (3)$$

where: in 1 year = 12 months, so: 936 kg LPG × 12 = 11,232 kg year^{-1}.

According to the equivalence value of biogas with LPG = 11,403,693.84 kg year^{-1}. So if calculated = 11,403,693.84 kg year $^{-1}$ – 11,232 kg year^{-1} = 11,392,461.84 kg year^{-1}. From the results of the calculation above, the production of landfill gas (biogas) in the landfill is still very sufficient for the needs of 104 households around the Talang Gulo landfill. Landfill gas production is still left at 11,403,693.84 kg year^{-1} of landfill gas or only used

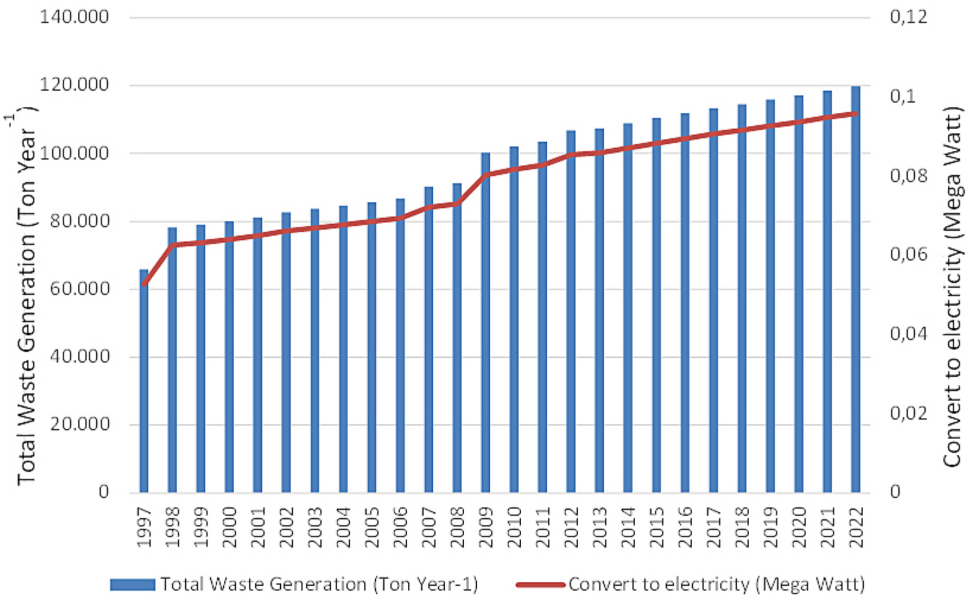

Figure 4. Conversion of waste to electricity under EPA

0.1% of the total landfill gas (biogas) available. From this calculation, it was found that the new gas landfill was used 0.1% per year for 104 households and was feasible to be developed in the future.

The potential of methane gas in the landfill depends on the volume of waste entering the landfill. The more landfills, the more methane gas is formed (Mønster et al., 2019). The appropriate strategy for waste management depends on waste generation and disposal, the level of economy, and the operation and management of each municipality (Bian et al., 2020). EPA (2014) states that 1 million tons of waste can be converted into 0.8 Megawatts of electricity. Based on Figure 4 regarding the conversion of waste into electricity at the Talang Gulo landfill, it can be calculated the amount of electricity that can be converted from waste. Results of converting waste into electricity in 2022: total waste in 2022 = 119,766.01 Mg.

The prediction of methane gas estimates that can be obtained in 2022 in the LandGEM-v302 Default CAA conventional software simulation obtained an estimated value of methane gas emissions of 12,395,319.39 m^3 $year^{-1}$. Conversion of methane gas into electrical energy (Norouzi et al., 2018) equivalence value of 1 m^3 of methane gas with electrical energy of 9.39 kWh. Methane gas production = 12,395,319.39 m^3 $year^{-1.}$ Converted to m^3 $hour^{-1}$ = 1,414.99 m^3 $hour^{-1}$.

$$\textit{Equivalence of methane gas to electrical energy} = \textit{methane gas production hour}^{-1} \times 9.39\ kW = 1{,}414.99\ m^3\ hour^{-1} \times 9.39\ kWh = 13{,}286.76\ kWh \approx 13.29\ MWh \quad (4)$$

Based on the total potential of electrical energy from methane gas at the Talang Gulo landfill from 1997 to 2022 of 182,862.08 kWh or 182.86 MWh and the electricity costs kWh^{-1} for low-class customers is IDR. 1,444.70 kWh^{-1} if the potential of methane gas in the Talang Gulo landfill is utilized, it will produce potential electrical energy worth around IDR. 264,180,852,39,- Stempien et al., (2015) stated that sustainable methane production can be obtained from CO2 capture through solid oxide electrolysis cells combined with methane synthesis reactors. maximum overall energy efficiency of 60.87%, maximum electrical energy efficiency 81.08% (based on lower calorific value), and maximum amount of methane production ~ 1.52 Nm^3 h^{-1} m^{-2} electrolysis.

CONCLUSIONS

Total landfill gas peaks in 2023 was equal $3{,}194 \times 10^4$ Mg $year^{-1}$. The estimated methane emissions produced by the Talang Gulo landfill based on LandGEM-v302 simulations for 1997–2022 reach a maximum of $8{,}530 \times 10^3$ Mg $year^{-1}$ in 2023. Assessment of the estimated production of methane gas as a source of fuel energy amounted to 11,403,693.84 kg $year^{-1}$ and electrical energy amounted to 182,862.08 kWh. The production of methane gas has great prospects as a renewable energy source and can be used for cooking and a substitute for fossil energy, so far methane gas has not been utilized optimally. This knowledge is needed as a possible step for the reduction of methane emissions.

Acknowledgements

The authors thank to the Rector of Jambi University, Director of Jambi University Postgraduate, Authors also thanks to Department of Environment of Jambi City, Talang Gulo Landfill for the partnership during the research.

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