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CARBON FOOTPRINT AND ENERGY ANALYSIS OF BIO-CH_4 FROM A MIXTURE OF FOOD WASTE AND DAIRY MANURE IN DENVER, COLORADO

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Abstract

Anaerobic digestion (AD) is a possible alternative to landfilling of food waste and conventional manure management in order to reduce methane emissions. Key results of this carbon footprint show that the AD Bio-CH_4 pathway has 15.5% lower greenhouse gas (GHG) emissions compared to the prior practice of composting of food waste and manure in Denver, CO. Results from modeling the GHG emissions for Bio-CH_4 production from AD conversion of food waste and manure with avoiding of food waste landfilling and conventional management of dairy manure emits -3.5 kg CO_2 equivalents / kg Bio-CH_4 assuming the electricity was generated using collected landfill gas. This emission intensity is favorable compared to that of fossil natural gas of 4.3 kg CO_2 equivalents / kg Bio-CH_4 equivalents of fossil natural gas. Effects of life cycle system parameters on GHG results are investigated in scenario analysis as well as time dependent analysis of avoided landfill emissions.

Novelty or Significance

A novel feature of this Bio-CH_4 LCA that distinguish it from previous studies are that input data for the anaerobic digestion (AD) process is from an actual operating facility; Heartland Biogas LLC in LaSalle, CO, rather from either modeled data or smaller scale processing. A second novel aspect is a transient analysis on avoided landfill emissions when food waste is diverted to the Bio-CH_4 process, whereas prior work used steady-state analysis. The LCA includes the effects of an innovative water recycle scenario where digestate from the AD process containing mineral nutrients is applied to local crop lands supporting diary operations.

Keywords

Keywords: life cycle assessment, carbon footprint, anaerobic digestion of food waste and manure, transient analysis

Introduction

Food waste generation

The majority of municipal solid waste (MSW) is from the industrial, commercial and residential sectors, which together account for 254 million short tons per year according to recent statistics in the US [1]. Organic materials constitute the majority portion of MSW in which 27% is paper and paperboard with food waste and yard trimmings accounting for 28%. The remainder is made up of plastic > metal > rubber-leather-textiles > wood > glass. The generated MSW is managed by different methods out of which only 12% is processed through incineration and energy collection systems, 53% is disposed to landfills, and 35% goes to recycling and composting [2]. In the USA, out of all the generated MSW the second highest component is organic food waste with 14.6% of total waste. When disposed in a landfill, food waste releases the highest amount of methane emissions per dry weight of disposed materials. Furthermore, the wastage of food is about 30-40% of the food supply, equaling more than 20 pounds of food per person per month. With the conversions of dry solids in food waste to methane, 216 Mg of dry food waste generates 4700 dekatherms of Bio-CH_4 through anaerobic digestion (AD), which is equivalent to 105.19 Mg of fossil natural gas (by taking the lower heating value of 47.14 MJ/kg). According to 2013 EPA report the US generates 36 million wet tons / yr of food waste, which if entirely converted to Bio-CH_4 has a potential to replace .74% of US total natural gas usage of 548 million tons annually (see Supporting information section-4 for calculations). In the US, 97% of the total food waste is buried in landfills where it causes odor as decomposes and produces methane [3].

Landfills and GHG emissions

Currently in the US, 44% of the landfills use gas collection systems plus flaring to reduce GHG emissions and there are about 850 such flaring landfills out of a total 1908 landfills [4]. The landfill methane outreach program (LMOP) currently tracks new landfill gas to energy projects in the US, which reports that there are 652 such landfills turning the methane into useful energy sources (electricity mostly). From 2014 statistics, total methane emissions from landfills in the US are 102.8 million metric tons CO_2 eq. [5]. Methane is more efficient in trapping infrared radiation than CO_2 by 25 times. Methane emissions are significant, account for 11% of overall GHG emissions (CO_2 eq.) in US, and in which landfills account for 20% and natural gas and petrol accounts for 33% of methane emissions [6]. From these statistics, landfilling of MSW represents one of the highest methane emission sources.

Manure generation and management

According to the EPA 2012 report, 20% of the world's non-CO_2 GHG emissions are created from animal agriculture, and in the US, agriculture GHG emissions account for 9% of the total emissions, which is 618 million metric tons out of 6870 total million metric tons of CO_2 equivalents [6]. Animal agriculture emissions include mostly enteric fermentation, the respiration of cattle and other animals. Manure management has great environmental impact, as it accounts for 14% of the overall GHG emissions from the agriculture sector. From among the US overall manure management emissions, nearly 43% of CH_4 emissions are from dairy farms [7]. Key sources for manure production in the US are cattle, swine and poultry, among which the cattle produced 920 million wet tons of manure, poultry 80 million wet tons, which includes litter, and swine production accounts for 110 million wet tons of manure in the year 2007 [8]. By considering the percentages of nutrient concentrations from

Combs et al. 1998, it is estimated to represent 7.44 million tons of N and 2.58 million tons of P from total manure (cattle, swine and poultry), assuming the moisture contents of cattle, swine, and poultry are 76, 80 and 40 respectively [9]. In comparison, US annual agricultural field application of commercial fertilizers in 2007 is about 13.1 million equivalent tons of N and 4.5 million equivalent tons of P. The most conventional manure management systems include: 1. Uncovered anaerobic lagoons, 2. Digesters (includes covered anaerobic lagoons), 3. Solid manure storage, 4. Dry Lots (includes feedlots), 5. Storage pits, 6. Liquid or Slurry systems, 7. Deep bedding systems (cattle and swine), 8. High-rise houses for poultry production without litter, 9. Poultry production with litter, 10. Aerobic treatment, and 11. Manure composting [10]. From the Intergovernmental Panel on Climate Change [11] manure methane emission factors are from 0.02 (most of the poultry breeds), to 1 (beef cattle) and 53 (dairy cows) kilograms per head per year [12], US EPA estimates the total methane emissions of 2.478 million tons of CH_4/yr. from livestock [12].

Composting for management of food waste

According to US 2014 statistics, there were 347 composting facilities accepting food waste from 36 states in the US, with 87 accepting mixed organics (leaves, vegetable scraps, tea bags etc.). Composting consumes more energy than land filling, but significant energy savings in composting are due to the compost replacement of chemical fertilizer in agriculture [13]. Compost, when applied to the field, has benefits such as reducing water runoff, soil erosion, and enhancing the metabolism of microorganisms, which improves the soil fertility. On the other side, it also has a negative impact on the environment such as CH_4 and CO_2 emissions from compost piles, and uses fossil fuel for transportation and in the composting equipment. Out of 254 million tons of MSW in 2013, only 3% of the 37 million tons of food waste is diverted from landfills to composting and it is reported that the composting methane emissions in the US are 3.3 million tons of CO_2 equivalents [5].

Both landfilling and composting of food waste has a high potential for uncontrolled methane emissions, so there is a necessity for reliable alternatives for the management of food waste that is produced each year. Biological treatments are the alternate way for the reduction of solid waste residues by biological activity [14-17]. Anaerobic treatment of food waste and manure has the potential to reduce methane emissions from both controlled and uncontrolled sources, as our study shows.

LCA Literature review

LCA studies have found AD to be more advantageous (i.e. it has less environmental impacts) than other organic waste disposal methods, such as incineration and landfilling. Most of the prior LCA work reported lower greenhouse gas emissions for Bio-CH_4 as a transportation fuel from different substrates such as energy crops and food waste compared with the fossil methane [18-20]. Betzabet et al conducted an LCA on optimization of AD process to see the effect of adsorption and desorption in the process [21]. Owen et al. performed an LCA on the emissions from manure management processes and their studies highlighted the areas to concentrate on to mitigate the GHG emissions [7]. ROU conducted an LCA of a windrow composting system in Australia including compost use and post application impacts [22]. Only a few LCA studies have analyzed transient landfill emission scenarios, and results show that the gas collection systems with flaring had higher emissions when compared with a landfill gas-to-energy scenario [23]. A prior life cycle carbon footprint found that emissions were much lower for windrow composting, high solids anaerobic digestion, or for co-digestion of the organic fraction of MSW with either industrial wastes or sewage sludge compared with the baseline process of composting of the food waste while landfilling of the remaining organic fraction [24] (with electricity generation of captured landfill gas). However, to date as far as we know no studies have analyzed the entire consequential life cycle assessment of Bio-CH_4 produced from AD of mixtures of food waste and dairy manure.

Research Objectives

The main research objective of this work is to model the cradle-to-grave environmental impacts (greenhouse gas emissions and fossil energy demand) of the anaerobic digestion of food waste mixed with dairy manure at a specific location near Denver, CO. The prior practice at this location was composting of the food waste and manure, and this prior case is modeled as a comparison. Additional analyses include a more general case of diverting food waste from landfills and animal manure from conventional manure management processes to produce Bio-CH_4 in AD facilities. Our study also investigates avoiding different landfilling scenarios (uncontrolled, gas collection and flaring and gas collection and electricity generation operating at steady-state). Finally, in an effort add more realism to the LCA modeling an investigation of the transient response of avoided landfill emissions was conducted.

Materials and Methods

Goal and Scope

The goal of this study is to make a consequential comparative life cycle analysis in two separate cases. Case 1 analyzes the use of food waste from Denver, CO restaurants and dairy manure in the vicinity of LaSalle, CO for compost production, which was the prior use of these waste materials, versus a new Bio-CH_4 production system. Case 2 is a more general case for the prior use of food waste and dairy manure that assumes food waste was landfilled with (Scenario-1) uncontrolled emissions from the landfill, (Scenario-2) a gas collection system with flaring of the collected landfill gases, and (Scenario-3) which represents landfilling of the food waste with a gas collection system and electricity generation. In all scenarios, conventional manure management is included as part of the avoided pathways. The impact category of primary interest is greenhouse gas emissions; however, fossil energy consumption is also evaluated. Scenario analyzes are modified to include transient landfill emissions that are avoided when food waste is instead used for Bio-CH_4 production.

Functional Unit

The basis for the analyses reported here in both cases is the processing of both the food waste and dairy manure for one day of operation of the Heartland AD facility near LaSalle, CO. This basis translated to 216 Mg (dry) of food waste and 62 Mg (dry) dairy manure converted in the AD process. The functional units we have chosen are mainly used in the analyses as a reference to compare the LCA results to the different alternatives. In Case 1 the functional unit is on the basis of 1 day of operation of the Heartland AD Bio-CH_4 facility to compare to the business-as-usual (BAU) composting of these wastes, and Case 2 is on the basis of 1 kg of Bio-CH_4 produced and used in place of BAU landfilling. All the calculations are based on the total feedstock input of 278 Mg (dry basis) / day which results in an output Bio-CH_4 of 99.15 Mg, which constitutes 35.66% of initial feedstock (food waste + manure).

System boundary

In Case 1, the framework for the analysis is designed to model the change to the environment when the pathways in the BAU composting system are changed to the Bio-CH_4 system. Both systems must provide the same societal benefit for production of compost, nutrients for agriculture, and energy from methane (or fossil natural gas). The system boundary for Case 1 BAU composting system is shown in Figure 1 and includes different pathways that are operating in the prior use of the food waste and manure. Pathway 1 is composting of food waste and manure. The composting process accounts for the emissions from transportation of feedstock (food waste, manure and wood chips), windrow process emissions (including decomposition), and compost land application emissions. The emissions from the composting process are calculated from prior studies [21,25,26] and are presented in the section-1 of the Supporting Information document. Pathway 2 includes manufacturing and use of synthetic fertilizers that will be replaced by nutrients in digestate that is produced in the AD system. This accounts for the emissions from manufacturing, transportation to fields and field application (calculation for synthetic fertilizer emissions from cradle-to-grave are considered from US average fertilizer mix attested to in section-1 of Supporting Information document). Pathway 3 in the BAU case is the fossil natural gas that is replaced by the Bio-CH_4 produced in the AD system, and therefore fossil natural gas is modeled. Accounted for were all the emissions from cradle-to-grave of fossil natural gas (extraction, process, transport, and combustion).

The Case 1 Bio-CH_4 system shown in Figure 2 also includes multiple pathways and processes. The first is AD of food waste and manure including the whole lifecycle of the AD Bio-CH_4 pathway starting from the transportation of food waste and manure until the end use of Bio-CH_4 product, byproduct compost and digestate (input data provided by Ag Energy). Secondly, compost pathway produces more compost from food waste than the AD Bio-CH_4 pathway, therefore to provide the same societal benefit, the remaining compost is made up by equivalent amounts of peat imported from Canada. The peat pathway considers all emissions from cradle-to-grave. The data regarding the infrastructure for storage of food waste and manure, for biogas production and purification are not included in the study because their impacts are assumed negligible for facilities that last decades when compared to the material and energy inputs to the processes during the life of the AD facility.

Figure 1: System boundaries for the Case 1 Business-as-Usual (BAU) system

Figure 2: System boundaries for the Case 1 Bio-CH_4 system

In Case 2, a modeling approach equivalent to that in Case 1 has been taken. However, LCA results can be obtained by taking the difference between two systems (BAU landfill system and Bio-CH_4

system) and combining into a single Bio-CH_4 system by considering the credit for emissions from avoided BAU landfill systems. This approach is a consequential LCA because, in addition to modeling the direct AD Bio-CH_4 pathway, avoided emissions are also modeled for all co-products that displace others in the market as well as avoided pathways in the BAU of landfilling and manure management. Three scenario analyses are studied in case 2 illustrated in Figures 3 & 4. The system boundary for case 2, scenario-1 (Bio-CH_4 system with avoiding uncontrolled landfilling) has multiple pathways in its life cycle: 1. AD Bio-CH_4 pathway, 2. avoiding uncontrolled landfilling, 3. avoiding manure management, 4. avoiding synthetic fertilizers and 5. avoiding peat production and use. Avoided uncontrolled landfill pathway includes the emissions from the transportation of food waste from Denver to the landfill and emissions during the landfill process (see Supporting Information section 3, Tables 53, 56-58 for details). Bio-CH_4 system uses manure for production of Bio-CH_4, so an emissions credit is taken assuming an equal amount of manure is managed by anaerobic lagoons. The emissions from manure management are calculated from Silver et al 2015 [7]. The compost produced in the AD Bio-CH_4 pathway is assumed to be met by an equivalent amount of Canadian peat in the BAU system so the emissions from the peat pathway are considered as credit to the Bio-CH_4 system. Digestate produced in the Bio-CH_4 system is assumed to displace the manufacture and application of synthetic fertilizers, so the emissions from synthetic fertilizers are accounted for as a credit to the Bio-CH_4 system and the emission factors for fertilizer land application as well as compost land application are taken from EPA's Waste Reduction Model (WARM) [27].

Figure 3: System boundaries for the Case 2 Bio-CH_4 scenario avoided BAU with different landfill systems

Figure 4: Case 2 Bio-CH_4 avoided BAU with different landfill scenarios pathways

Case 2, Scenario-2 Bio-CH_4 system with avoided landfill gas collection and flaring includes multiple pathways, which are the same as Scenario 1 except for the avoided pathway of landfilling with gas collection system and flaring (see Supporting Information section 3, Tables 54, 56-58 for details). Case 2, scenario-3 Bio-CH_4 system with avoided landfill gas collection and electricity generation also includes multiple pathways like scenario-2, except the avoided landfill electricity is made up by the electricity generated with natural gas (see Supporting Information section 3, Tables 55,56-58 for details).

Allocation

Case 1 is a consequential system, and therefore no allocation is needed. For Case 2, allocation is avoided by expanding the system boundary to include environmental savings from displacing production of materials in the market by co-products from Bio-CH_4 production (fertilizers and peat) and by avoiding the food waste landfilling and manure anaerobic lagoon storage for the waste management. Peat is selected as an alternative for compost in the Bio-CH_4 life cycle in both cases. Both compost and peat have different characteristics (Compost consists of humic carbon and peat does not) but can be compared on a 1:1 volume basis [25]. AD digestate fertilizers replace synthetic fertilizers in the analysis.

Inventory Analysis

All the inputs to the different pathways in Cases 1 and 2 are listed in Tables 1-11 below (the reader is referred to section-3 in SI document for more information about specific eco-profiles used). Different eco-profiles are used to calculate the impacts of each process input in the pathways (section-1 in SI document). Emissions in CO_2 equivalents for peat manufacturing, packaging, transport and market for both scenarios are from a Canadian peatmoss study [28] listed in Table 12.

Impact Assessment

The main impacts analyzed in this study are: 1) global warming and 2) fossil energy use. Energy use impacts are quantified using the Cumulative Energy Demand method in SimaPro version 8.0.3.14, which accounts for all the process energy conversion efficiencies and other energy uses from cradle-to-grave. The global warming impacts are calculated by the IPCC 2013 GWP 100, a method in SimaPro with global warming potentials (GWP) of CO_2: 1, N_2O: 265, $CH_{4,fossil}$: 28 and $CH_{4,biogenic}$: 25.25. GWP values for all other greenhouse gases included in the developed inventory, such as refrigerants and some solvents, are also included in this method.

Results and Discussion

Case 1 BAU composting versus Bio-CH_4

The GHG emissions from Case 1 are shown in Tables 13 and 14. The BAU composting system has total net emissions of $9.7x10^5$ kg CO_2 eq. /day for 216 tons/day of dry food waste feedstock and 62 tons/day dry dairy manure. Main emission sources include, in decreasing order, composting process emissions, natural gas production and emissions, and field emissions for compost application. The Bio-CH_4 system emissions shown in Table 14 total $8.2x10^5$ kg CO_2 eq./day for the same input rate of dry food waste and dairy manure and is mainly caused by Bio-CH_4 combustion, AD process-CO_2 separation, and peat manufacture-use. From this work, the Bio-CH_4 system exhibits 15.5% lower emissions than the BAU composting system.

For fossil energy use in case 1, the Bio-CH_4 system is calculated based on the input energy supply by electricity and natural gas for the AD process, transportation, peat process, and output energy production from Bio-CH_4 system with the help of SimaPro Cumulative Energy Demand method. Fossil energy use for Bio-CH_4 system is calculated to be $2.93x10^6$ MJ/day, where as in the BAU composting system energy use was calculated to be $6.3x10^6$ MJ/day, which includes the energy usage for process operations in natural gas, composting, and fertilizer pathways. When comparing the Bio-CH_4 system with the BAU composting system, the Bio-CH_4 system has 53.4% savings as shown in the Figure 5.

Figure 5: Fossil energy demand for BAU composting system and Bio-CH_4 system in units of MJ/day

Case 2 Scenario steady state analyses

The GHG emissions from individual pathways in scenario-1, scenario-2 and scenario-3 are shown in Figure 6. All emission calculations for CO_2 and CH_4 emissions in the three scenarios are reported in the Supporting Information document section 2. In the steady-state scenario-1, the Bio-CH_4 system with the avoided BAU uncontrolled landfill system has –17.76 kg CO_2 eq. / kg of Bio-CH_4. Scenario-2 with avoided BAU landfill with gas collection system and flaring has -5.49 kg CO_2 eq. / kg of Bio-CH_4 production. Scenario-3 with avoided BAU landfill with gas collection and electricity generation has -3.51 kg CO_2 eq. / kg of Bio-CH_4 production. The main advantage of the AD process for production of Bio-CH_4 is the avoiding of landfill and manure management emissions because the savings are much greater than the emissions from the AD Bio-CH_4 pathway. Emissions from the AD Bio-CH_4 pathway are 6.1 kg CO_2 eq. / kg Bio-CH_4, without considering the substantial avoided emissions, and by its own is higher than fossil natural gas (4.3 kg CO_2 eq. / kg Bio-CH_4 eq. of fossil natural gas). In all scenarios, savings of emissions are greatest for the avoided landfill pathway, followed by avoided manure management, then peat production, and finally avoided synthetic fertilizers.

Figure 6: Case 2, Bio-CH_4 emissions avoiding different BAU steady-state landfill scenarios

Case 2 transient analysis

When food waste is deposited in a landfill, emissions of CH_4 and CO_2 are not generated to full potential immediately, but instead the landfill AD processes require several decades to complete the biomass decomposition. In order to introduce a more accurate avoided landfill emissions calculation, a transient model for CH_4 and CO_2 generation and emissions from landfills was derived in section 2 of the SI document for both uncontrolled landfills and for landfills with gas collection and flaring systems. The equation representing the avoided landfill emission rate for both CH_4 and CO_2, respectively, are

$$= M/2(1 - e^{-kt}) * 16/12$$

$$= M/2(1 - e^{-kt}) * 44/12$$

, where *M* is the annual rate of food waste landfilled (metric tons carbon/yr.), which in our calculations is the same as the annual food waste C input rate to the AD Bio-CH_4 facility, *k* is a first order reaction rate constant for decomposition of food waste and production of Bio-CH_4 and CO_2 by the AD process (0.12 yr^{-1}), and *t* is time in years [26]. These avoided landfill emissions increase exponentially until steady-state is achieved after approximately 50 years (see section 2 of the SI for derivations).

Case 2 transient results are modeled for three scenarios. In Scenario-1, the Bio-CH_4 system avoids the BAU landfill assuming uncontrolled emissions. In scenario-2, the Bio-CH_4 system substitutes for a BAU landfill emissions with gas collection system and flaring. In scenario-3, the Bio-CH_4 system substitutes for a BAU landfill emissions with gas collection and electricity generation. Figure 7 shows transient emissions from scenario-1, 2 and 3 over a 50-year time frame based on one kg of generated Bio-CH_4. The Bio-CH_4 emissions in scenario-1 drop sharply over the 50-year simulation. From our simulation, emissions from Bio-CH_4 are always lower than fossil natural gas over the entire simulation period from years 1 – 50 (except for scenario-1 at 1 year). The Bio-CH_4 system for scenario-1 has a savings of -17.76 kg eq. CO_2 emissions for a kg of Bio-CH_4 by the end of the 50-yr cycle.

Figure 7: Case 2, Bio-CH_4 emissions avoiding the BAU landfilling a) uncontrolled Scenario-1, b) gas collection system (GCS) & flaring Scenario-2, and c) landfill gas collection with electricity generation (LFGE) Scenario-3

In scenario-2 most of the methane emitted in the uncontrolled landfill scenario is captured (assumption of 75% collection efficiency and is flared) using a gas collection system and flared as CO_2 thereby avoiding the emission of high GWP CH_4. The simulated results of the transient scenario-2 are shown in the Figure 7. In scenario-2, GHG emissions of AD Bio-CH_4 pathway are always lower than fossil natural gas over the entire 50-year modeling time. After 50 years avoiding the emissions from BAU with landfill gas collection and flaring system, the Bio-CH_4 emits -5.49 kg CO_2 eq./kg Bio-CH_4, thus reducing global warming effect with each unit of production of Bio-CH_4. These favorable emissions are compared to that of fossil natural gas, 4.3 kg CO_2 eq. / 1.06 kg fossil natural gas, which contains mostly fossil methane [30], where the factor of 1.06 is the ratio of LHV of BioCH_4 (50 MJ/kg) to fossil natural gas (47.14 MJ/kg). This comparison shows the significant benefit of the AD Bio-CH_4 pathway with respect to fossil natural gas. Scenario-3 is also shown in Figure 7 and has an overall savings of -3.51 kg CO_2 eq. /kg Bio-CH_4 by the end of 50 years.

Fossil Energy Consumption for Case 2

The steady-state fossil energy consumption for the Bio-CH_4 system when avoiding the BAU landfill, either uncontrolled or gas collection and flaring, is calculated as $1.69\text{x}10^6$ MJ/99.15 tons of Bio-CH_4, or 17.06 MJ/kg Bio-CH_4. By comparison, fossil natural gas uses 59.0 MJ fossil energy /1.06 kg fossil natural gas. Fossil energy demand for the Bio-CH_4 system scenario-3 is calculated as 49.26 MJ/kg Bio-CH_4. Bio-CH_4 fossil energy consumption is 71.1 % lower than fossil natural gas in scenario-1 and scenario-2, and is 16.5 % lower in scenario-3. Figure 8 shows the contributions by different processes in the AD Bio-CH_4 toward the cumulative fossil energy consumption. The AD process is the largest contributor to fossil energy demand among all of the pathway stages in scenario-1 and scenario-2. The makeup of avoided landfill electricity generation using natural gas is the largest contributor to fossil energy demand in scenario-3.

Figure 8: Fossil energy demand for case 2, scenario-1, scenario-2, and scenario-3

By summarizing the discussed GHG emission results from our study, we show that AD of food waste and dairy manure in scenarios that avoid landfilling provides the best reductions in GHG emissions compared to composting of the wastes. A similar conclusion was made from the study by Yoshida et al. on AD of food waste and organics in MSW[23], which also showed the best GHG emission savings for avoided landfilling rather than composting.

Broader impacts of AD in the US

If implemented on a national scale in the US, a savings of 0.74% of the present annual natural gas energy demand can be realized from production of Bio-CH_4 through AD of all food waste and a significant fraction of total dairy manure. Our results show that per kg of Bio-CH_4 produced from food waste and dairy manure, net emissions after avoiding landfilling with gas collection and flaring and avoiding conventional dairy manure management saves 5.49 kg CO_2 eq. emissions, the uncontrolled landfilling scenario saves 17.76 kg CO_2 eq., and the gas collection and electricity generation landfilling scenario saves 3.51 kg CO_2 eq. These savings do not factor in the additional emissions savings when fossil natural gas is displaced, so net savings will be larger still. From data on landfilling there are 850 landfills with flaring and gas collection, 400 uncontrolled landfills, and 658 landfills with gas collection and electricity generation, which if avoided in the future through AD of food waste would provide a weighted average savings of 7.37 kg eq. CO_2 emissions per kg of Bio-CH_4 produced from food waste and manure blend.

Based on the ratios provided by AgEnergy, 19 million short tons of manure from dairy production in the US alone can provide sufficient blending for the total 36 million tons of food waste that is landfilled. By diverting the food waste and manure to anaerobic digestion, approximately 0.41% of overall GHG emissions of the approximately seven billion tons CO_2 eq. can be saved in the US annually using approximately 100 Heartland-scale AD facilities. It is important to point out other sustainability benefits of Bio-CH_4 production from food waste and dairy manure beyond conservation of fossil energy and reductions in GHG emission. These potential benefits include the recycling of mineral nutrients from food waste and manure to agricultural fields and associated reduction of environmental impacts of in synthetic fertilizer production and conserving natural resources. Although water is consumed in the AD process, digestate water is delivered to surrounding agricultural fields to offset some irrigation water usage. Large-scale deployment of AD of food waste / manure mixtures in the US would stimulate economic growth and create many engineering, facility operator, and spinoff jobs. More comprehensive sustainability analyses should be conducted to better understand the full set of potential benefits and costs (loss of jobs in landfilling and natural gas industries, possible odor issues) from large-scale production of Bio-CH_4 in the US.

Conclusions

This paper investigated lifecycle GHG emissions of Bio-CH_4 production from food waste and dairy manure. This study showed that the Bio-CH_4 system emits lower greenhouse gases and requires less net fossil energy during its whole lifecycle when compared to an equivalent amount of fossil natural gas. It also has lower emissions than other treatment processes in the US for these solid wastes, because the GHG emissions savings from avoiding the conventional management of manure and landfilling of food waste have a significant benefit on the overall GHG reduction potential of Bio-CH_4.

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Table 1: Inputs to AD Bio-CH_4 pathway (basis of 1 day): Case 1 and Case 2

AD pathway (Bio-CH_4)	Process		**Amount**	**Unit**
	1.Manure transportation from local farm to facility	Inbound trip	4.69×10^{3}	t*km
		Return trip	3.75×10^{3}	t*km
	2.Food waste transportation from Denver to facility	Inbound trip	5.76×10^{4}	t*km
		Return trip	4.61×10^{4}	t*km
	3.AD process	Electricity	132	MWh
		Natural gas	3.2×10^{8}	btu
	4. Bio-CH_4 Combustion emissions (Bio-CH_4 combustion)		99151.2	kg CH_4 combusted
	5. CO_2 Fugitive emissions from AD (CO_2 emissions from AD)		99151.2	kg CO_2 emitted
	6. Transportation of compost from AD to Denver market	Inbound trip	9.71×10^{3}	t*km
		Return trip	7.77×10^{3}	t*km
	7. AD digestate N field application (Liquid digestate N_2O emissions on field application)		2.34×10^{3}	kg of N
	8. AD compost field application (CO_2 emissions from AD compost soil application)		1.22×10^{5}	kg

Table 2: Inputs to compost pathway (basis of 1 day): Case 1 BAU

Compost pathway (BAU)	Process		**Amount**	**Unit**
	1.Manure transportation from local farms to compost facility	Inbound trip	4.66 x10^3	t*km
		Return trip	3.73 x10^3	t*km
	2.Wood pallets transportation from nearby	Inbound trip	221.3	t*km
		Return trip	177	t*km
	3.Food waste transportation from Denver to compost	Inbound trip	8.11 x10^4	t*km
		Return trip	6.49 x10^4	t*km
	4.Diesel used in tractor for composting	Tractor	4.92 x10^3	Kg
		Turner	16.8	kg
		Grinder	594	kg
	5.Composting decomposition emissions (CO_2) (Composting Decomposition Emissions (CO_2))		322.94	tons dry compost
	6.Composting decomposition emissions (CH_4&N_2O) (Composting Decomposition Emissions (CH_4 and N_2O))		1.18 x10^3	tons (wet) compost
	7.Compost land application (at 50% moisture) (CO_2 Emissions from Compost Land Application)		395.3	tons wet compost
	8. Compost (wet) transportation from compost facility to Denver market	Inbound trip	44550.31	t*km
		Return trip	35640.24	t*km

Table 3: Inputs to natural gas pathway: Case 1 BAU

Natural gas pathway (BAU)	**Process**	**Amount**	**Unit**
	1.Emissions from natural gas transport, extraction processing, distribution and usage	3.97×10^6	MJ of heat

Table 4: Inputs to synthetic fertilizer pathway: Case 1 BAU

Synthetic fertilizer pathway (BAU)	**Process**		**Amount**	**Unit**
	1.Emissions from synthetic fertilizers manufacturing process and market	Nitrogen	$2.34\text{x}10^{3}$	kg
		Phosphate	$0.75\text{x}10^{3}$	kg
		Potassium	$2.91\text{x}10^{3}$	kg
	2. Synthetic fertilizer transport from Denver market to farm Inbound trip Return trip		44.9	t*km
			35.9	t*km
	3. Fertilizer N field application (Emissions of N2O from synthetic N fertilizer applied to Field)		$2.34\text{x}10^{3}$	kg of N

Table 5: Inputs to peat pathway: Case 1 Bio-CH$_4$

Peat pathway (Bio-CH$_4$)	**Process**		**Amount**	**Unit**
	1.Emissions from peat moss manufacturing, transport and use (Peat moss Manufacturing, Transport and Use (CO$_2$ Emissions))		546	m^3 make up peat
	2. Transportation of Peat moss from Canada(Saskatchewan) to Denver	Inbound trip	1.42 x10^5	t*km
		Return trip	1.14 x10^5	t*km

Table 6: Inputs to avoided landfill without gas collection pathway: Case 2 Scenario-1

Avoided landfill pathway uncontrolled emissions	**Process**		**Amount**	**Unit**
	1.Transportation of food waste from Denver to landfill	Inbound trip	8.42 x10^3	t*km
		Return trip	6.74 x10^3	t*km
	2. Emissions from landfill without gas collection CH_4 and CO_2 (Steady state) Uncontrolled		216.6	tons (dry) food waste input to landfill

Table 7: Inputs to avoided landfill with gas collection and flaring: Case 2 Scenario-2

Avoided landfill pathway with gas collection and flaring	**Process**		**Amount**	**Unit**
	1.Transportation of food waste from Denver to landfill	Inbound trip	8.42 $x10^3$	t*km
		Return trip	6.74 $x10^3$	t*km
	2. Emissions from landfill with gas collection and flare CH_4 and CO_2 (Steady state) (Landfill Emissions GCS steady state)		216.6	tons (dry) food waste input to landfill

Table 8: Inputs to avoided landfill with gas collection & electricity pathway: Case 2 Scenario-3

Avoided landfill pathway with gas collection and electricity generation	**Process**		**Amount**	**Unit**
	1.Transportation of food waste from Denver to landfill	Inbound trip	8.42 x10^3	t*km
		Return trip	6.74 x10^3	t*km
	2. Emissions from LFGE (landfill with gas collection and electricity generation) CH_4 and CO_2 (steady state)		216.6	tons (dry) food waste input to landfill
	3. Electricity generation from Natural gas		287	MWh

Table 9: Inputs to avoided synthetic fertilizer pathway: Case 2

Avoided Synthetic fertilizer pathway	**Process**		**Amount**	**Unit**
	1.Emissions from synthetic fertilizers manufacturing process and market	Nitrogen	$2.34x10^3$	kg
		Phosphate	$0.75x10^3$	kg
		Potassium	$2.91x10^3$	kg
	2. Transportation of synthetic fertilizers from LaSalle market to fields	Onward trip	44.9	t*km
		Return trip	35.9	t*km
	3. Fertilizer N field application (Emissions of N_2O from synthetic N fertilizer applied to Field)		$2.34x10^3$	kg of N

Table 10: Inputs to avoided peat moss pathway: Case 2

Avoided peat pathway	**Process**		**Amount**	**Unit**
	1.Emissions from peat moss manufacturing, transport and use (Solid digestate compost from AD) (Peat moss Manufacturing, Transport and Use (CO_2 Emissions))		245	m^3
	2. Transportation of Peat moss from Canada(Saskatchewan) to Denver	Inbound trip	6.4×10^4	t*km
		Return trip	5.12×10^4	t*km

Table 11: Inputs to avoided manure pathway: Case 2

	Process	**Amount**	**Unit**
Avoided manure pathway	1.Anaerobic lagoon emissions	40.49	tons (dry basis)
	2. Slurry storage tanks	6.23	tons (dry basis)
	3. Solid manure piles	15.58	tons (dry basis)

Table 12: GHG emissions for peat manufacturing, packaging transport and use

Category	Unit	Harvest	Package	Transport	Soil application	In situ decomposition	Total
GHG Emissions	Kg CO_2 equivalent	4.03	2.53	15.63	183	60.79	269.7

Table 13 Case 1: Business As Usual composting system (Basis of 1 day)

Process	**kg CO_2 eq.**	**% Contribution**
Composting Pathway		
1. Feedstock transport	29,592.63	3.06
2. Composting process equipment fuel use	20,796.49	2.14
3. Decomposition of feedstock in composting process	367,988.1	37.92
4.Transportation from compost facility to market	15,313.93	1.58
5. Land application of compost	173,939.4	17.93
Fossil Natural Gas Pathway		
6. Natural gas production and combustion	317,870.7	32.76
Synthetic Fertilizer Pathway		
7. Synthetic fertilizer production and market	18,904.28	1.95
8. Synthetic fertilizer transport from market to farm	13.92	0.0014
9. Synthetic N fertilizer soil application	25,786.51	2.66
Total	**970,206**	**100**

Table 14: Case 1: Bio-CH_4 system (Basis of 1 day)

Process	**kg CO_2 eq.**	**% Contribution**
AD Bio-CH_4 Pathway		
1. Manure transportation from dairy farm to AD	1,453.99	0.17
2. Food waste transport from Denver to AD facility	17,856.1	2.17
3. Anaerobic digestion Process	134,499.6	16.39
4. CO_2 separation from AD biogas and venting	121,956	14.86
5. Biogas CH_4 combustion	272,665.8	33.23
6. AD digestate soil application	25,786.5	3.14
7. AD compost transport to Denver	3,010.29	0.36
8. AD compost applied to land	53,824.3	6.56
Peat Pathway		
9. Peat manufacturing, transport, use	145,217.1	17.69
10. Peat transport from Saskatchewan to Denver	44,278.6	5.39
Total	**820,548.3**	**100**

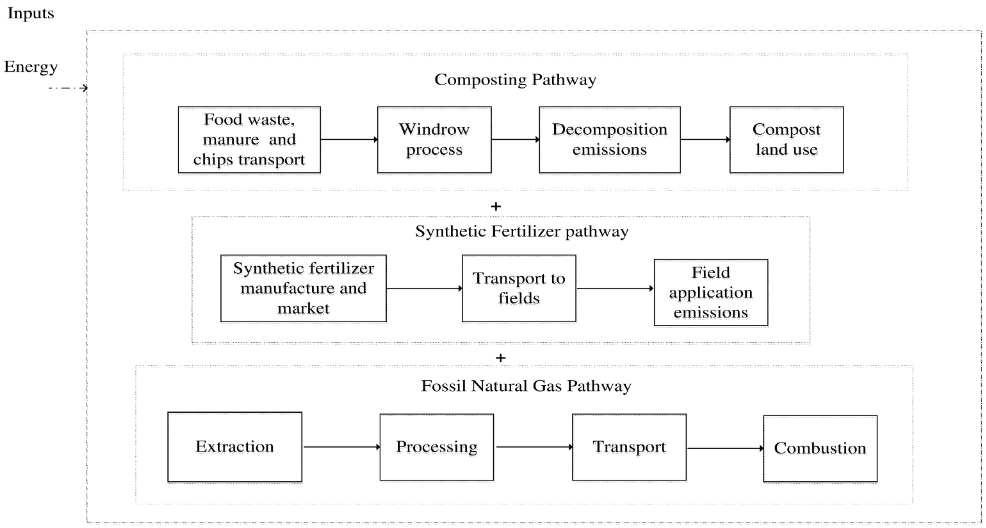

Figure 1: System boundaries for the Case 1 Business-as-Usual (BAU) system

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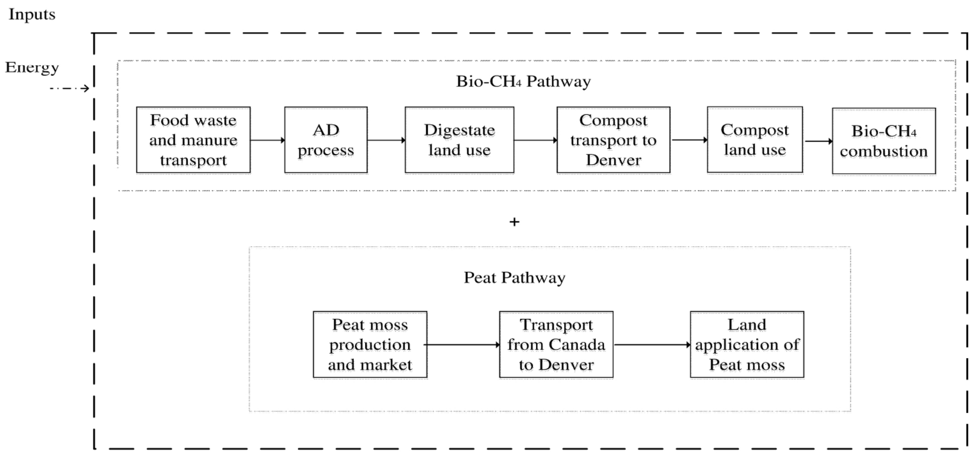

Figure 2: System boundaries for the Case 1 Bio-CH4 system

111x57mm (600 x 600 DPI)

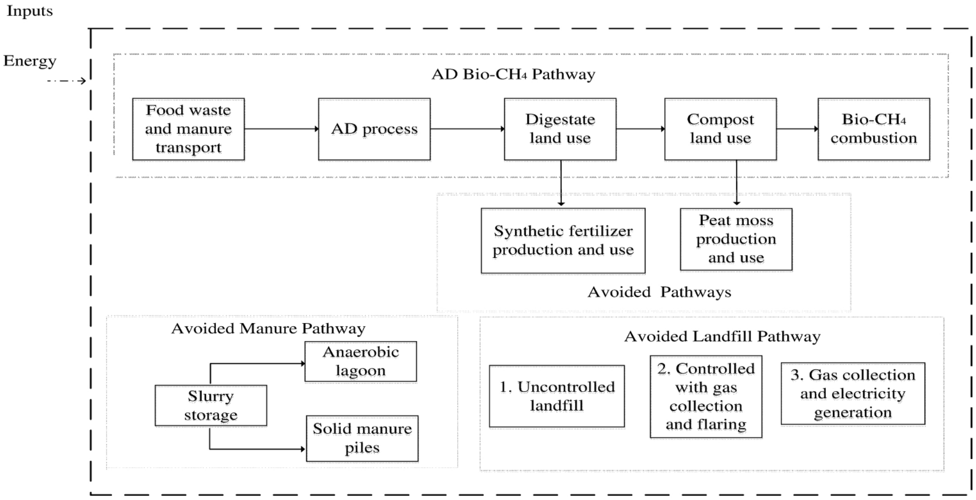

Figure 3: System boundaries for the Case 2 Bio-CH4 scenario avoided BAU with different landfill systems

112x59mm (600 x 600 DPI)

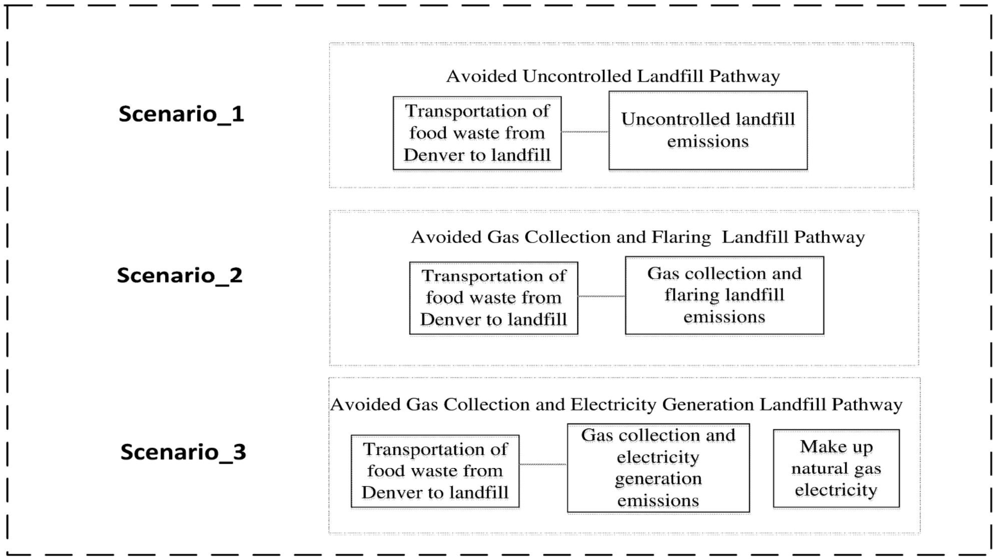

Figure 4: Case 2 Bio-CH4 avoided BAU with different landfill scenarios pathways

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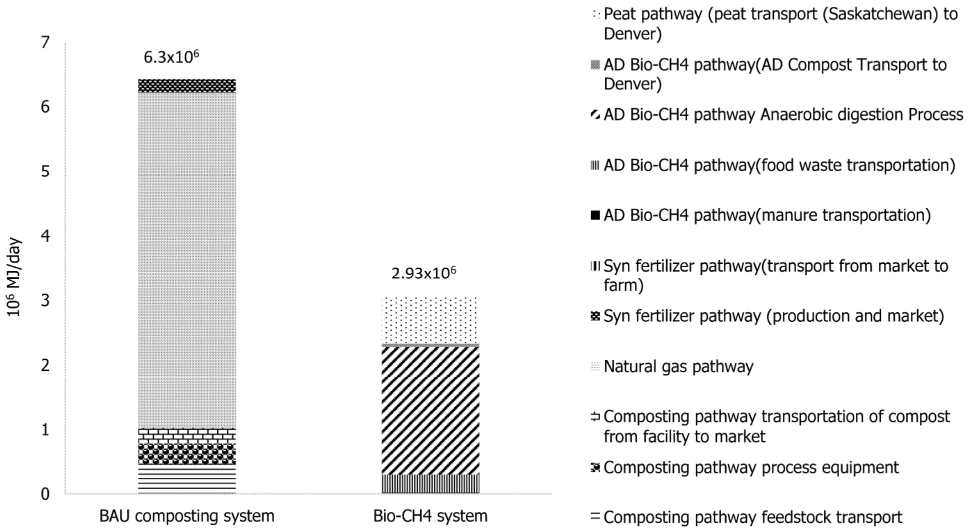

Figure 5: Fossil energy demand for BAU composting system and Bio-CH4 system in units of MJ/day

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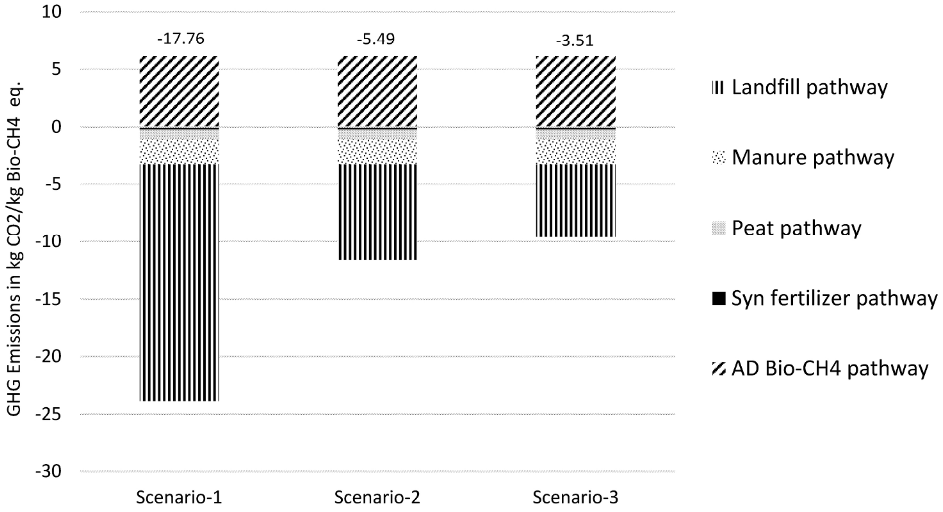

Figure 6: Case 2, Bio-CH4 emissions avoiding different BAU steady-state landfill scenarios

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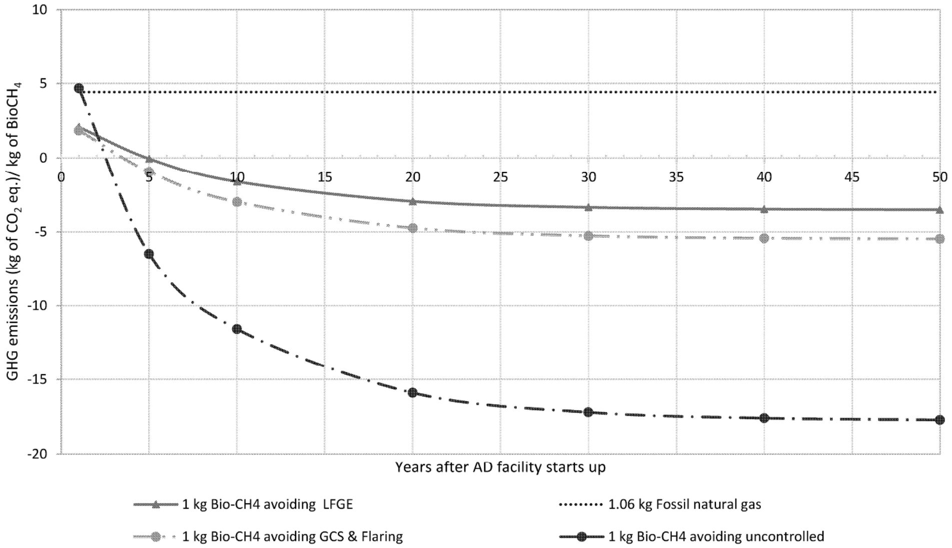

Figure 7: Case 2, Bio-CH4 emissions avoiding the BAU landfilling a) uncontrolled Scenario-1, b) gas collection system (GCS) & flaring Scenario-2, and c) landfill gas collection with electricity generation (LFGE) Scenario-3

121x70mm (600 x 600 DPI)

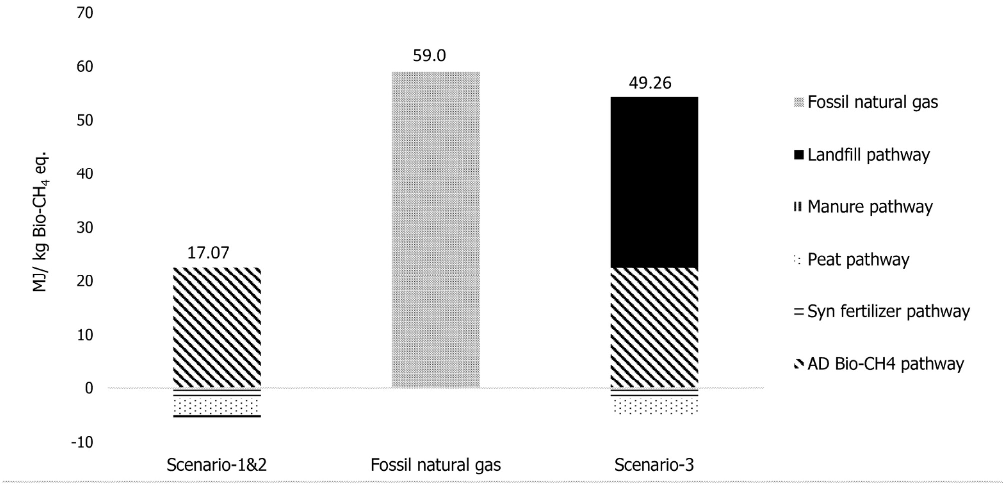

Figure 8: Fossil energy demand for case 2, scenario-1, scenario-2, and scenario-3

108x57mm (600 x 600 DPI)