Biogas Beyond Boundaries: Novel Algebraic Equations for Life Cycle Global Warming Potential of Anaerobic Digestion Systems

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Abstract

Amidst rising interest in biogas as a sustainable alternative to traditional energy vectors like natural gas, this study focuses on its role in achieving net-zero targets—where carbon emissions are balanced with sequestration. Biogas, derived from carbon-neutral organic waste, offers significant greenhouse gas (GHG) emission reductions. Life cycle assessments (LCA) are crucial for evaluating the global warming potential (GWP) of biogas, ensuring its effectiveness in offsetting fossil fuel equivalents. Due to renewed interest in anaerobic digestion in offsetting carbon, new robust easily calculable algebraic equations are proposed. Our study introduces two complementary sets of equations, grounded in published literature and LCA databases. Despite their differing structures due to distinctive specific activities across life cycles, both sets yield closely aligned estimations, reinforcing confidence in these models. The GWP is sensitive to the feedstock type, electricity and heat consumption, and fugitive emissions. The statistical distributions show the mean GWP of 0.54 per m^3 biogas, 0.09 per kWh biomethane and 0.73 per kWh electricity production rates of cradle-to-grave systems with all plausible technologies available in the database. The lowest GWP meets the UK's 50 g CO_2e per kWh biomethane target by 2030 for gas grid injection. The GWP in g CO_2e per kg AD feedstock is 93-104 (manure), 16-26 (sludge), and 273 (grass silage), etc. The biowaste AD system reduces at 0.5-0.7 kg CO_2e per kWh of electricity generated, requiring 1.5 MWh of minimum threshold electricity generation to reduce 1 tonne of CO_2e.

1.0 Introduction

Biogas or anaerobic digestion (AD) systems can mitigate global warming potential (GWP), but carbon trading is complex. Successful carbon offsetting requires AD systems to adhere to key carbon crediting or offsetting programs, such as Verra's Verified Carbon Standard (VCS), Gold Standard (GS), Climate Action Reserve (CAR) and American Carbon Registry (ACR) by standardizing life cycle GWP reporting. For example, there are 147 ongoing VCS carbon offsetting projects with biogas estimated to reduce 16.93 Mt (million tonnes) CO_2e [1]. There are 322 ongoing GS carbon offsetting projects with biogas estimated to reduce 22.88 Mt

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(million tonnes) CO_2e [2]. This study focuses on creating algebraic equations for calculating the GWP of biogas, crucial for carbon crediting or offsetting programs and net-zero goals, which balance carbon emissions and sequestration. Biogas, derived from carbon-neutral organic waste and used as a substitute for natural gas, contributes to reducing greenhouse gas (GHG) emissions. With increases in carbon markets and the value of selling carbon offsets, it is important to predict GWP savings from replacing fossil fuels, and a comprehensive life cycle assessment (LCA) is thus necessary. The study develops two novel methods for GWP calculation based on published literature and the Ecoinvent life cycle inventory (LCI) database. These methods, which differ in how they group life cycle activities, are compared to assess their predictive accuracy. The methods conduct a rigorous and significant modular synthesis approach, assigning a distinct GWP to the life cycle stages or activities in the system. This study's models are thus essential for an effective and thorough life cycle GWP assessment in AD systems.

Sustainable development, encompassing economic, environmental and societal dimensions, is often defined as the capacity of society to fulfil present needs while safeguarding those of the future [3]. The challenge to mitigate greenhouse gas (GHG) emissions, explore alternative energy sources, and reduce reliance on fossil fuels has become a global issue. Despite continuous technological advancements that make production processes more sustainable, achieving a sustainable energy framework and minimising GHG emissions remains a worldwide challenge [4,5]. Simultaneously, substantial quantities of organic waste are generated from various sources such as industries, households, institutions and agriculture [6]. Organic waste, within a broad context, refers to those originating from living microorganisms or biological sources (e.g., food residues, sewage sludge and manure), predominantly consisting of organic substances [7]. This type of waste can be decomposed under anaerobic conditions to produce biogas.

AD is a well-established technology to produce biogas composed of 50–70% methane, making it a renewable energy which can generate both heat and power if utilized through a combined heat and power (CHP) plant [8]. Due to the diverse range of feedstocks, extensive operation in a commercial environment and the production of carbon-neutral biofuel, AD has been extensively studied [9]. Investigating new raw materials, optimizing the process and improving gas upgrading technologies for the injection of the final product into the natural gas grid have been the research targets in recent years [10,11]. The vast majority of biodegradable organic materials can be utilized as feedstock for AD; however, the extent of their decomposition depends on their physiochemical characteristics. The biogas produced from the AD of organic matter is widely used either directly for cooking or electricity generation and heat recovery by CHP facilities or upgraded into biomethane for injection into the natural gas grid [10,12]. Diverse renewable resources, including non-agricultural materials such as food industry by-products, excess produce from wholesale markets, animal waste, food waste, non-woody garden clippings and organic waste from municipal disposal serve as viable feedstocks for biogas production [13]. Moreover, energy crops like beet, sugarcane, maize and potato plants cultivated with the specific intention of fuel production, constitute other potential feedstocks for AD. So far, various AD technologies, e.g. mesophilic or thermophilic, one-stage or two-stage, wet or dry digestion, have been adopted for biogas production.

Biogas has been found to have direct impacts and contributions to 12 out of the 17 sustainable development goals (SDGs) [14]. Biogas production by region and by feedstock type are shown in Figure 1. The development of biogas has been uneven across the world, as it depends not only on the availability of feedstocks, but also on policies that encourage its production and use. Europe, China, and the United States account for 90% of global production. A wide variety of feedstocks can be used to produce biogas. Crops and their residues, together with animal manure are the largest sources of feedstock, particularly where the agricultural sector plays a prominent role in the economy. With the worldwide concerns of the living environment, it is highly important to investigate and understand the environmental impacts of each technology and feedstock, for decision-makers to develop the future energy management plan. This understanding is crucial for decision-makers in formulating strategies for managing these organic materials using circular economy principles.

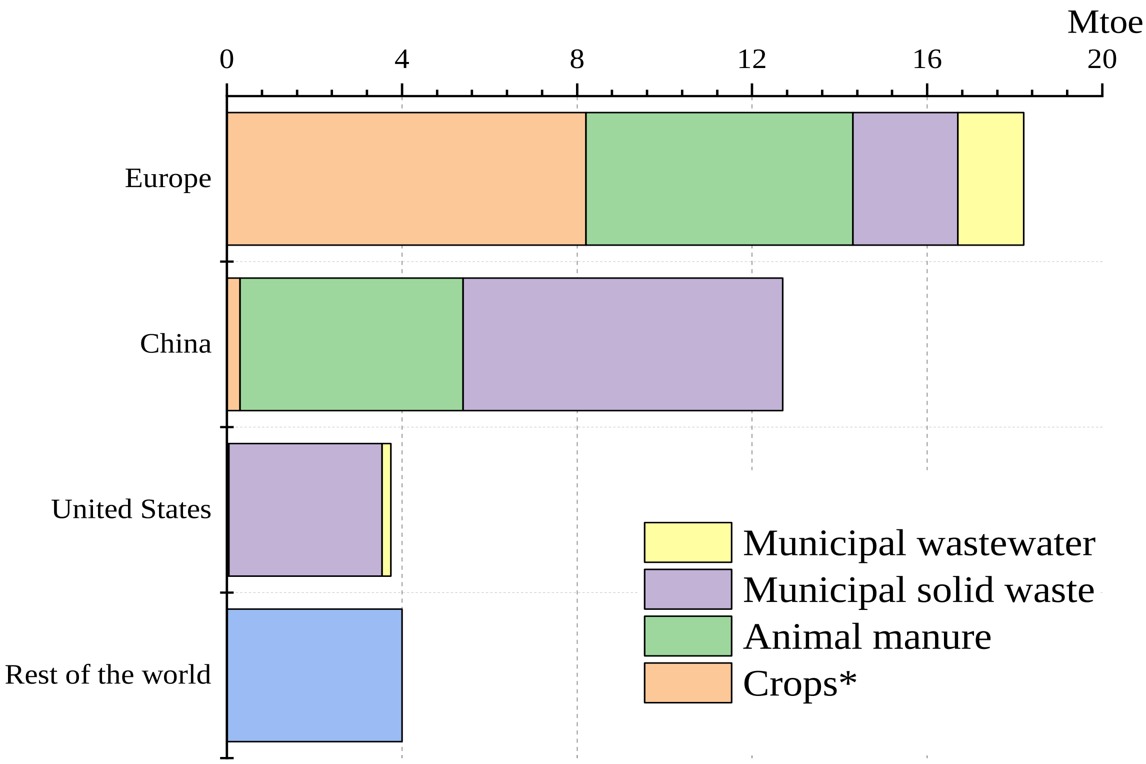

*Figure 1 Biogas production by region and by feedstock type by 2018. * Crops include energy crops, crop residues and sequential crops. Note: 1 Mtoe = 11.63 terawatt-hours (TWh) = 41.9 petajoules (PJ). Source: IEA [15].*

LCA, aligning with the International Organization for Standardization (ISO) 14040-44 guidelines, has been widely adopted by numerous scholars as a standardized and scientifically rigorous methodology for appraising the environmental impacts of a process or product throughout its entire life cycle. As per ISO 14040–14044 [16], LCA is defined as the "compilation and evaluation of the inputs, outputs and potential environmental impacts of a product system over its entire life cycle" [17]. This assessment technique proves to be an effective instrument for understanding and resolving environmental issues stemming from biogas production utilizing a diverse range of feedstocks [18].

Many researchers have conducted LCA for biogas production [19]. Table 1 provides an overview of various studies employing the LCA approach to investigate biogas production using different feedstocks in AD systems, with a focus on carbon footprint assessment. The purpose of analyzing these papers was to compare the factors and parameters addressed, and the results obtained in different productive scenarios, seeking patterns and trends in LCA of AD system and the conclusions of those works. As can be seen from the table, the goal and scope of LCA, where the boundaries of the study (temporal and geographical), functional unit, apportionment approaches and reference flow varied among different case studies. Different studies used different life cycle impact assessment (LCIA), where the flows defined in the inventory are converted into environmental impacts by multiplying the gross values by equivalence factors that refer to results in common units.

Thus far, these variations pose challenges in comparing results across different LCA studies, as they might be founded on distinct definitions. Herrmann and Moltesen [20] illustrated differences among various LCA software in certain instances. Most studies used LCA software and databases to calculate GWP values. Styles et al. [21] described a formula to calculate the carbon footprint and plant operating parameters in relation to 16 types of feedstocks. The paper also considered the implications of indirect land use change (ILUC) resulting from the cultivation of crops intended for biogas production. However, the paper did not compare its results with established databases, such as Ecoinvent, so there is a lack of comparability.

Optimization methodologies play a crucial role in addressing challenges related to the transition to clean and affordable energy systems, encompassing issues like geographic limitations for resources and technologies, along with the growing demands for energy and materials [22]. LCA models remain pivotal for conducting in-depth analyses of the performance and environmental impacts of technological alternatives. The integration of these two models can prove immensely valuable to decision-makers in formulating long-term or real-time production and operational plans. For instance, incorporating a carbon footprint calculation formula into the optimization model for biogas production control ensures not only the maximization of biogas production and cost-efficiency, but also the minimization of carbon emissions. Additionally, when decision-makers are faced with different types of feedstocks for digestion, the combination of these models aids in devising next year's purchasing or digestion plan. This holistic approach enables finding a balance between profit and sustainable development.

Furthermore, there are strong policy drivers which need robust formulations for GWP calculations. In the light of recent policy changes, a new Green Gas Support Scheme (GGSS) has been delivered to support biomethane produced using AD in the UK, with a focus on biomethane productivity and purity [23]. Biomethane is produced by upgrading biogas, i.e., primarily through the removal of CO_2 (along with other impurities) and this is done using carbon capture technologies, discussed later.

Hence, it is crucial to develop a universally robust LCA model to conduct structured and reliable evaluations of LCA, ensuring the results remain comparable with those from LCI databases. Thus, our approach results in two sets of algebraic equations, one based on published literature and the other based on the Ecoinvent LCI database. The predictions between the two models are compared, so that the former set of algebraic equations based on published literature can be easily applied in other studies to calculate the GWP of biogas in various contexts. Our approach emphasizes ease of updating and can be used in long-term or short-term scheduling and control optimization models, achieving the same quality of results as the LCI database. In this study, we pursued several objectives: (i) a comprehensive analysis of LCA results for various feedstocks used in AD systems worldwide; (ii) an exploration of the impact of different AD system variabilities on LCA through sensitivity analysis; (iii) the development of LCA-based algebraic formulae to evaluate the environmental footprint of cradle-to-grave (literature-based) and cradle-to-gate (both literature-based and Ecoinvent LCI-based) AD systems across different scenarios, feedstocks, geographic locations, etc.; and (iv) a comparison between the two approaches. It can be noted that Ecoinvent LCI data for cradle-to-grave AD systems are aggregated and indivisible by life cycle stage or activity. Consequently, Ecoinvent LCI-based formulae are limited to cradle-to-gate up to biomethane production systems. In contrast, literature-based formulae cover holistic cradle-to-grave systems with contributions of individual life cycle stages or activities. Furthermore, comparisons of the literature-based model with the SimaPro 9.4.0.3v combined with Ecoinvent-based predictions are conducted to reveal closely aligned results, affirming their robustness.

The paper is structured as follows. Relevant literature data are assimilated, and the published literature-based algebraic equations are developed to calculate the GWP. The second set of equations are developed to calculate the GWP based on the Ecoinvent LCI data. The results of both the models including sensitivity analyses are discussed. Furthermore, statistical analyses of all relevant LCA databases are presented to give confidence in the model. The two models' predictions are then compared, assessed, and discussed, before the conclusions.

Table 1 Summary of the basic description of AD system setup in the LCA studies under review in recent years, along with an analysis of the findings from these respective AD LCA studies.

Paper	Location	Feedstock	Phases of AD processes	Functional unit	LCA software LCA method	CHP plant size	Mono-digestion / Co-digestion
Ampese et al. (2023) [24]	Brazil	Apple pomace	Cultivation, transportation, AD operation, energy generation[1], digestate treatment	1 kg feedstock	Open LCA CML-IA	N.A.	Mono-digestion
Zhao et al. (2023) [25]	China	Food waste from canteen at university	Transportation, AD operation, CHP operation, digestate treatment	1 t feedstock	SimaPro Recipe 2016	Large-scale (>500kW)	Mono-digestion
Sarrion et al. (2023) [26]	Spain	Food waste from food distribution platform	Feedstock pre-treatment, transportation, AD operation, biogas upgrading, energy generation, digestate treatment, wastewater treatment	1 kg wet feedstock	SimaPro 9 Environmental Footprint 3	N.A.	Mono-digestion
Hossain et al. (2023)	Bangladesh	Manure and food waste from a fruit	AD operation, digestate treatment	1 MJ of biogas energy	OpenLCA CML 2002 baseline	N.A.	Mono-digestion and co-digestion

[1] Energy generation: generally, refers to processes that use biogas to generate energy other than CHP, along with specific energy production technologies not explicitly discussed in the literature.

[27]		and vegetable market					
Azolim et al. (2023) [28]	Brazil	Manure	AD plant construction, AD operation, manure storage	10.0 m^3 of liquid swine manure	SimaPro ReCiPe midpoint	N.A.	Mono-digestion
Demichelis et al. (2022) [29]	Italy	Waste activated sludge, cow agricultural sludge	Transportation, AD operation, CHP operation	1 t of wet feedstock	SimaPro 9.0 ReCiPe midpoint	Large-scale (>500kW)	Mono-digestion and co-digestion
Tan et al. (2022) [30]	Malaysia	Manure, dry maize silage, waste dairy	Transportation, AD operation, CHP operation, digestate treatment	1 MWh of electricity	OpenLCA CML2001 IA	Large-scale(>500kW)	Mono-digestion and co-digestion
Freitas et al. (2022) [31]	Brazil	Pig manure and silage	Cultivation, transportation, AD operation, energy generation, digestate treatment	1 t of feedstock	SimaPro 8.0 CML2 baseline 2000	Large-scale (>500kW)	Mono-digestion and co-digestion
Lee et al. (2020) [32]	US	Food waste, yard waste, biosolid	AD construction, feedstock production, transportation, AD operation, CHP operation, digestate treatment	1 t of wet waste	SimaPro TRACI 2.1	1,000 kW	Co-digestion
Ascher et al.	UK	Household solid waste	Transportation, AD operation, energy	1 t of feedstock	GaBi ReCiPe 1.08	Large-scale	Mono-digestion

(2020) [33]			generation, digestate treatment		Midpoint	(>500kW)	
Mehta et al. (2022) [34]	Northern Ireland	Manure and dry silage	AD operation, energy generation, digestate treatment	1 MJ of energy	SimaPro v9 N.A.	N.A.	Mono-digestion and co-digestion
Slorach et al. (2019) [35]	UK	Household food waste	AD construction, CHP construction, transportation, AD operation, CHP operation, digestate treatment	1 t of household food waste	GaBi V8 ReCiPe Midpoint	1,000 kW	Mono-digestion
Pérez-Camacho et al. (2018) [36]	UK	Food waste, dry grass silage and cattle manure	Cultivation, transportation, AD operation, CHP operation, biogas upgrading, digestate treatment	1 MWh of electricity supplied to the power grid	SimaPro 8.3 ReCiPe Midpoint	500 kW	Mono-digestion and co-digestion
Di Maria et al. (2018) [37]	UK	Maize, sorghum, triticale	Cultivation, transportation, AD operation, energy generation	1 kWh of net electrical energy	SimaPro 8.2 ILCD midpoint	N.A.	Co-digestion

[1] TVS: the total volatile solids in the reactor.

[2] vs: Volatile solids

2.0 Material and methods

2.1 Comparative literature analysis

In this section, some LCA dimensions are compared, including: the goal and scope, where the boundaries of the study are defined; the functional unit and LCI, which reflects data on mass and energy flows that enter and leave the various stages of the product life cycle.

Many of the papers analyzed omit some stages of the system due to an absence of data [38], or due to low contributions from the stages to the potential impacts produced. The differences of system boundaries are also reflected in the Table 1, with each study considering different "cradles", "graves" or "gates". Land use change, feedlot, AD plant construction and biogas upgrading are usually poorly analyzed phases within the biogas production life cycle in previous literature. Most studies started their system analysis from the transportation, followed by AD plant operation, digestate treatment, and use of the biogas for energy generation. Also, studies often miss growth phase of energy crops and fugitive emissions, etc.

The functional unit must be specific for the production system under assessment and can be defined according to either: (a) the mass of the raw material, expressed in kg or t, when the study aims to analyze or compare the performance of production systems, and (b) the volume of biomethane/biogas produced, when it is desired to know the quantity of raw material necessary to achieve a given production, like 1 kWh electricity.

Various raw materials, including manures and sewage sludge, can serve as substrates for biogas production either in combination (co-digestion) or individually (mono-digestion). In Table 1, the majority considered co-digestion. The right blend of substrates can effectively increase energy output and reduce external energy input, thereby reducing carbon emissions. Co-digestion is to maximize the biogas production to maximize the subsidies and income [28,[34]. In the present global scenario and given advancements in scientific understanding, the use of anaerobic co-digestion is increasing and this could be due to the avoidance of feedstock supply intermittency [39]. Moreover, in commercial AD facilities, co-digestion recipes are being employed partly to address feedstock availability issues. Thus, novel co-digestion equations are developed using Ecoinvent LCI database-based predictions presented in the latter section.

Some researchers have emphasized the minimal impact of transportation distances on the overall environmental footprint [40]. Certain LCA papers examining the AD of livestock manure may omit transportation considerations. In these instances, AD systems are typically on-site, rendering transportation negligible and thus excluded from the analysis. Transportation is usually done by diesel powered vehicles. Fuel consumption is modelled depending on the weight of the collected waste and the average distance travelled, considering both full and empty loads. However, when it comes to food waste, the scenario differs. This discrepancy arises due to the fact that food waste is typically gathered from individual households and businesses, whereas other feedstocks are usually sourced from more centralized locations [41].

The energy requirements for the operation may vary depending on the operating conditions of the plant, such as temperature, digester type and retention time. In the studies shown in Table 1, most do not emphasize their pre-processing technology or related energy usage. The energy demand of the plant is affected by variations in maceration, pumping and mixing requirements. Different pre- or post-treatment methods may reduce or increase GWP values. For example, Zhao et al. [25] examine integrated AD and hydrothermal carbonization in food waste treatment, which not only removes water from digestate with low parasitic energy usage, but also converts the digestate into hydrochar. The hydrochar has a positive impact because the carbon is stabilized and stored. Furthermore, in other studies, AD is assisted by hydrothermal treatment and nutrient recovery, with this framework seen as a promising circular economy concept for food waste valorization, while reducing the carbon footprint [26].

In most studies considered in Table 1 (9 out of 14), biogas is burned directly in on-site CHP units. CHP plants can generate electricity and heat from the combustion of the biogas or biomethane produced by AD [42]. Based on references, there are three categories in terms of electrical power generation (kWe): small, under 250 kWe; medium, between 250 kWe and 500 kWe [43], and large, over 500 kWe [44]. However, the parameters related to CHP in most papers include both electrical and thermal conversion rates. With emerging net-zero strategies, biomethane injection to the grid is increasingly favoured [23]. Some of the electricity and biomethane generated are used directly on site and the remainder is sold back to the mains distribution. However, AD sites have less year-round heat demand, and heat energy is more difficult to transport than electricity, so much of the heat energy is often wasted [45].

Digestate is a better fertilizer than crude manure, since more nutrients are available and the risk of soil contamination is lower, due to the reduction of pathogens by the high temperatures of the AD process [46]. Eleven out of the 14 studies in Table 1 expanded the study frontier to include the digestate use including as fertilizer or disposal to landfill.

In order to calculate the environmental impacts of the different categories, software or spreadsheets associated with the Ecoinvent database have been used, such as: SimaPro (9 articles), OpenLCA (3 article), and GaBi (2 articles), as reported in Table 1. There are many LCIA methods available for evaluation of different impact categories. In the different studies analyzed, CML, IPCC and ReCiPe methods were the most used (Table 1). All LCIA methods employ the common GWP characterisation method by the IPCC.

2.2 GWP model based on literature data

Given that the Ecoinvent database is proprietary, a GWP model accounting for activity-wise GWP based on published literature is invaluable in terms of open-sourcing, transparency, quick applicability, adaptability, and comparability. This study thus offers a fresh perspective on calculating the GWP performance of biogas, utilizing data from literature. The intended recipients of this study encompass governmental agencies, environmental engineers, the scientific community, and energy companies.

2.3 Goal and scope definition

The functional unit is defined as the generation of 1 m^3 biogas (assumed to be 55% biomethane) through AD. Many parameters are relevant to the UK context. A system boundary includes the processes analyzed for the algebraic formulations based on the literature data. The system boundaries of the different scenarios are shown in Figure 2 [47]. The boundary of the LCA includes feedstock acquisition, plant operation, transport, CHP operation, and usage of digestate [48] (Figure 2).

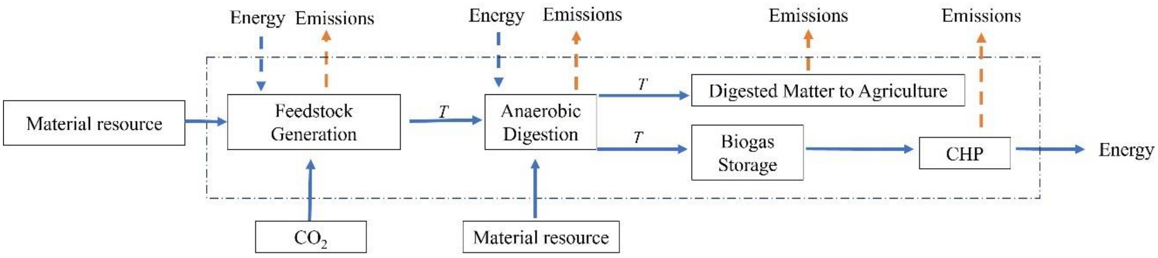

Figure 2 Interactions between AD system and the environment for LCA. T stands for transport.

2.4 GWP calculator

Developing a LCI and gathering data stand as a pivotal phase in any LCA investigation. Equation 1 follows the format for GWP measurements, regulations, and reporting of the EU directive, consisting of GWP from individual life cycle stages, i.e., resource acquisition or cultivation, transportation including feedstock and digestate, AD plant operation, CHP systems, and digestate application. Further, avoided GWP includes GWP from natural gas production (displaced by cradle-to-gate AD systems), or GWP from grid electricity and heat, and conventional fossil-based fertilizer (displaced by cradle-to-grave AD systems). The net GWP saving by AD systems is the difference between avoided GWP and GWP impacts. Commendably, this novel model provides the formulation in a format similar to the EU Directive of the European Parliament and of the Council by establishing a minimum threshold for greenhouse gas emissions savings [49].

Table 2 summarizes the GWP model developed from the literature in this study. It shows all the formulas applied to calculate activity data, and emissions in the cradle-to-grave system, including CHP operation, and usage of digestate, in relation to a functional unit of 1 Nm^3 biogas (usually, biogas at 60% biomethane content (more common with slurries and food waste) or at 55% biomethane content (more common with crops)). To allow the flexibility in the user-defined biogas composition, we have included 'Fraction of CH_4 in biogas' in the formulations. Similarly, the fugitive emissions including emissions from storage are made to be user-defined as a fraction of 'Fraction of CH_4 in biogas' in the formulations. The cradle-to-grave activities' GWP impacts are (economically) allocated to the biogas. In Table 2, we give novel calculation formulas for all activities within the cradle-to-grave system boundaries in Figure 2. In practical applications, this can be simplified according to specific system boundary considered.

$$GWP\ impact = (GWP_C + GWP_T + GWP_{AD} + GWP_{CHP} + GWP_{D\_T} + GWP_{D\_A})$$

$$Avoided\ GWP = GWP_N\ or\ (GWP_E + GWP_H + GWP_F)$$

$$Net\ GWP\ removal = Avoided\ GWP - GWP\ impact \qquad \text{(Equation 1)}$$

Table 2 Novel formulations developed based on published literature to predict GWP impact in $kg\ CO_2e/Nm^3$ biogas 'Cultivation' (C) or any other activities are shown as subscripts in the corresponding GWP formulations.

Activities	Formula and data to calculate primary emissions in relation to AD
Cultivation (C)	GWP_C = kg DM[1] feedstock for 1 Nm^3 biogas yield × Crop cultivation burdens (Table 3) × 1.1 (including crop loss)
Transportation (T)	GWP_T = t wet feedstock for 1 Nm^3 biogas yield × Distance for feedstock transportation (km) × Burden per tkm for trucks (Table 3)
AD plant operation (AD) AD system fugitive emissions (L) AD parasitic energy usage (P)	GWP_{AD} = GWP_L + GWP_P + N_2O emissions (kg/t wet feedstock) × t wet feedstock for 1 Nm^3 biogas yield × 273 [50] GWP_L = Fraction of CH_4 in biogas × Fraction of leakage × 0.67 kg/m^3 × 27 [50] GWP_P = $GWP_{electricity}$ (Table 3) × Onsite usage of electricity (kWh/t wet feedstock) × t wet feedstock for 1 Nm^3 biogas yield + GWP_{heat} (Table 3) × Onsite usage of heat (kWh/t wet feedstock) × t wet feedstock for 1 Nm^3 biogas yield
CHP systems (CHP)	GWP_{CHP} = Fraction of CH_4 in biogas × (1 – Fraction of leakage) × 1.15 kg/m^3 × GWP of Biogas combustion (Table 3)
Digestate transportation (D_T)	GWP_{D_T} = t wet digestate/t wet feedstock × t wet feedstock for 1 Nm^3 biogas yield × Distance for digestate transportation (km) × Burden per tkm for trucks (Table 3)
Digestate application (D_A) N_2O emission by digestate fertilizer application (D_N)	$GWP_{D\_A} = GWP_{D\_N}$ + Spreading energy usage (kWh/t wet feedstock) × t wet feedstock for 1 Nm^3 biogas yield × $GWP_{electricity}$ (Table 3) GWP_{D_N} = t wet feedstock for 1 Nm^3 biogas yield × total N kg/t wet feedstock × Fraction of total N emitted as N_2O-N from digestate application (Table 3) × 273 [50]
Avoided natural gas generation (N)	GWP_N = GWP_{N_T} (Table 3) × (1 - Fraction of leakage) × Fraction of CH_4 in biogas
Avoided grid electricity generation (E)	GWP_E = $GWP_{electricity}$ (Table 3) × CHP electrical efficiency × Net calorific value (kWh/ Nm^3 biogas)

Avoided heat generation (H)	GWP_H = GWP_{heat} (Table 3) × CHP heat efficiency × Net calorific value (kWh/ Nm^3 biogas)
Avoided fertilizer manufacture (F)	GWP_F = t wet feedstock for 1 Nm^3 biogas yield × Total of N, P, K kg/t wet feedstock × Burden of N, P, K fertilizer production (Table 3)

[1] DM: dry matter. The fraction of leakage is a user-defined fraction of the 'Fraction of CH_4 in biogas'.

Delivery vehicles conversion factors, $GWP_{electricity}$, GWP_{heat}, Fuel conversion factor are from UK Government GHG Conversion Factors Reports [51] and GWP_{N_T} is GWP on traditional natural gas production from Ecoinvent [52]. The 100-yr GWP factors for CH_4 and N_2O are 27 and 273 respectively based on IPCC AR6 [50]. Other parameters like parasitic energy usage, biogas yield and others vary among different cases, are collected from the literature. The model's equations are adaptable, and certain parameter values employed in the calculations are relevant to reports and studies of AD systems in the UK. Users have the flexibility to modify these parameters to attain results more reflective of their specific circumstances, depending on the geographical location of their system. GWP impacts per reference unit are shown in Table 3.

Table 3 GWP impacts of key inputs and activities.

Input/activity	Reference unit	GWP kg CO_2e
Crop cultivation burdens		
Grass silage [53,54]	kg DM	0.39-0.47
Maize silage [53,55]		0.19-0.28
Other silage [52,54]		0.31-0.47
Transportation		
lorry 16-32 metric ton [35,52]	t*km	0.10-0.26
CHP combustion		
Biogas combustion [51]	Nm^3	0.57
Avoided burdens		
Electricity generation [51]	kWh	0.21
Natural gas production [52]	Nm^3	0.36
Heat generation [51]	kWh	0.18
K fertiliser production [56,57]	Kg	0.78-0.96
P fertiliser production [56,57]		1.80-2.60
N fertiliser production [56,58]		6.6-8.90
Fraction	Fraction	0.8-4.7%

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2.5 GWP model based on Ecoinvent database

The

The framework of LCA includes the definition of a goal and the scope, the inventory analysis, impact assessment and interpretation of results. Figure 3 illustrates the Ecoinvent data structure for LCIA which includes all main process steps and contains resources used, as well as emissions to the air, water or surrounding land. Life cycle stages in the systems have been considered, including transport and infrastructure. It is known to the LCA community that transport and infrastructure have less than 3% GWP contribution of products [47]. While under certain circumstances, for example, when food wastes are imported from long distances to sites, or where high moisture content wastes (e.g. sewage sludge) are transported, this assumption may not hold [57].

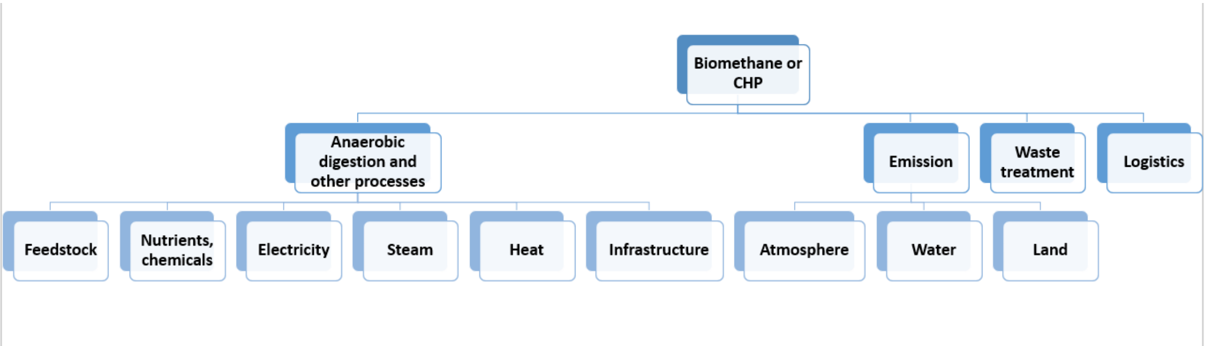


Figure 3 Ecoinvent data structure for LCIA.

LCI

For

Upon extraction of the relevant Ecoinvent 3.6 APOS datasets (the names can be found in Section 4.2), GWP impacts are calculated. The energy and raw material requirements for producing 1m^3 of biogas can be obtained from Ecoinvent LCI database, while the associated GWP for each element can be extracted from the LCIA. These analyses are merged through a novel simple equation, Equation 2, developed to calculate the GWP of the cradle-to-gate (biogas production) system. The main user input variables are the weight of feedstock and usages of electricity, heat, and steam in the entire cradle-to-gate (biogas production) system. Ecoinvent 3.6 APOS datasets provide two sets of geographic locations, Switzerland: CH and the rest of the world: ROW, five sets of feedstock types, manure, sludge, used vegetable cooking oil (UCO), biowaste, and grass silage. $a_{i,j}$, $u^{e}_{i,j}$, $u^{h}_{i,j}$ and $u^{s}_{i,j}$ are the correlation constant and coefficients for the usages of electricity (e), heat (h) and steam (s), respectively. The two sets i and j correspond to the feedstock type and location, respectively.

Table 4 shows the matrix of the correlation constants and coefficients for the (five times two equals to) ten sets. The most sensitive variables are considered independent variables in the GWP equations, weight of feedstock and usages of electricity, heat, and steam, and their correlation coefficients were predicted from the LCI and LCIA. For example, the total electricity usage in a cradle-to-gate system can be found from the corresponding 'Unit' LCI dataset of Ecoinvent. Similarly, the total feedstock in the cradle-to-gate system is assimilated from the corresponding 'Unit' LCI dataset of Ecoinvent. The usage of electricity per unit feedstock (kWh/t) is thus calculated from a simple ratio. LCIA of the 'Unit' LCI dataset provides the GWP for each activity allowing to calculate the correlation coefficients for each of usages of electricity, heat, and steam for a set. An average weighted method was adopted to calculate the correlation coefficient for the total electricity and heat usage per unit amount of AD feedstock.

The other variables' GWP impacts including from fugitive emissions and other raw materials' acquisition are available together (as par the relevant Ecoinvent data structures) as correlation constant as a function of feedstock quantity in the GWP equation, Equation 2. Consequently, Equation 2 is designed to calculate GWP values based on factors such as the amount of feedstock fed, and the consumption of electricity and heat. These equations then create a GWP calculator that allows end-users to determine GWP values by inputting their specific parameters such as amount of each feedstock and energy usages.

$$GWP_{i,j}\ (kgCO_2e) = (weight\ of\ feedstock\ (t))_{i,j} \times \{a_{i,j} + u^e_{i,j} \times \left(usage\ of\ electricity\ \left(\frac{kWh}{t}\right)\right)_{i,j} + u^h_{i,j} \times \left(usage\ of\ heat\ \left(\frac{MJ}{t}\right)\right)_{i,j} + u^s_{i,j} \times \left(usage\ of\ steam\ \left(\frac{kg}{t}\right)\right)_{i,j}\} \qquad \forall i \in feedstock, \forall j \in location \qquad \text{(Equation 2)}$$

$a_{i,j}$, $u^e_{i,j}$, $u^h_{i,j}$ and $u^s_{i,j}$ are the correlation constant and coefficients for the usages of electricity (e), heat (h) and steam (s), respectively. The two sets i and j correspond to the feedstock type and location, respectively.

Table 4 Correlation coefficients and constant in Equation 2 deduced from Ecoinvent 3.6 LCI datasets and ReCiPe (M) (H) LCIA estimated GWP.

Feedstock i	$a_{i,j}$	$u^e_{i,j}$	$u^h_{i,j}$	$u^s_{i,j}$	Location j
Manure	87.8	5.5	5.8		CH
Manure	88.8	84.8	15.2		ROW
Sludge	14.3	13.3	5.3	14.6	CH
Sludge	23.7	44.7	8.2	20.8	ROW
UCO	245.4	0.005	0.005		CH
UCO	136	620.4	110.8		ROW
Grass	224.7	31.9	19.8		CH

The correlation coefficient for the feedstock item was calculated based on the amount of total feedstock used to produce 1 m^3 biogas. Note that in Table 4, where values are missing, these could be due to inadequate data in the Ecoinvent database. Steam is only used in sewage sludge AD systems likely in chemical resourcing in the upstream processes. There is no LCI data for grass silage in ROW in Ecoinvent. The 'Unit' or 'System' Ecoinvent LCI data structure is the same for biowaste and thus, its equation would not fit the simple format in novel Equation 2. It would take 792+ input variables corresponding to the fundamental primary resource flows to comprehensively present biowaste AD GWP. Thus, for biowaste an overall GWP of the system per unit biogas can be presented, as shown latter in the Results section. The LCI and LCIA results for 1 m^3 cradle-to-gate biogas production system based on which Equation 2 is built are shown in Table 5. The $\left(usage\ of\ electricity\ \left(\frac{kWh}{t}\right)\right)_{i,j}$, $\left(usage\ of\ heat\ \left(\frac{MJ}{t}\right)\right)_{i,j}$, $\left(usage\ of\ steam\ \left(\frac{kg}{t}\right)\right)_{i,j}$ and $(weight\ of\ feedstock\ (t))_{i,j}$ are from corresponding sets' Ecoinvent 3.6 'Unit' LCI data (aggregated and weighted average) and $GWP_{i,j}$ is the calculated GWP of the corresponding 1 m^3 cradle-to-gate biogas production system using ReCiPe (M) (H) in SimaPro 9.4.0.3v.

Table 5 LCI and LCIA results for 1 m^3 cradle-to-gate biogas production system based on which Equation 2 is built.

i	$\left(usage\ of\ electricity\ \left(\frac{kWh}{t}\right)\right)_{i,j}$	$\left(usage\ of\ heat\ \left(\frac{MJ}{t}\right)\right)_{i,j}$	$\left(usage\ of\ steam\ \left(\frac{kg}{t}\right)\right)_{i,j}$	$(weight\ of\ feedstock\ (kg))_{i,j}$	j	$GWP_{i,j}(kgCO_2e/m^3biogas)$
Manure	0.04	0.8		8.64	CH	0.8
Manure	0.0367	0.8066		8.64	ROW	0.9
Sludge	0.0329	0.1509	0.005886	19.8	CH	0.31
Sludge	0.0298	0.1006	0.007861	15	ROW	0.39
UCO	0.1578	3.4653		1.18	CH	0.29
UCO	0.1578	3.4653		1.18	ROW	0.73
Grass	0.1362	2.2373		1.5	CH	0.41

Furthermore, simple weighted average Equation 3 is applied to calculate the GWP of co-digestion systems.

$$Codigestion\ GWP_j = \sum_i GWP_{i,j} \times w_{i,j}$$

$$\sum_i w_{i,j} = 1 \qquad \forall i \in feedstock, \forall j \in location \text{ (Equation 3)}$$

$w_{i,j}$ is the fraction of feedstock i in location j.

3.0 Results

There are two reported sets of results in this work. First, based on published literature, equations are developed in Table 2, and results are reported for some representative cases. Thereafter, the results of the Ecoinvent 3.6 biogas-related LCI databases are shown. The final section discusses the comparison of results between the two approaches and provides recommendations for biogas GWP estimation.

3.1 Literature based GWP modelling results

This section provides the GWP impacts of cradle-to-gate (biogas production), and cradle-to-grave (CHP generation and digestate application) systems for four different AD feedstocks, different fugitive emissions values and different CHP system efficiencies based on literature reference data. The GWP is calculated using IPCC GHG characterizations [50]. The GWP results are primarily presented per m^3 biogas (assumed to be 55% biomethane). The system boundaries are indicated as considered in individual plots. Table S1 shows the parameters used in model calculations for the current scenario. Figure 4 shows the cradle-to-gate (biogas production) AD system GWP for the four feedstocks, food waste, cattle manure, grass silage and sewage sludge using the published literature-based model. For easily transferable results into other studies, GWP impacts of per m^3 biogas are shown. Cattle manure has the highest GWP impact primarily owing to its lower biogas production, with grass silage closely trailing due to the need for accounting carbon emissions during the cultivation process. The inset in Figure 4 shows embedded GWP consideration within the AD feedstock and GWP accounting up to the biogas generation leaving the system gate.

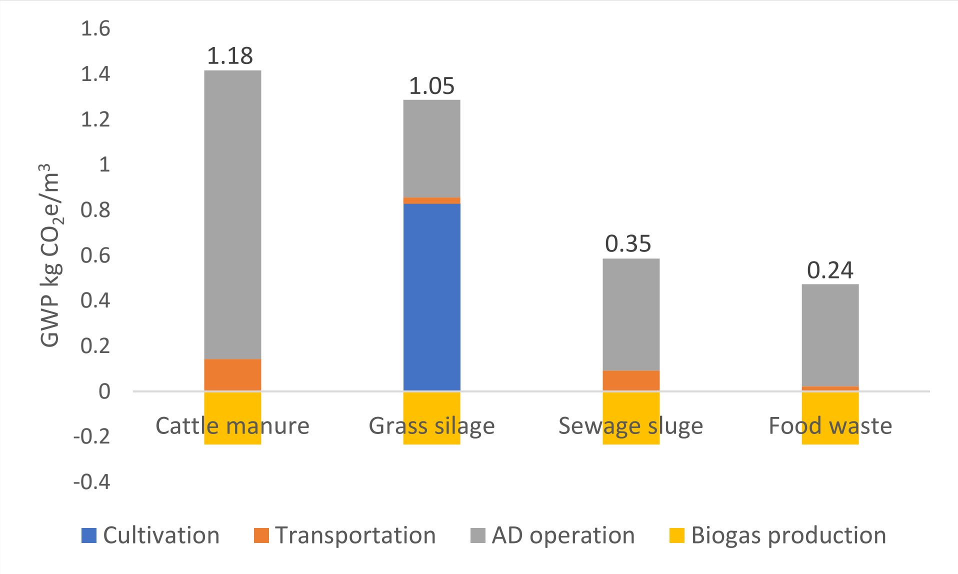


Figure 4 GWP of cradle-to-gate (biogas production) AD system for four feedstocks using the published literature-based model. The net GWP values are shown.

Figure 5 shows the cradle-to-grave (CHP generation) AD systems' net GWP using the published literature-based model. Biomethane is produced from biogas and the CHP related parameters are shown in Table S1.

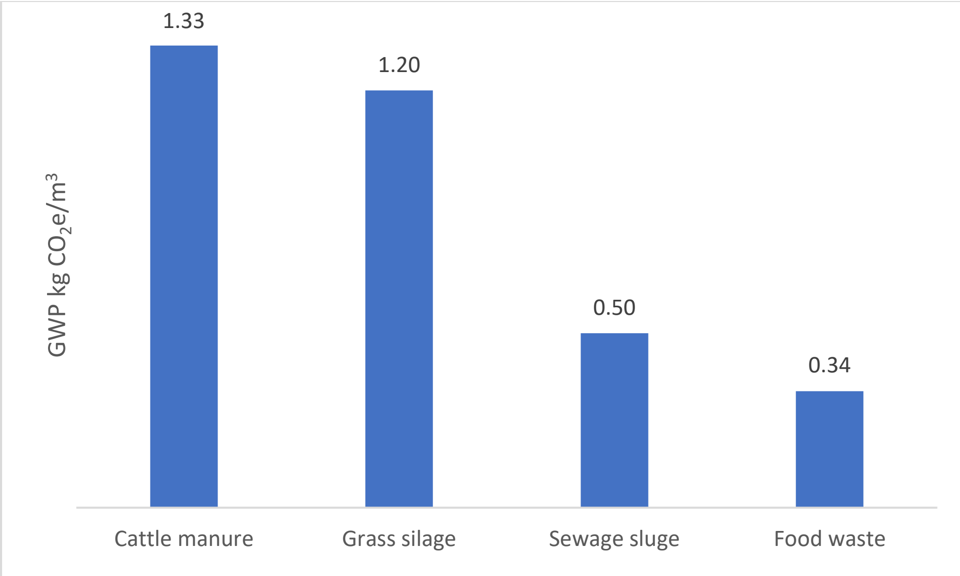


Figure 5 Net GWP of cradle-to-grave (CHP production) AD system for four feedstocks using the published literature-based model.

If we consider cradle-to-grave (digestate application), taking food waste as an example, the GWP impacts of each stage are shown in Figure 6. Hot spot analysis is used to identify which activities or process steps cause the greatest environmental impact. Figure 6 shows the hotspot analysis for food waste for the GWP impact categories considered. The process phases that contribute most to the total GWP are the CHP unit (20%), where the production of energy occurs, and the AD operation (25%). The burdens are mainly due to methane losses from the plant in the latter, and to emissions of unburnt methane in the former. Other feedstocks' results are similar to that of food waste. Figure 6 incorporates the utilization of digestate, accounting for carbon emissions resulting from its application as fertilizer and the emissions avoided through the production of fertilizer ($GWP_T + GWP_{AD} + GWP_{CHP} + GWP_{D_T} + GWP_{D_A} - (GWP_E + GWP_H + GWP_F)$).

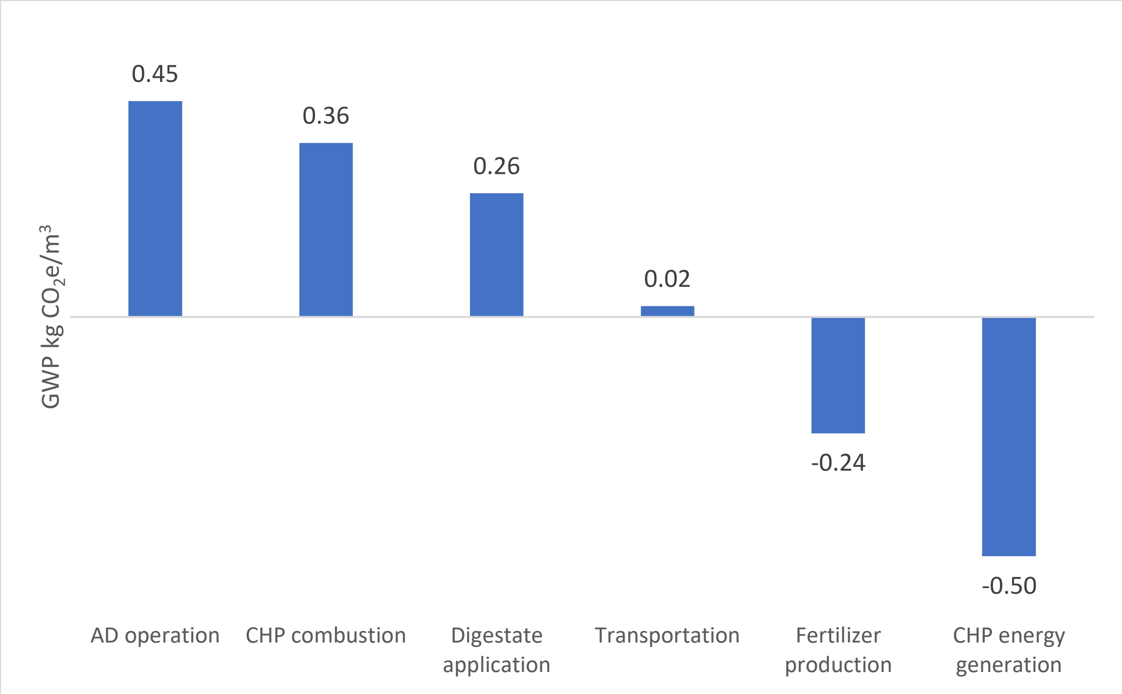


Figure 6 Stage or activity-wise GWP of cradle-to-grave (digestate application) using the published literature-based model for food waste.

LCA studies are always associated with uncertainties, especially when data are not obtained directly from a specific plant. In this work, key parameters with potentially large impact on models for specific technologies and on the overall results are investigated: fugitive emissions percentage and electricity and heat production.

In the sensitivity analysis, three different values for methane fugitive emissions are considered, expressed as percentages of the total methane in the biogas. Figure 7 shows the results for GWP of cradle-to-grave (digestate application) with different fugitive emissions percentage. Halving this value reduces the total CO_2e GWP by 30%. On the other hand, increasing the percentage of methane fugitive emissions to 5% increases the GWP by more than 87%, while if the fugitive emissions are increased to 15%, the GWP triples. This clearly shows the importance of emission monitoring and control in biogas production, since fugitive losses have a great impact on the overall environmental performance of a biogas production system.

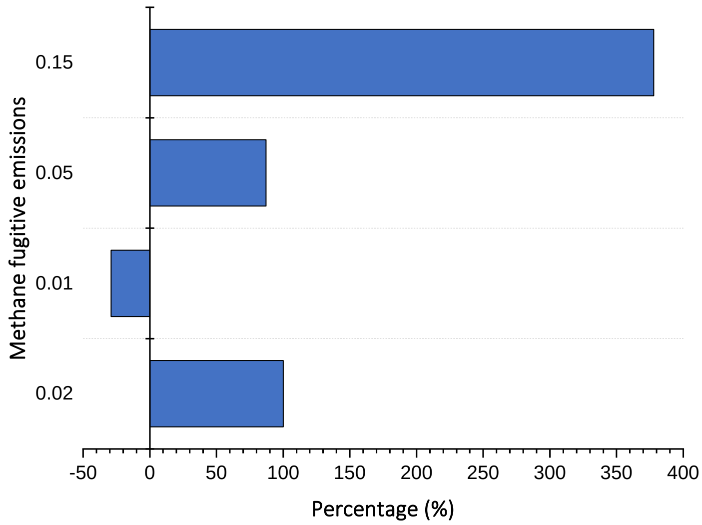


Figure 7 Effect of methane losses on GWP impacts compared to baseline. The baseline fugitive emissions of methane are 2%.

The efficiency of internal combustion engines running on biogas can vary widely. This study assumes an electrical efficiency of 32% and a thermal efficiency of 50% as baseline parameters. Sensitivity analysis is conducted on this parameter, and two different scenarios are then considered: scenario 1, with an electrical efficiency of 30% and thermal efficiency of 60%; and scenario 2 with 40% electrical efficiency and 45% thermal efficiency [62]. Based on the GWP impacts per reference unit in Table 3, changes in CHP efficiency have little impact on the total GWP. Note that these factors primarily represent the UK context.

3.2 AD system results using Ecoinvent LCI database

This section provides the GWP impacts of cradle-to-gate (biogas production), cradle-to-gate (biomethane production) and cradle-to-grave (CHP generation) systems for five different AD feedstocks, three different biomethane purification or pre-combustion carbon capture technologies and four different CHP systems as available in the Ecoinvent 3.6 LCI database to validate Equation 1, addressed in the following section. The GWP results are primarily presented per m^3 biogas, kWh biomethane and kWh electricity output. The feedstock weight and GWP values per m^3 biogas in Table 5 allow the calculation of GWP in g CO_2e per kg feedstock, 93-104 (manure), 16-26 (sludge), 245-618 (UCO), and 273 (grass silage). The lower end values correspond to CH and higher end to ROW, respectively. For biowaste, the AD feedstock constituents are broken down into fundamental primary resources. Thus, an individual fundamental primary resource flow in the biowaste-to-biogas database is an aggregation of all of its flows in the feedstock, infrastructure, and operations, etc. The system boundaries are indicated as considered in individual plots. Allocation has been applied based on APOS database assumption, i.e., economic allocation at individual products' levels, as shown in the plots.

Figure 8 shows the cradle-to-gate (biogas production) AD system GWP for the five feedstocks, manure, sewage sludge, UCO and biowaste in two geographic contexts, CH:

Switzerland and ROW: Rest of the World, using the Ecoinvent 3.6 APOS datasets, named on x-axis. The Ecoinvent data for grass silage is only present for CH. For easily transferable results into other studies, GWP impacts per m^3 are shown (Table 5). Consistently, the GWP impacts are higher in the case of ROW than CH. A higher difference is observed for UCO because of coal and fuel oil-based heat supply in ROW compared to natural gas-based heat in CH. The inset in Figure 8 shows embedded GWP consideration within the AD feedstock and GWP accounting up to the biogas generation leaving the system gate.

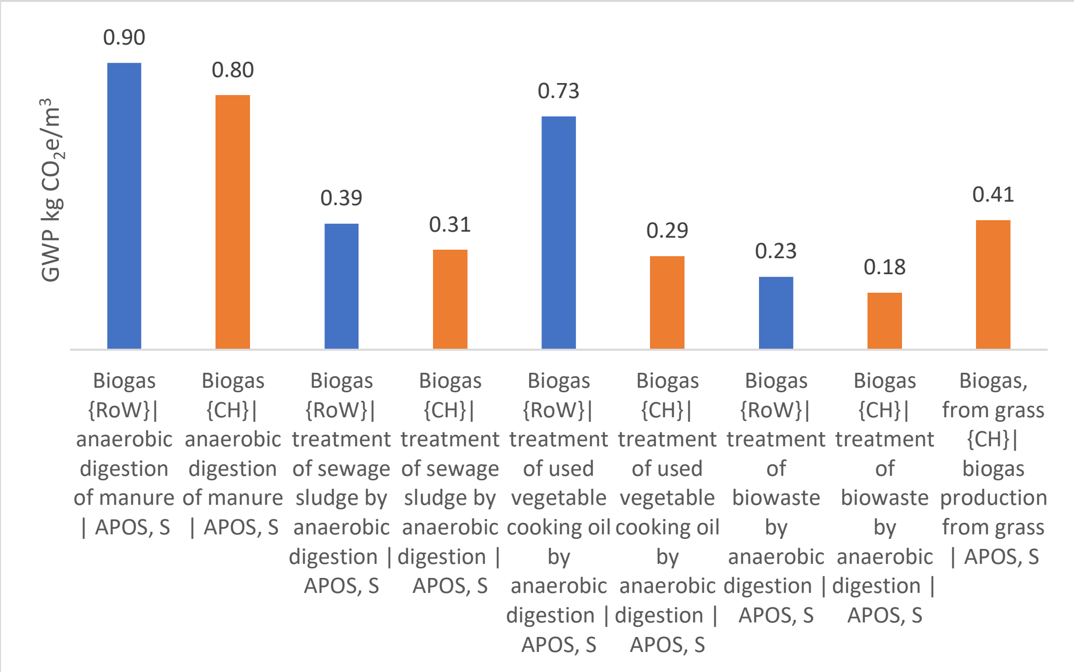


Figure 8 GWP of cradle-to-gate (biogas production) AD system in two geographic contexts and for five feedstocks; X-axis labels show the Ecoinvent 3.6 database names for transparency.

Figure 9 shows the GWP impact of cradle-to-gate (biogas production) activity-wise GWP split for cattle manure. The activity-wise split method differs from the published literature-based model, which segregates GWP based on various stages or processes. For e.g., Ecoinvent 3.6 data structure allows the GWP calculations for liquid and solid manures and different types of manure feedstocks, which are due to their separate calculated values. Consequently, the comparability between the two sets of equation structures is low. However, the overall results are very close, as shown in the latter section.

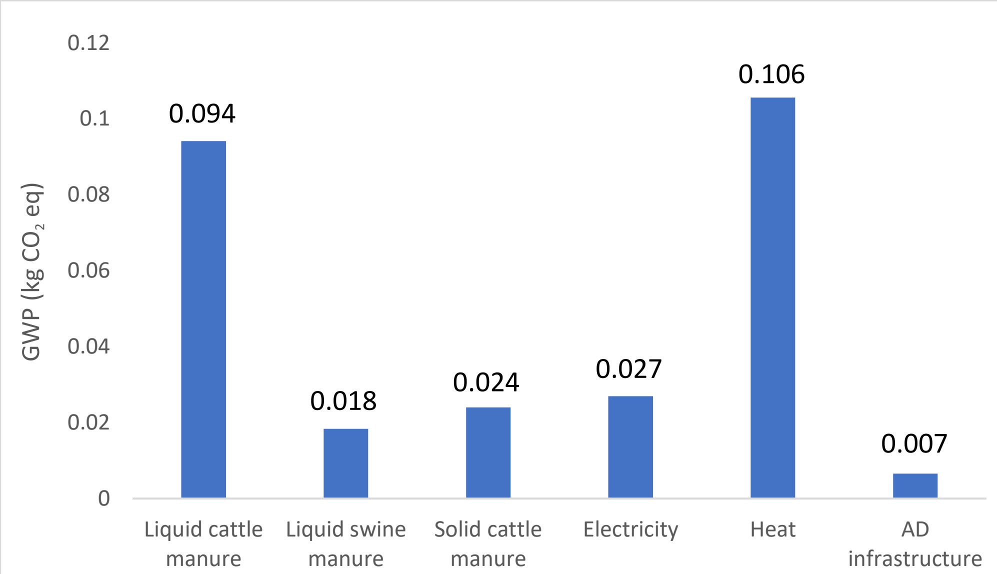


Figure 9 Cradle-to-gate (biogas production) activity-wise GWP split.

In a similar manner, Figure 10 is created showing the cradle-to-gate (biomethane production) AD system GWP in the context of CH, using the Ecoinvent 3.6 APOS datasets, named on x-axis. Biomethane (40 MJ/m^3) (52%, ranging 50-65% by volume of biogas) is produced from biogas by three types of upgrading techniques, namely amino (amine) washing, membrane and pressure swing adsorption as par the Ecoinvent LCI database. The embedded GWP in biogas and the GWP of the upgrading techniques are considered in allocating the GWP impact to 1 m^3 biogas. The GWP is the least for the membrane technique because of the clean electricity usage in the CH context. For the other two upgrading techniques, natural gas-based heat and materials' usage creates more GWP impacts.

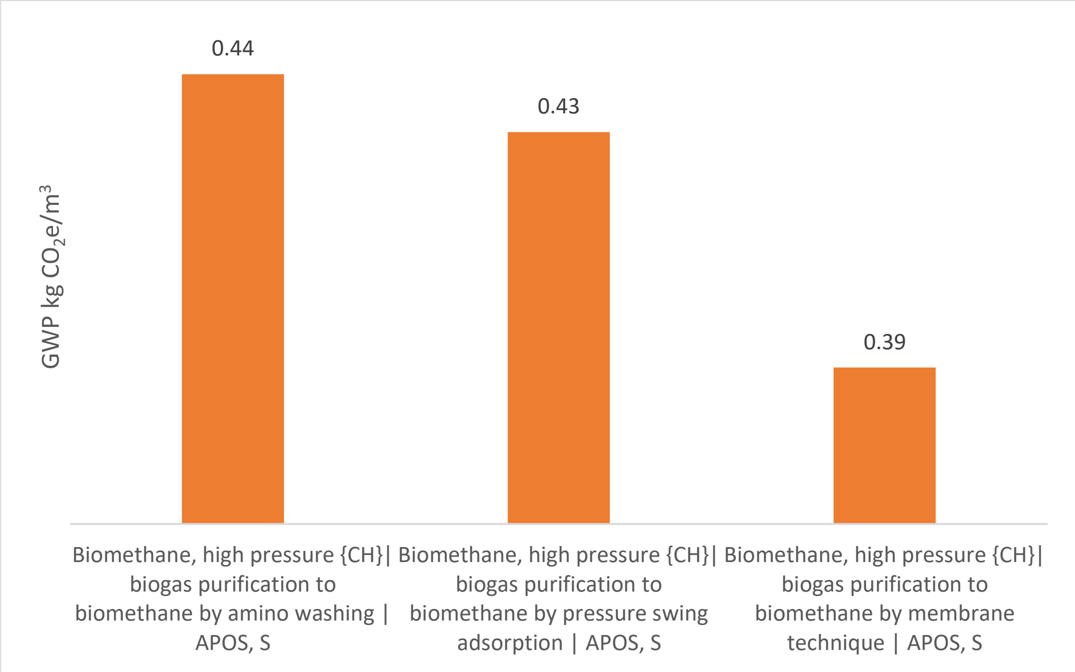


Figure 10 GWP of cradle-to-gate (biomethane production) AD system in CH geographic context for three pre-combustion carbon capture technologies; Ecoinvent 3.6 database names are shown on x-axis. It can be noted that their GWP differs only by 10%.

Figure 11, in a similar way, shows the cradle-to-grave (CHP generation) AD system GWP in the context of CH, using the Ecoinvent 3.6 APOS datasets, named on x-axis. The four CHP generation techniques using biomethane in Ecoinvent are micro gas turbine (MGT), polymer electrolyte membrane fuel cells (PEMFC), solid oxide fuel cells (SOFC) and SOFC-MGT. The electricity generation by the four techniques in kWh/m^3 biogas are 2.5, 2.63, 3.5 and 4.09, respectively. Only the cradle to grave GWP impact per m^3 biogas utilization allocated to electricity generation is shown.

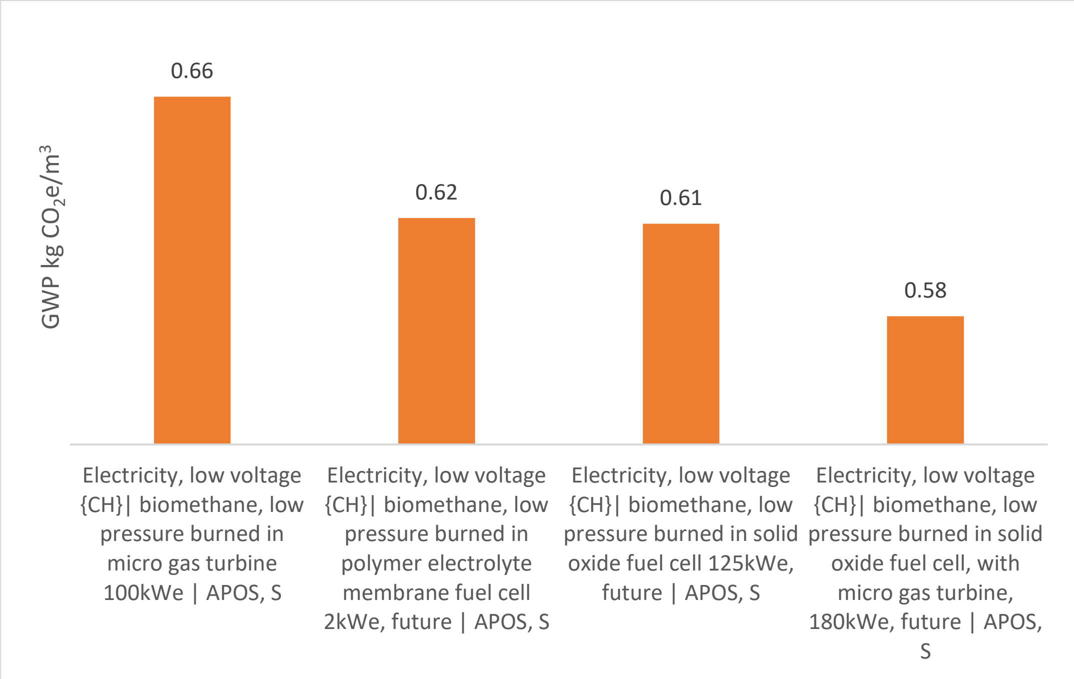


Figure 11 GWP of cradle-to-grave (CHP production) AD system for five feedstocks; Ecoinvent 3.6 database names are shown on x-axis.

As Figure 10-Figure 11 illustrate the whole system including embedded impacts from the upstream systems (cradle), it is worthwhile to separate the impacts of individual four CHP and three pre-combustion carbon capture techniques, as shown in Table 6. Table 6 thus summarizes the GWP impacts of individual processes (alongside the cradle-to-gate biogas production) impacts, so these can be combined into sixty different system configurations (five feedstocks × three pre-combustion carbon capture techniques × four CHP techniques in the CH context) to analyze GWP impact distributions in Figure 12. The GWP impacts of individual processing steps and the cradle-to-gate (biogas production) are shown per unit outputs as appropriate.

Table 6 GWP of individual process stages, cradle-to-biogas, biogas purification or pre-combustion carbon capture to biomethane generation, and biomethane-to-CHP, in AD systems.

CHP PROCESS	**kg CO_2e/kWh -electricity**	**kg CO_2e/m^3 -biomethane**	**kg CO_2e/kWh -biomethane**	**kg CO_2e/m^3 -biogas**
MICRO GT	0.0073	0.0085	0.0008	0.0044
PEMFC	0.0351	0.0430	0.0039	0.0224
SOFC	0.0148	0.0240	0.0022	0.0125
SOFC-GT	0.0121	0.0230	0.0021	0.0120
PRE-COMB CARBON CAPTURE PROCESS				
AMINO WASH		0.2840	0.0256	0.1477
MEMBRANE		0.1980	0.0178	0.1030
PSA		0.2660	0.0239	0.1383
AD FEEDSTOCK (CRADLE-TO-GATE BIOGAS PRODUCTION)				
MANURE				0.7957
SLUDGE				0.3120
UCO				0.2925
BIOWASTE				0.1785
GRASS				0.4053

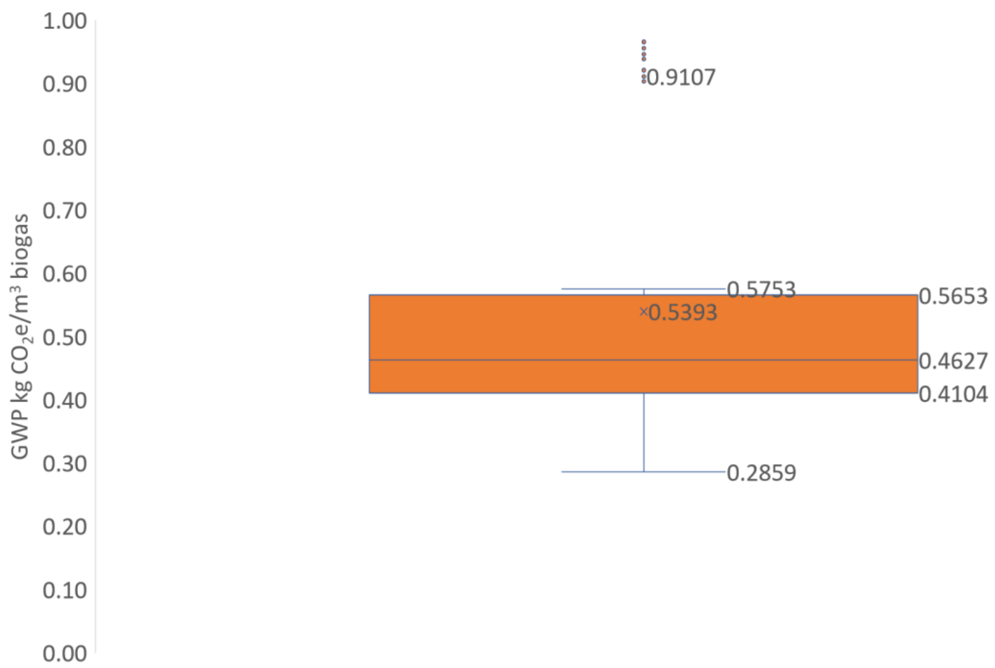
Building on the GWP impacts of individual processing techniques and the cradle-to-gate (biogas production) as shown per unit outputs as appropriate in Table 6, Table 7 has been created to show the GWP of cradle-to-grave (CHP generation with pre-combustion carbon capture) sixty different system configurations, considering five AD feedstocks, three pre-combustion carbon capture techniques and four CHP techniques in the CH context. The GWP impacts are reported per unit biogas (volume), biomethane (energy and volume) and electricity production rates. It can be seen that GWP per kWh electricity is the least for the membrane-SOFC-MGT combination, while based on biogas or biomethane rate, the GWP is the least for the membrane-MGT combination. The membrane-SOFC-MGT combination gives the highest electricity generation efficiency, which explains why the combination has the least GWP impact per kWh electricity output. Similarly, the highest biogas or biomethane production rate in the case of membrane-MGT combination explains the reason why the combination shows the least GWP impacts per unit biogas or biomethane production rate. Amongst the AD feedstocks, biowaste has the least GWP impact, followed by UCO, sludge, grass silage and manure, respectively, in the order of increasing GWP impact.

Table 7 GWP of sixty different AD-pre-combustion carbon capture-CHP (cradle-to-grave) options for five feedstock types based on Ecoinvent 3.6 AD system-related databases. The shaded cells show the least impact technological choices. The boxed values signify the least GWP impacts of biowaste cradle-to-grave systems compared to any other AD feedstocks.

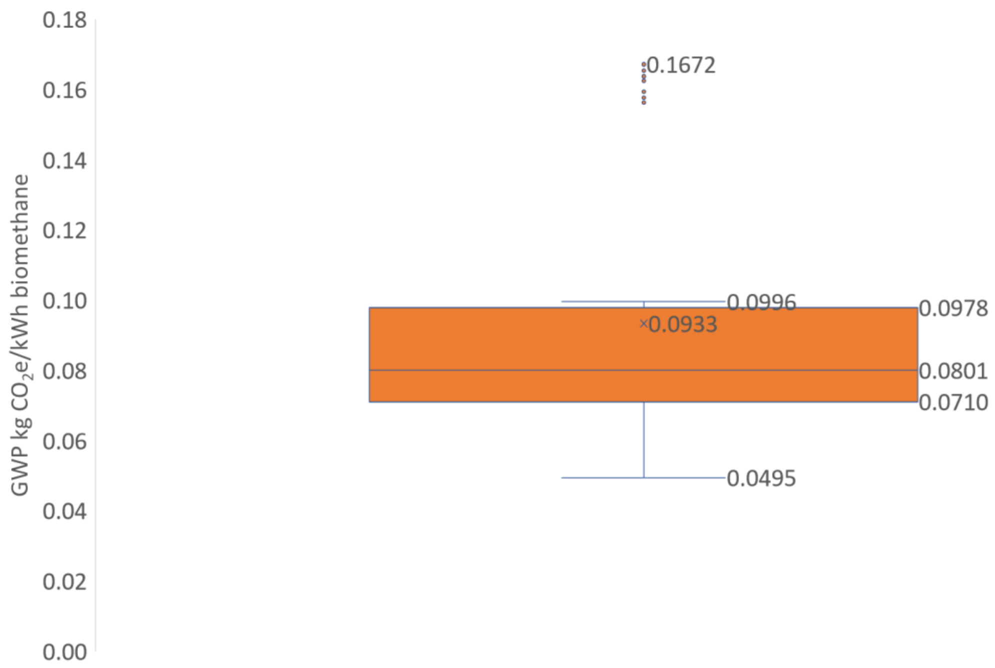
CRADLE-TO-GRAVE AD-CHP SYSTEM VIA BIOMETHANE	kg CO_2e/kWh -electricity	kg CO_2e/m^3 -biomethane	kg CO_2e/kWh -biomethane	kg CO_2e/m^3 -biogas
manure-amino washing-micro gas turbine	1.5692	1.8227	0.1640	0.9478
manure-amino washing-PEMFC	1.5172	1.8572	0.1672	0.9658
manure-amino washing-SOFC	1.1322	1.8382	0.1654	0.9559
manure-amino washing-SOFC-MGT	0.9643	1.8373	0.1654	0.9554
manure-membrane-micro gas turbine	1.4951	1.7367	0.1563	0.9031
manure-membrane-PEMFC	1.4469	1.7712	0.1594	0.9210
manure-membrane-SOFC	1.0793	1.7522	0.1577	0.9111
manure-membrane-SOFC-MGT	0.9191	1.7513	0.1576	0.9107
manure-PSA-micro gas turbine	1.5537	1.8047	0.1624	0.9385
manure-PSA-PEMFC	1.5025	1.8392	0.1655	0.9564
manure-PSA-SOFC	1.1212	1.8202	0.1638	0.9465
manure-PSA-SOFC-MGT	0.9548	1.8193	0.1637	0.9460
sludge-amino washing-micro gas turbine	0.7684	0.8926	0.0803	0.4642
sludge-amino washing-PEMFC	0.7574	0.9271	0.0834	0.4821
sludge-amino washing-SOFC	0.5593	0.9080	0.0817	0.4722
sludge-amino washing-SOFC-MGT	0.4761	0.9071	0.0816	0.4717
sludge-membrane-micro gas turbine	0.6944	0.8066	0.0726	0.4194
sludge-membrane-PEMFC	0.6871	0.8411	0.0757	0.4374
sludge-membrane-SOFC	0.5063	0.8220	0.0740	0.4275
sludge-membrane-SOFC-MGT	0.4310	0.8211	0.0739	0.4270
sludge-PSA-micro gas turbine	0.7529	0.8746	0.0787	0.4548
sludge-PSA-PEMFC	0.7426	0.9091	0.0818	0.4727
sludge-PSA-SOFC	0.5482	0.8900	0.0801	0.4628
sludge-PSA-SOFC-MGT	0.4667	0.8891	0.0800	0.4623
UCO-amino washing-micro gas turbine	0.7361	0.8550	0.0770	0.4446
UCO-amino washing-PEMFC	0.7267	0.8895	0.0801	0.4625
UCO-amino washing-SOFC	0.5362	0.8705	0.0783	0.4526
UCO-amino washing-SOFC-MGT	0.4564	0.8695	0.0783	0.4522
UCO-membrane-micro gas turbine	0.6621	0.7690	0.0692	0.3999
UCO-membrane-PEMFC	0.6564	0.8035	0.0723	0.4178
UCO-membrane-SOFC	0.4832	0.7845	0.0706	0.4079
UCO-membrane-SOFC-MGT	0.4112	0.7835	0.0705	0.4074
UCO-PSA-micro gas turbine	0.7206	0.8370	0.0753	0.4353
UCO-PSA-PEMFC	0.7119	0.8715	0.0784	0.4532
UCO-PSA-SOFC	0.5251	0.8525	0.0767	0.4433
UCO-PSA-SOFC-MGT	0.4469	0.8515	0.0766	0.4428
Biowaste-amino washing-micro gas turbine	0.5474	0.6358	0.0572	0.3306
Biowaste-amino washing-PEMFC	0.5476	0.6703	0.0603	0.3485
Biowaste-amino washing-SOFC	0.4011	0.6512	0.0586	0.3386
Biowaste-amino washing-SOFC-MGT	0.3413	0.6503	0.0585	0.3382
Biowaste-membrane-micro gas turbine	0.4733	0.5498	0.0495	0.2859
Biowaste-membrane-PEMFC	0.4773	0.5843	0.0526	0.3038
Biowaste-membrane-SOFC	0.3482	0.5652	0.0509	0.2939
Biowaste-membrane-SOFC-MGT	0.2962	0.5643	0.0508	0.2934
Biowaste-PSA-micro gas turbine	0.5319	0.6178	0.0556	0.3213
Biowaste-PSA-PEMFC	0.5329	0.6523	0.0587	0.3392
Biowaste-PSA-SOFC	0.3900	0.6332	0.0570	0.3293
Biowaste-PSA-SOFC-MGT	0.3319	0.6323	0.0569	0.3288
grass-amino washing-micro gas turbine	0.9228	1.0719	0.0965	0.5574
grass-amino washing-PEMFC	0.9038	1.1064	0.0996	0.5753
grass-amino washing-SOFC	0.6698	1.0873	0.0979	0.5654
grass-amino washing-SOFC-MGT	0.5702	1.0864	0.0978	0.5649
grass-membrane-micro gas turbine	0.8488	0.9859	0.0887	0.5127
grass-membrane-PEMFC	0.8336	1.0204	0.0918	0.5306
grass-membrane-SOFC	0.6168	1.0013	0.0901	0.5207
grass-membrane-SOFC-MGT	0.5251	1.0004	0.0900	0.5202
grass-PSA-micro gas turbine	0.9073	1.0539	0.0949	0.5480
grass-PSA-PEMFC	0.8891	1.0884	0.0980	0.5660
grass-PSA-SOFC	0.6587	1.0693	0.0962	0.5561
grass-PSA-SOFC-MGT	0.5608	1.0684	0.0962	0.5556

Figure 12 shows the cradle-to-grave GWP distributions of the results data in Table 7 per unit biogas, biomethane and electricity production rates. The mean GWP impacts in kg CO_2e are 0.54 per m^3 biogas, 0.09 per kWh biomethane and 0.73 per kWh electricity production rates. Furthermore, it can be noted that the current regulatory drivers target GWP impact in kg

CO_2e per kWh biomethane production rate, for up to the biomethane production gate system. The logic for the cradle-to-gate biomethane production system consideration is that biomethane could end up in chemical or material production, keeping the carbon in it in circulation. An example is the 50 g CO_2e per kWh biomethane production rate requirement by 2030 for gas grid injection of biomethane in the UK's net-zero electricity carbon intensity requirements [61]. Thus, another instance of GWP distribution could be generated for the cradle-to-gate (biomethane producing) AD system, as shown in Figure 8, with slightly lower GWP impacts compared to those in Figure 12b. There are fifteen such configurations, i.e., five AD feedstocks times three pre-combustion carbon capture techniques. The resultant minimum GWP impact in Figure 12b and Figure 13 meets the 50 g CO_2e per kWh biomethane production rate target by 2030 for gas grid injection of biomethane in the UK's net-zero electricity strategies [61]. However, wider distributions (most occurrences) can be seen between 50th and 75th percentiles with higher GWP impact values >0.078 kg CO_2e per kWh biomethane production rate. These are aligned with what has been noted for food waste, maize, wet manure and sewage sludge at 80, 130, 86 and 78 g CO_2e per kWh biomethane [62]. The plots in Figure 12-Figure 13 show the ranges, outliers, and 25th, 50th and 75th percentile GWP impact values. The plots thus capture uncertainty in GWP impact values.



(a)



(b)

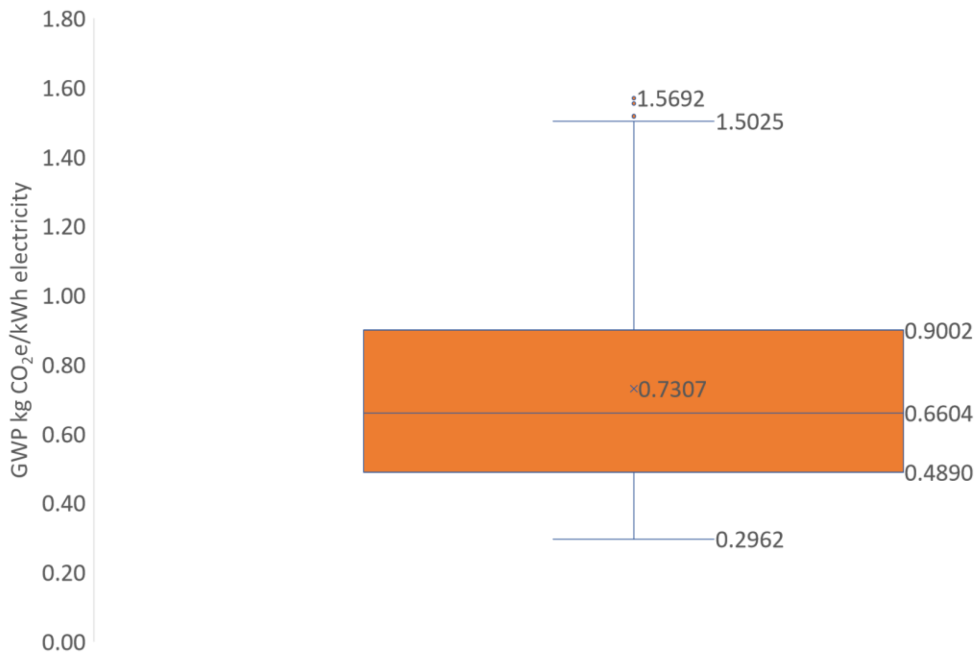


Figure 12 GWP distribution of cradle-to-grave (CHP production with pre-combustion carbon capture) AD system (a) per m3 biogas, (b) per kWh biomethane, and (c) per kWh electricity. x: mean value; range, 25th, 50th and 75th percentile values and outliers are shown.

(c)

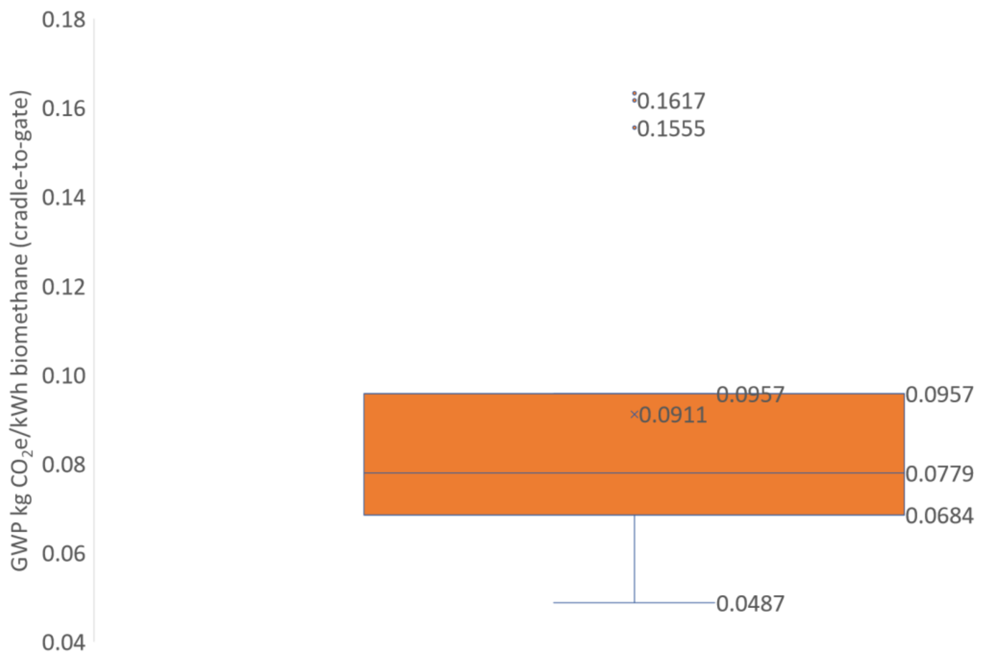


Figure 13 GWP distribution of cradle-to-gate (biomethane production with pre-combustion carbon capture) AD system per kWh biomethane. x: mean value; range, 25th, 50th and 75th percentile values and outliers are shown.

The Greenhouse Gas Protocol of IPCC encourages reporting of biogenic GHG separately [63], which is a key characteristic of the CHP configurations utilizing biomethane, as shown in Figure 14. These biogenic quantities have rapid sequestration potential, closing the carbon cycle partially through the cradle-to-grave AD system.

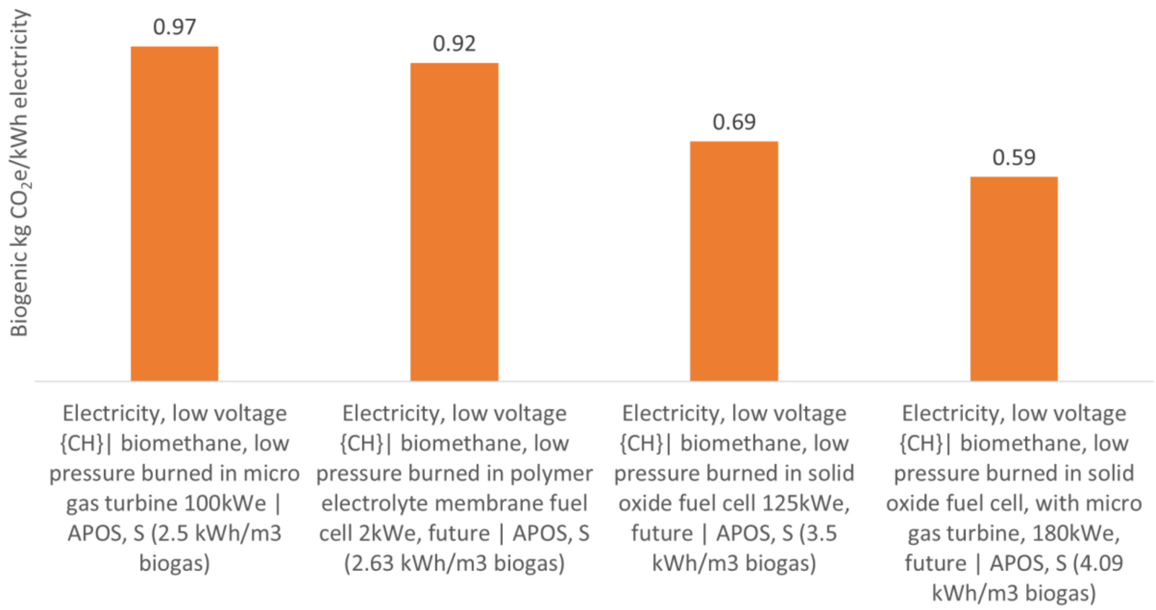


Figure 14 The biogenic part of cradle-to-grave (CHP production) AD system.

The best set of cradle-to-grave GWP impact results from Table 7, i.e., for biowaste as AD feedstock, membrane as pre-combustion carbon capture technique and four CHP configurations, is shown in Figure 15. For comparison, cradle-to-grave natural gas GWP impact (Ecoinvent 3.6 datasets) is shown. The biogenic attribution is shown as negative GWP impact or GWP reduction. It can be seen that without the consideration of the biogenic attribution, the AD system has a lower environmental performance than the natural gas system. The net GWP saving per kWh of electricity production via the biowaste AD system from the displacement of natural gas system is 0.5-0.7 kg CO_2e/kWh electricity generation. Thus, 1 tonne of CO_2e saving by AD system would require at least 1.5-2.1 MWh electricity generation.

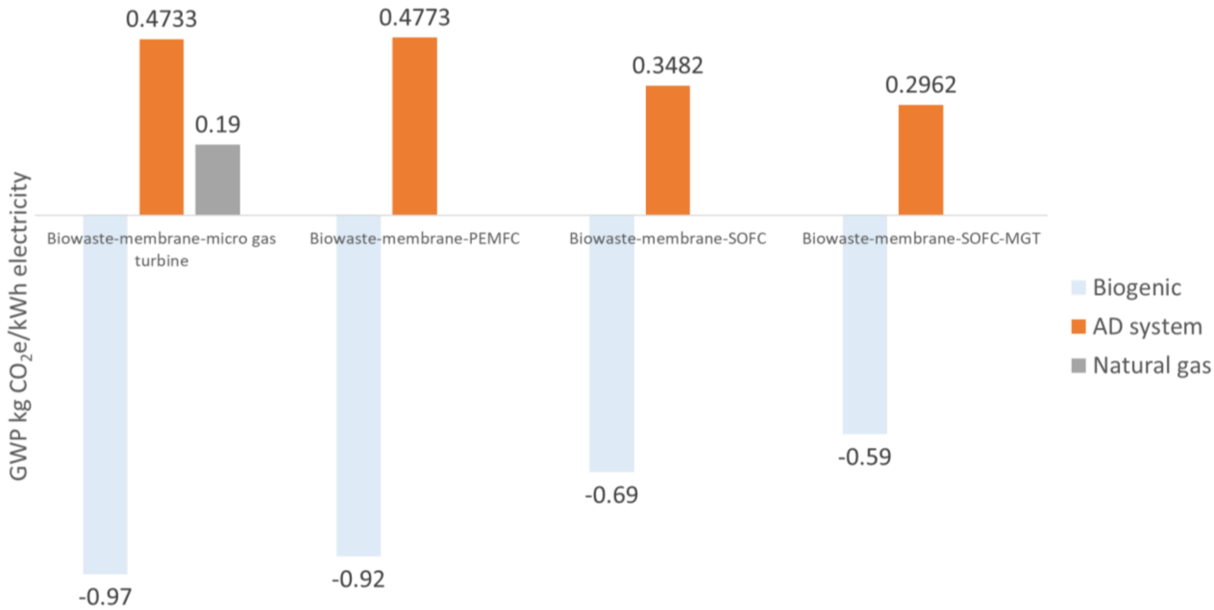


Figure 15 GWP and biogenic attributions of cradle-to-grave (CHP production) AD system, biowaste feedstock via three pre-combustion carbon capture techniques purifying biogas into biomethane, followed by biomethane combustion in four CHP configurations. These are compared against cradle-to-grave natural gas system.

4.0 Discussion

This section compares the two novel models, first time presented in this work, published literature-based and using Ecoinvent LCI database-based estimations, developed for GWP of biogas systems, both in terms of GWP results and variabilities (Table 8). Further, it discusses how the models can help the GWP estimation of biogas systems. Both the cradle-to-gate (biogas production) (Figure 4 and Figure 8) and cradle-to-grave (CHP generation) (Figure 4 and Table 7) AD systems' GWP (kg CO_2e/m^3 biogas) comparisons between the two models show a close match.

Table 8 Comparison between two novel models in terms of GWP results and variabilities.

Criteria	Published literature-based	Ecoinvent database-based	Unit
Cradle-to-gate biogas production GWP			
Feedstock	(Figure 4)	(Figure 8)	
Food waste	0.18	0.18-0.23	kg CO_2e/m^3
Sludge	0.35	0.31-0.39	kg CO_2e/m^3
Grass silage	1.05	0.41	kg CO_2e/m^3
Manure	1.18	0.8-0.9	kg CO_2e/m^3
Cradle-to-grave CHP generation GWP			
Feedstock	(Figure 5)	(Table 7)	
Food waste	0.34	0.29-0.35	kg CO_2e/m^3
Sludge	0.5	0.42-0.48	kg CO_2e/m^3
Grass silage	1.2	0.5-0.58	kg CO_2e/m^3
Manure	1.33	0.9-0.97	kg CO_2e/m^3
Input variables			
kg DM feedstock for a given Nm^3 biogas production t wet feedstock for the given Nm^3 biogas production Distance for t feedstock transportation (km) N_2O emissions (kg) per t wet feedstock Fraction of CH_4 in biogas Fraction of leakage Onsite usage of electricity (kWh) per t wet feedstock Onsite usage of heat (kWh) per t wet feedstock t wet digestate per t wet feedstock Distance for t digestate transportation (km) Spreading energy usage (kWh) per t wet feedstock Total N kg per t wet feedstock CHP electrical efficiency CHP heat efficiency Net calorific value (kWh/Nm^3 biogas) Total of N, P, K kg per t wet feedstock		t wet feedstock for the given Nm^3 biogas production Total usage of electricity (kWh) for given Nm^3 biogas Total usage of heat (MJ) for given Nm^3 biogas Total usage of steam (kg) for given Nm^3 biogas	

It can be observed from the comparisons between the two models in Table 8 that in general the new published literature-based model gives higher (or more conservative) GWP estimations than the new Ecoinvent database-based model, thus setting the minimum GWP thresholds for regulations. The resulting lower end GWP values from the latter are consistently lower than the literature-based model prediction. This is because the lower end GWP values from the latter represent the Swiss cases that enjoy lower impact renewable resources in the systems. The new published literature-based model is more granular needing more user control of individual stage-wise specific inputs, requiring user-defined/measured data. The new Ecoinvent database-based model demands fewer user-defined input variables, only the feedstock and energy consumption data. Depending on the data availability, user can choose either model for measuring, regulating, reviewing, and reporting GWP. The two models are thus complementary, necessitating their side-by-side presentation. Commendably, the new literature-based model (Equation 1 and Tables 2-3) provides the GWP of biogas/AD formulation in a format similar to the EU Directive. Equation 1 specifies a methodology for assessing GHG savings by defining a GWP threshold for each life cycle stage or activity using the EU Directive-defined easily applicable/adaptable format. Tables 8-3 and S1 provide the novel formulations developed based on published literature to predict GWP impact and reduction.

The Ecoinvent data structure is a prominent framework for LCA data, providing a comprehensive and consistent database for the AD process. While Ecoinvent aims to offer a standardized approach to data collection and GWP reporting, difficulties can arise when accounting for the GWP performance of various life cycle stages. Conducting a comprehensive LCA of AD involves considering multiple stages, including AD operation, CHP, digestate and fertilizer production, energy recovery and logistics. Each stage has its unique set of environmental impacts, making it necessary to precisely quantify GWP performance across all stages. This emphasizes the need for the AD system's GWP reporting using Equation 1 and Tables 2-3. Establishing clear, transparent, and easy-to-use calculation methodologies shown in this study thus can help improve the accuracy and reliability of GWP assessments across the life cycle.

Although biogas/AD systems promise to reduce GWP, the practicality of carbon trading with such systems is challenging. Effective participation necessitates AD systems becoming verified carbon offset schemes, complying with national and international carbon offset standards. For certification with them, companies must present their life cycle GWP in a standardized format. This study's models (Equation 1 and Tables 2-3 and Equation 2 and Tables 4-5)are thus crucial for efficiently, comprehensively, and robustly reporting the AD system's life cycle GWP impacts.

5.0 Conclusion

There has been an upsurge of renewed interest in the comparative LCA of biogas/AD as a mechanism to standardize climate change impact reduction potential. This study offers a fresh perspective on calculating the GWP performance of AD setups utilizing data from literature and the Ecoinvent LCI database. First, based on a detailed comprehensive literature review, a GWP prediction model with equations focused on the GWP of each activity in the AD system has been developed. Second, Ecoinvent 3.6 LCI data of all AD-related systems are assimilated to create another GWP prediction model. Both models are then tested to see how they compare. They show good agreement, despite some distinguishing characteristics. In the process of detailed exploration of the possibility of open-source models based on literature and the Ecoinvent database, some scopes are identified, e.g., Swiss (or alternatively rest of the world) data availability in Ecoinvent. The published literature-based model shows more inclusivity in terms of global contexts, allowing LCA stage-specific GWP factors updating based on geographic contexts. Both models capture sensitivity of feedstock variations in GWP prediction and energy related GWP variations, demonstrating robust comprehensive GWP calculations. Furthermore, the Ecoinvent 3.6 LCI database allowed analysis of GWP due to variations in biomethane purification or pre-combustion upgrading technologies (amino washing, membrane, and pressure swing adsorption) and CHP technologies (micro gas turbine (MGT), polymer electrolyte membrane fuel cell, solid oxide fuel cell (SOFC) and SOFC-MGT). Our modular synthesis approach demonstrates distinguishable GWP from each feedstock and technology type, allowing a statistical analysis that shows GWP variations, 25th, 50th and 75th percentile values, and mean values in transferable units, per unit volume of biogas and biomethane, and per unit energetic value of biomethane and electricity, for the cradle-to-grave systems. Some key quantitative GWP measures are as follows. The cradle-to-grave AD system's GWP (kg CO_2e/m^3 biogas) from the literature-based and Ecoinvent data-based models is manure: 1.33 and 0.9-0.97, sludge: 0.5 and 0.42-0.48, food waste or biowaste 0.34 and 0.29-0.35, and grass silage 1.2 and 0.5-0.58. The GWP in g CO_2e per kg AD feedstock is 93-104 (manure), 16-26 (sludge), 245-618 (UCO), and 273 (grass silage). The intended recipients of this study encompass governmental agencies, environmental engineers, the scientific community, feedstock community and energy companies, informing emerging policies on net-zero.

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3.3 Appendix A. Supplementary data

Table S1 Other Parameters for the treatment of feedstock via anaerobic digestion for case study.

Inputs/activities	Reference unit	
AD plant [35]		
Parasitic electricity usage by AD plant	kWh/t feedstock	23
Parasitic heat usage by AD plant	kWh/t feedstock	82
Fugitive emissions	-	2%
CHP [66]		
Electrical conversion efficiency	-	0.32
Thermal conversion efficiency	-	0.5
Fraction of CH_4 in biogas	-	65%
Net Calorific value of biogas	kWh/Nm^3	6.4