LIFE CYCLE ANALYSIS FOR DIGESTATE GASIFICATION COUPLED WITH COMBINED HEAT AND POWER GENERATION

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ABSTRACT

Anaerobic digestion is a proven technology, increasingly deployed worldwide. Its slurry by-product, known as digestate, is commonly spread on farmland, but this practice has become un-economical, due to low nutrient density, storage, transportation costs. Digestate gasification, coupled with combined heat and power production is a promising solution to the challenge. However, its environmental benefits have not yet been fully investigated. The plant analysed is based on downdraft gasification technology, and it would be suitable for the average farm in Northern Ireland. The solution would be of particular interest for the area, due to its intensive livestock farming, and new legislation liming the spread of digestate on land. The process analysed includes digestate separation, drying, gasification, syngas conditioning and combustion in a combined heat and power unit. The results of the analysis show that digestate gasification is superior to land spreading in all damage categories considered: Human Health, Ecosystems and Resources. The avoided production of heat and electricity accounts for most of the negative emissions. By assuming gasification ash and char can be utilized as soil amendment and that the ammonium sulphate produced in the ammonia scrubbing unit can be marketed as fertilizer, this scenario is further improved, although only marginally.

Keywords: Life cycle assessment, small scale gasification, anaerobic digestion, combined heat and power generation

1 INTRODUCTION

Anaerobic digestion is an energy recovery and waste management technology, in which selected micro-organisms break down various organic feedstocks (wastes and energy crops) into their constructive blocks, and further to carbon dioxide and methane (biogas).

In the UK, 662 anaerobic digestors are currently in operation, 41 of which are located in Northern Ireland, with a total installed capacity of 28 MWe [1]. The biogas in most plants in Northern Ireland is used on site for cogeneration applications (heat is utilised on site and surplus electricity is sold to the national grid). The slurry by-product of anaerobic digestion, the digestate, contains nutrients useful for plant development (N, P, K) and organic carbon [2]. As a result, digestate can be used as fertiliser or soil amendment, alleviating the environmental impact of organic fertiliser, produced through carbon intensive processes.

However, digestate management can become cumbersome in practice, due to storage and transportation requirements. In Northern Ireland, 4-6 month storage must be ensured for the digestate generated, resulting in additional land requirement for storage tanks [3]. Moreover, proper sealing must be ensured to limit storage emissions of methane, ammonia and nitrogen dioxide.

Due to the low density of nutrients in whole digestate, its transport is also expensive: digestate transport costs are as high as a third of the total costs incurred for biogas plant operation [4]. Due to the risk of nitrate leakage to underground water and eutrophication in developed countries, the application of nitrogen fertilisers in several regions (nitrate vulnerable zones) is restricted by law. This means the digestate needs to be transported further from the AD plant, incurring additional costs, posing higher biosecurity risks and increasing its environmental impact.

Currently the two main routes preferred for digestate disposal are as fertiliser on agricultural land or landfill disposal. In the UK, commercial AD sites disposed of digestate at a price, while farm operators either offered it to farmers for free (or in some cases at a price) or used it in their own business. The most common method of digestate disposal from industrial plants remains landfilling, which comes at a price (gate fees) and with associated emissions [5].

Energy recovery from digestate has only recently been investigated, starting with the work of Kratzeisen et al. [6] found that burning digestate pellets from farm based AD plants gives slightly lower performance to those of wood pellets, due to the digestates' lower calorific value. Pecchi and Baratieri [7] review the most relevant couplings between the thermal processing technologies and anaerobic digestion, highlighting the lack of economic and environmental studies on this subject. In fact, only the work of Wu et al. [8] investigated the economics of coupling AD with gasification, and performed a preliminary environmental impact evaluation. To the best of the authors knowledge, no study so far has thoroughly investigated the environmental impact of digestate gasification. This paper aims to fill this gap, providing the first life cycle assessment study for the digestate thermal processing via gasification and combined heat and power generation.

2 MATERIALS AND METHODS

2.1 Goal and scope of the study

The main goal of this study is to investigate the environmental impacts of small-scale gasification for digestate valorization and compare them with a reference scenario, digestate land spreading as fertilizer.

For the functional unit, we selected 1 tonne of digestate, to be either spread on agricultural land or processed via gasification.

We neglect the environmental impact of the construction of the thermal processing units, in accordance with other LCA studies and we do not consider capital goods contribution.

We chose an attributional LCA approach, with system expansion to account for the avoided production of fertilizers (in the baseline scenario) and that of the biochar, electrical energy and heat (in the thermal processing scenario).

We performed LCA modelling employing the widely used commercial software SimaPro, for which we selected regional background data specific to the UK, rather than European or global averages, when available.

2.2 Scenario definition

The AD facility analysed is typical for a farm-fed Northern Ireland digester, with a processing capacity of 20, 000 tonnes per year (tpa) for a mix of cattle manure (70% w) and grass silage (30% w).

This AD facility produces 18,665 tpa digestate and a 1,100,590 Nm3/year of biogas (60% v methane and 40% v carbon dioxide) [8].

Digestate spreading on agricultural land

The baseline scenario is spreading whole digestate on agricultural fields surrounding the AD facility.

In line with UK/Northern Ireland legislation outlined in the Nutrients Action Programme, whole digestate can only be spread between February and October and must comply with the nitrogen and phosphorous soil loading limits. Generally, a maximum of 30 m^3 whole digestate can be spread over 1 ha farmland, using low emission slurry spreading equipment [9].

We assume the storage facility for digestate is designed to hold 6 months' worth of digestate (cca 9 500 m^3) in sealed storage tanks, to minimize ammonia and methane emissions. Following best practices in term of digestate storage and application ensures that nutrients are best conserved in the digestate, leading to highest possible fertilizer replacement and minimum emissions during storage.

To apply the stored digestate on agricultural land, the digestate is transported using suitable liquid transport lorries. The digestate transportation to agricultural land was modelled based on current practices, using lorries with a 32t capacity following the EURO 4 emissions directive.

The application of digestate on agricultural land was modelled using the data in the Ecoinvent database for liquid manure spreading using a vacuum tanker, available in SimaPro.

Digestate gasification

For the digestate gasification scenario we propose a digestate gasification installation composed of the following units: a mechanical separator, a belt dryer to reduce digestate moisture, a small scale downdraft gasifier, a gas cleaning system (cyclone plus water scrubber) and an internal combustion engine.

Prior to gasification, the whole digestate is separated into a solid fraction (with a relatively high dry matter content) and a liquid phase (nitrogen-rich but with low solid content). We assume the separation is performed using a decanter centrifuge, as it has a high separation efficiency and can concentrate digestate nutrients in the solid phase.

The solid-liquid separation step reduces significantly the storage requirements, in terms of land occupancy, and associated emissions. The storage period is also significantly shortened (2-3 days), assuming continuous operation of the gasification unit.

Following separation, the solid fraction of the digestate has a large moisture content (70%), which must be reduced to 10%, to ensure suitable gasifier operation. For the drying process, we assume a belt dryer is employed using hot air as a drying agent and evaluate the thermal energy required, using mass and energy balances.

The wet air exiting the dryer will have a high ammonia concentration and as such must be treated before being recycled to the drier, in an ammonia recovery unit using a sulfuric acid solution.

Following the drying process, the digestate is sent to the gasification unit. Due to the relatively low availability of the gasification feedstock (<1 Mt per year of dried solid digestate) we propose that a downdraft gasifier would be a suitable choice. Downdraft gasifiers produce the least amount of tar (compared to other gasifier configurations) and have a simple construction and operation requirements [10].

We model the gasification process using a thermodynamic model proposed and validated in our previous work [11]. Using the mathematical model, we optimize the operating temperature to ensure the CHP unit produces the maximum quantities of heat and electricity.

Following gasification, the ash and char are recovered at the bottom of the gasifier, while the syngas and tar travel further through the cleaning process. We assume that the biochar produced can be sold as soil amendment. For heat recovery purposes, we assume a heat exchanger is placed before the cleaning unit, lowering the syngas temperature to 400 °C, to avoid tar condensation.

The syngas cleaning unit consists of a cyclone, to remove the remaining char and ash particles, and a water scrubber, to ensure the tar concentration is below the allowed limit for CHP engines. Water is recirculated in the scrubbing tower until the tar solubility limit is reached and then sent to a wastewater treatment plant facility.

The clean syngas is then burnt in the internal combustion engine. We assume the heat recovered by the engine can be used on-site in its entirety (heating the AD reactor, digestate drying) and the electricity can be sold to the electrical grid, avoiding the emissions produced by natural gas/electricity mix in the UK.

2.3 Life cycle assessment methodology and data aquisition

A dried digestate sample was obtained from AFBI Hillsborough AD plant, fed with cattle manure and grass silage. Its ultimate and proximate composition was determined in the lab, according to accepted protocols. The nutrient composition for 1 tonne of whole digestate is 3.6 kg N-NH_3, 1.7 kg P_2O_5 and 4.4. K_2O, typical for a farm-fed anaerobic digestion facility [12].

For the land spreading scenario, the emissions derived from digestate storage are computed using the correlations proposed by Styles et al. [13]. The emissions associated with digestate transport are found in SimaPro. We initially assume a transport distance of 5 km and perform a sensitivity analysis to monitor the effects of increasing the transport distance up to 250 km on the scenarios' environmental impact. The emissions to air and water following digestate spreading are computed using literature correlations [13].

For the gasification scenario, the mass and energy fluxes are obtained from mathematical modelling and literature sources, as to the authors' best knowledge no such installation is in operation in Northern Ireland, Figure 1.

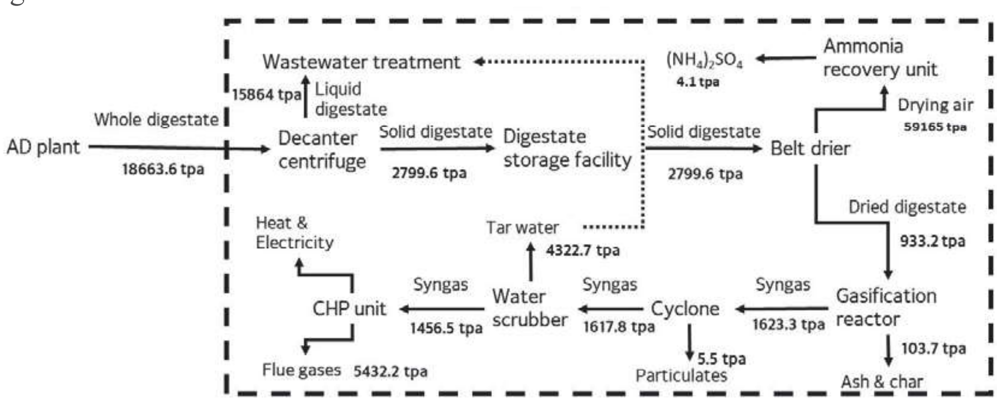

Figure 1. Mass balance for the proposed gasification scenario

The resulting emissions from all scenarios are listed in Table 1.

Table 1. Emission inventory for the two scenarios considered

Scenario 1	**Emissions (per FU)**	**Scenario 1**	**Emissions (per FU)**
Digestate storage	To air CH_4 – 0.02 kg NH_3 - 0.02 kg NOx – 0	Digestate storage	To air CH_4 – 0.0015 kg NH_3 - 0.002 kg
Digestate spreading	To air NH_3 - 0.633 kg N_2O - 0.145 kg To water NO_3- 1.533 kg PO_4 - 0.034 kg	CHP unit	To air CO2 (biogenic)- 56.9 kg CO - 236 g Water vapor – 17.5 kg NO_x – 250 g NMVOC -10 g

Secondary data regarding wastewater treatment, transportation and spreading equipment emissions were taken from the Ecoinvent database implemented in SimaPro.

The two scenarios were evaluated following the ReCiPe 2016 assessment method, available in SimaPro. The endpoint hierarchist method was selected to provide a weighted single score environmental value for each scenario considered, allowing a comparison of their overall environmental impact.

3 RESULTS AND DISCUSSION

The two scenarios are compared and the results are presented in Table 2. The results show that digestate gasification is the environmentally superior treatment, showing negative values (positive environmental impact) in all damage categories: Human Health, Resources and Ecosystems. In contrast, in the best case digestate spreading scenario, only the Resources category shows a positive environmental impact.

Table 2. LCIA results – ReCiPe 2016 endpoint (H) damage assessment

Damage category	Unit	Digestate land spreading (d = 5 km)	Digestate land spreading (d = 100 km)	Digestate land spreading (d = 250 km)	Digestate gasification
Human health	DALY	6.18E-05	9.25E-05	1.41E-04	-2.40E-06
Ecosystems	species.yr	1.66E-07	2.50E-07	3.81E-07	-2.43E-08
Resources	USD2013	-1.23	1.12	4.835	-2.105

The process contributions for each damage category are presented in Figure 2 for the digestate gasification and in Figure 3 for the land spreading scenario.

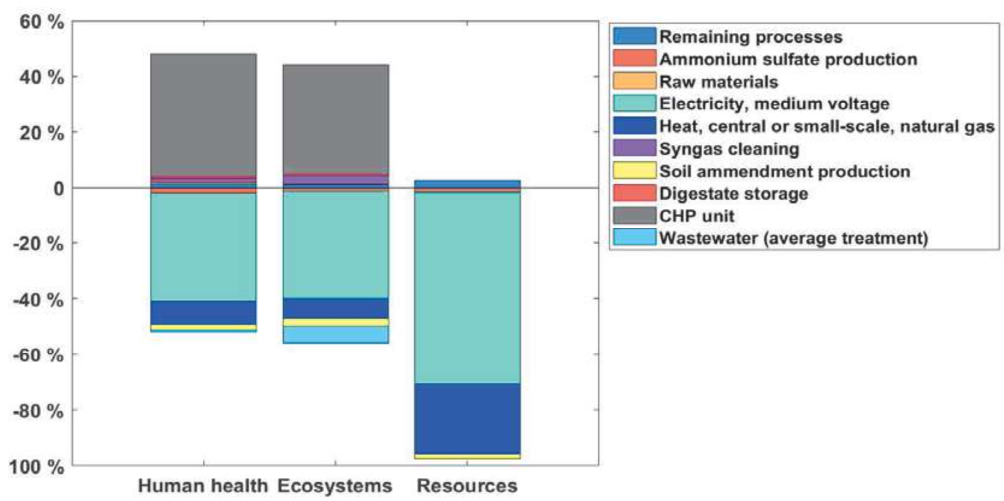

Figure 2. Process contribution for digestate gasification in the damage categories

In the digestate gasification scenario, the avoided production of heat and electricity accounts for most of the negative emissions. By assuming gasification ash and char can be utilized as soil amendment and that the ammonium sulphate produced in the ammonia scrubbing unit can be marketed as fertilizer, this scenario is further improved, albeit only marginally. The wastewater treatment required after digestate centrifuge separation and syngas cleaning has avoided emissions in the Human health and Ecosystems category, more markedly in the latter.
The emissions generated from the CHP unit have the largest contribution to the environmental performance in the Human health and Ecosystems category, where they account for 92% and 89%, respectively of the positive environmental damage contribution.
The syngas cleaning and digestate storage processes account for smaller fractions of the impact (between 3 and 6% and 1%, respectively) in both categories.
For the land spreading, we only present here the optimal scenario, where the digestate is applied on farmlands within a 5 km distance. The avoided production of NPK fertilizers has the most important beneficial impact in each of the damage categories considered. Among them, the avoided production of nitrogen fertilizers has the most significant impact.

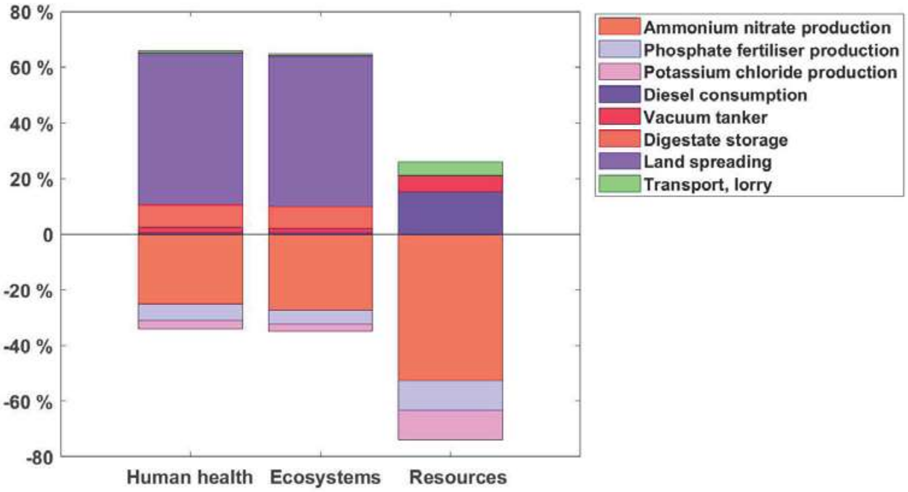

Figure 3. Process contribution for digestate land spreading in the damage categories

The main processes that contribute to the net negative environmental impact in the Human Health and Ecosystems damage categories are the land spreading process (which accounts for the air and water emissions resulting from the application of digestate) and the digestate storage (which is a source of methane and ammonia emissions in this scenario). The impact of digestate transport in these damage categories is negligible, while the operation of the vacuum tanker for fertilizer application also shows small negative impacts. In the Resources category, the lorry transport and vacuum tanker operation still have similar damage indices, but they are more significant, with the greatest contribution made by the consumption of diesel fuel during vacuum tanker operation for digestate application.

4 CONCLUSIONS

The results of the endpoint analysis show that the digestate gasification is superior to digestate land spreading in all damage categories.
For land spreading scenario, the avoided fertilizer production (most significantly that of nitrogen fertilizer) is the highest contributing process to the net damage category score. The prolonged digestate storage and the emissions to both air and water as a result of fertilizer application are the main drawbacks of the analysed scenario, in the Human health and Ecosystems categories. For the Resources damage category, the transportation, vacuum tanker application and associated diesel fuel consumption are the significant contributors to its negative environmental impact.
In the digestate gasification scenario, the avoided heat and electricity production is the process contributing to the positive environmental index in the three damage categories considered by the ReCiPe 2016 endpoint

method. The carbon monoxide, NO_x, SO_2 and particulate matter emissions, resulting from syngas combustion in the CHP unit, are the main processes having a detrimental impact in the Human health and Ecosystems categories.

Although the overall environmental score of the digestate gasification scenario shows a marginally net positive value, it also shows a strong dependency on the heat and electricity mix it displaces. Moreover, the analysis did not consider the emissions from the construction of the gasification plant and the material goods (reactors, pumps, heat exchangers, etc.). From a circular economy point of view, the recovery of digestate nutrients in a more concentrated manner (so they can be safely stored and easily transported) prior to gasification, would significantly improve the environmental impact of gasification.

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IMPACT OF $Ca(OH)_2$ ON THE COMBUSTION PROCESS OF WOODY BIOMASS

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ABSTRACT

To reduce the degradation process in outdoor stored biomass, different additives are discussed. $Ca(OH)_2$ has been applied to increase the the pH value to reduce block the microorganisms' life cycle. In this way the mass loss of the stored biomass could be reduced up to 30 wt% by the addition of 1.5 or 3 wt% additive respectively.

To ensure that no negative effect of an additive on the thermo-chemical conversion of biomass can be expected in commercial scale, combustion tests were provided using a laboratory scale fluidized bed reactor.

Clean poplar wood chips and chips with additive were tested in a bubbling fluidized bed combustion reactor. During these combustion tests, the additive concentration and oxidizing agent amount were varied to observe the gas quality at different conditions. Furthermore, the impact of the additive on agglomeration of the bed material was verified. During the tests, the temperature and pressure was measured continuously, gas sampling and online analysis was provided each 15 minutes.

It was demonstrated that during the combustion of wood chips with or without additive no agglomeration occurred. No other negative effects due to the addition of $Ca(OH)_2$ could be observed.

Keywords: Biomass, Combustion, Additive, Ash melting

1 INTRODUCTION

Woody biomass is a renewable source offering high potential for production of bio-fuels, -chemicals and -energy. Furthermore, the produced bio char could serve as a CCS (carbon capture and storage) medium.

During the outdoor storage, a biodegradation processes in biomass take place based on activity of fungi and bacteria, which leads to mass reduction.[1] This effect is favoured at higher moisture rates. To avoid or minimize these microbial processes, the biomass could be dried. However, the drying process is energy demanding. Thus, an alternative way for reduction of biomass mass losses was chosen. In this case, the biomass (poplar wood chips) was mixed with $Ca(OH)_2$ in different ratios. To ensure, that this additive does not negatively influence further thermo-chemical conversion (e.g. by fluidized bed combustion), the wood chips without additive and with 1,5% and 3% of $Ca(OH)_2$ were tested in $20kW_{fuel\ input}$ bubbling fluidized bed under different operational conditions. In literature[2], similar research has been published mainly for energy grass and not woody biomass [eg. 7].

Furthermore, the woody ash with and without additive was examined using an ash melting microscopy[3]. It was demonstrated that the addition of $Ca(OH)_2$ does not negatively influence ash melting behaviour, ash melting temperature respectively. The effect of additives on thermo-