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Life cycle environmental impacts of substituting food wastes for traditional anaerobic digestion feedstocks.

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In this study, life cycle assessment has been used to evaluate life cycle environmental impacts of substituting traditional anaerobic digestion (AD) feedstocks with food wastes. The results have demonstrated the avoided GHG emissions from substituting traditional AD feedstocks with food waste (avoided GHG-eq emissions of 163.33 CO_2-eq). Additionally, the analysis has included environmental benefits of avoided landfilling of food wastes and digestate use as a substitute for synthetic fertilisers. The analysis of the GHG mitigation benefits of resource management/circular economy policies, namely, the mandating of a ban on the landfilling of food wastes, has demonstrated the very substantial GHG emission reduction that can be achieved by these policy options – 2151.04 kg CO_2 eq per MWh relative to UK Grid. In addition to the reduction in GHG emission, the utilization of food waste for AD instead of landfilling can manage the leak of the nutrients to water resources and eliminate eutrophication impact which occurs typically as the result of field application. The results emphasise the benefits of using life-cycle thinking to underpin policy development and the implications for this are discussed with a particular focus on the analysis of policy development across the climate, renewable energy, resource management and bioeconomy nexus while recommendations are made for future research priorities.

Keynotes:

- LCA of feedstock substitution for biogas production from anaerobic digestion utilising operational data.
- Environmental advantages of biowaste AD vs landfilling for Northern Ireland.
- Sensitivity analysis of key parameters:

(1) Biogas yield of the food waste.

(2) Utilisation of different rates of synthetic fertilisers and digestate produced in the plant.

(3) Distances considered in the food waste model.

- LCA study on biogas utilisation with a focus on informing resource management, bioeconomy and renewable energy policies.

1. Introduction

The need to rapidly reduce greenhouse gas (GHG) emissions, increase renewable energy production and improve resource efficiency has seen the introduction of a range of policies at European, National and Regional levels. With the entry into force of the Paris Climate Agreement in October 2016, the EU has reinforced its 20:20:20 targets of 20% cut in GHG emissions (from 1990 levels), 20% of EU energy from renewables and 20% improvement in energy efficiency (Commission, 2010). In addition, the European Commission has adopted the Communication "Towards a circular economy: a zero waste programme for Europe", which include actions to phase out landfilling of bio-waste by 2015 and show how industrial symbiosis can move us towards zero-waste (Commission, 2014). In Northern Ireland, policies on renewable energy, waste and resource management and climate are driving the development of anaerobic digestion (AD).

Legislative and policy drivers for AD in Northern Ireland.

Renewable energy policy.

The Northern Ireland Renewables Obligation (NIRO) is the main policy instrument for incentivising renewable electricity generation in Northern Ireland. When a business generates renewable energy, they are issued with Renewables Obligation Certificates (ROCs) based on the technology they are using and the amount of energy they produce. (Economy, 2016). This is summarised in Table 1.

<<INSERT TABLE 1>>

Resource management and circular economy policy.

While the key driver to date in the growth of the AD sector has been the policy support for renewable energy, in Northern Ireland (NI) a further driver exists in the form of waste and resource management policy. In 2013 the NI Assembly introduced Food Waste Regulations, which places a duty on food businesses (e.g. businesses involved in food preparation or the sale of food) to present food waste for separate collection from April 2016, bans the landfilling of source separated food wastes and additionally places an obligation on councils to provide receptacles for the separate collection of food waste from households by 1 April 2017 (Ireland, 2015). This has created a strong driver for a project that support the development of circular/bioeconomy policies and research. One example of this, in which the Northern Ireland region was a partner, is the ReNEW project which has demonstrated that more than 13,000 jobs could be created if NI moved to a circular economy, identifying particular opportunities in food and drink, biorefining and the bioeconomy (Mitchell & Doherty, 2015).

Climate change policy.

The NI Executive has published a GHG Reduction Action Plan (Executive, 2011) which has identified actions to reduce GHG emissions. The agri-food sector in NI accounts for a higher proportion of the economy than the UK average, as it is the region's largest employer (Economy, 2017) and accounts for a much higher proportion of the regions total GHG emissions (29% as opposed to 9% in the rest of the UK) (Change, 2011). In addition, the sector has set ambitious growth targets to 2020 (grow sales by 60% to £7bn and sales outside NI by 75%), which will result in a commensurate growth in wastes and GHG's from this sector. The Agri-food sectors Strategic Vision for 2020 includes both the production of low carbon food and the promotion of renewable energy (Board, 2013)

In this context, the production of biogas from AD is receiving increasing attention as a contributor to renewable energy policy and renewable energy (N. Curry & Pillay, 2012), waste and resource management (Davidsson, la Cour Jansen, Appelqvist, Gruvberger, & Hallmer, 2007) and mitigating emissions of GHG's from agriculture and food production (Kaparaju & Rintala, 2011) (J Bacenetti, Duca, Negri, Fusi, & Fiala, 2015) (J Bacenetti et al., 2016).

AD is an established technology in which organic materials are degraded and stabilised under an oxygen free environment. It is aided by microbial organisms to produce biogas, a mixture of methane and carbon dioxide at a ratio of 50-75% and 50-25% respectively, along with trace gases (AEBIOM, 2010). Digestate is also produced in the AD and it is where the most of nutrients remain after the process thus being composed of a mixture of microbial biomass from the digester with multiple applications (Chen, Cheng, & Creamer, 2008).

The most common utilisation option for the biogas is its combustion in a biogas engine to produce electricity and/or heat (Holm-Nielsen, Al Seadi, & Oleskowicz-Popiel, 2009). However, the biogas can also be upgraded for other utilisation options such as biomethane or biodiesel as part of a wider bioenergy system (Murphy, Devlin, Deverell, & McDonnell, 2014), or utilised for producing energy and chemicals within the biorefinery concept (Cherubini, 2010).

However, although AD to biogas has a demonstrated potential to reduce GHG emissions by substituting for fossil fuels, the GHG emission reductions achieved can vary greatly depending on a range of factors such as regional land-use management practises (Dressler, Loewen, & Nelles, 2012), feedstock/s and biogas yields (Alkanok, Demirel, & Onay, 2014) (Nizami, Orozco, Groom, Dieterich, & Murphy, 2012) (Pitk, Kaparaju, Palatsi, Affes, & Vilu, 2013), plant management and efficiency (pre and post-treatment, methane slip (Carrere et al., 2016) (Kondusamy & Kalamdhad, 2014)), and biogas and digestate end uses (Whiting & Azapagic, 2014) (Evangelisti, Lettieri, Borello, & Clift, 2014) (Vázquez-Rowe et al., 2015). On the other hand, other methods of valorisation for manure, like for instance superheated steam drying, have shown lower GHG emissions than AD (Hanifzadeh et al., 2017) which also depends on the local conditions and management possibilities.

This emphasises the need for policies which seek to promote renewable sources of energy, particularly from biogas to be underpinned by evidence based on life-cycle thinking and analysis, to ensure the assumptions underlying the policies are robust (Fiorentino, Ripa, Protano, Hornsby, & Ulgiati, 2015).

Earlier studies

There have been a range of studies carried out on the life-cycle impacts of biogas production and use systems. Examples include comparison of the environmental impacts of AD with energy and organic fertiliser production with incineration, with energy production and landfill with electricity production (Evangelisti et al., 2014) (Astrup, Tonini, Turconi, & Boldrin, 2015), using life cycle assessment to compare the relative greenhouse gas reduction merits of different biomass/bioenergy systems (Thornley, Gilbert, Shackley, & Hammond, 2015), the role of AD in mitigating GHG emissions from the agri-food sector in Italy (J Bacenetti et al., 2015), to assess the environmental performance of two different crop systems in terms of biomethane potential production (Jacopo Bacenetti, Fusi, Negri, Guidetti, & Fiala, 2014), to compare the environmental performance of two alternative bioenergy systems (González-García, Iribarren, Susmozas, Dufour, & Murphy, 2012) and the impacts of regional farming practices on biogas production from maize and the conversion of biogas into electricity (Dressler et al., 2012).

Aims of the study

The overall aim of this study was to evaluate the life cycle environmental impacts of substituting food wastes for traditional anaerobic digestion feedstocks (traditional – maize and grass silage and cattle slurry; and alternative – food wastes). The following underlying objectives underpinned this aim:

- To carry out an integrated analysis of implications for policy development across the climate, renewable energy, resource management and bioeconomy nexus; and
- To gain an understanding of the usefulness of life cycle analysis in evaluating bioenergy and bioeconomy systems and make recommendations for future research priorities.

We believe this work has a number to novel elements relative to previous LCA studies of AD to biogas/bioenergy, including:

- ;
- Analysis based on a full-scale operational biogas/bioenergy facility, using primary data for both plant operation and feedstocks; and
- Inclusion of the avoided emissions from landfilling of food wastes and substitution of digestate for artificial fertilisers.

This paper takes as its starting point a newly operational anaerobic digestion plant in Northern Ireland currently processing maize/grass silage and cattle manure to produce biogas for electricity production and heat and uses life cycle analysis to compare the environmental impacts of the current operation with one processing food wastes. Additionally, the analysis includes a sensitivity analysis of key plant input, operation and production/use assumptions which have previously been demonstrated to have a significant impact of environmental performance, namely, variations in type of food waste and the assumptions made on quantities of biogas produced from each (Alkanok et al., 2014) (Pitk et al., 2013) (Roati et al., 2012) (Browne & Murphy, 2013), digestate treatment and use (Rehl & Müller, 2011) and transportation of feedstock/s.

This is the first study of these characteristics to be developed in Northern Ireland using data from an operational plant. It can be used for the evaluation of the impacts of renewable energy and also be incorporated as a latest best practice guidance for the biogas supply chain including energy and source recovery. This last being met by the section 3.3 where it shown how by utilising part of electricity generated in the plant, emissions are lowered.

2. Methodology

In the current study, LCA has been used to evaluate the environmental impacts of an operational industrial biogas plant in operation in Northern Ireland. The study follows the ISO 14040/14044 standard (ISO, 2006). SimaPro version 8.3 with Ecoinvent database 3.3 has been used to run the life cycle assessment studies. The methodology, plant systems and assumptions are described in detail in the following sections.

2.1. Goal and scope

The goal of the study is to measure the environmental impacts of feedstock substitution on an operational industrial biogas plant in operation in Northern Ireland, currently utilising silage and cattle slurry. For the purposes of the study two scenarios have been created; a baseline scenario of the current plant operation using maize/grass silage and cattle slurry as feedstock and an alternate feedstock scenario comparing the impacts of switching the plant feedstock to food wastes. The plant of study is composed of two anaerobic digesters to produce biogas which then is used in the CHP plant to produce electricity and heat. Part of the electricity and heat are used for self-consumption in the whole plant while the rest of electricity is put into the national grid. The two systems studies are illustrated in Figures 1 and 2

In addition to the two baseline scenarios considered, it was relevant to study the LCA of the landfilling of food waste and the comparison of the source of electricity utilised in the AD plant. On the same way, several sensitivity analyse were performed to evaluate the environmental impact of the biogas yield of the food waste, the utilisation of different rates of synthetic fertilisers and digestate produced in the plant and several distances considered for the food waste model.

Note about functional unit and system boundaries.

Different functional units can be chosen for LCA analysis depending on the scope of the LCA and the intended use of the outputs (for example, to inform policy development). This presents a particular challenge in the evaluation of bioenergy and waste bioenergy systems, where materials move from policy and management of tonnes of waste, to production of energy and products. In the evaluation of two different aspects of the regional impact of biogas production (agricultural processes, with the particular of maize production) and bioenergy production, Dressler et at used two different functional units (kg and kWh) to address this issue (Dressler et al., 2012) while Choudhary et al showed that choice of reference system and functional unit significantly changes the competition between different bioenergy systems (Choudhary et al., 2014). However, since the focus of the evaluation is mitigations of GHG's, the functional unit has been defined as 1 MWh of electricity injected into the electricity grid. Figure 1 shows the system boundary (black lines) for the scenario 1 where maize/grass silage and cattle slurry are used for the production of biogas which is then converted to electricity and heat in a combined heat and power plant. The CHP produced enough electricity to cover the plant necessities and still add the rest into the electricity network. Part of the heat being produced is taken for the heating of the digester. Studies under development are seeking at how to use the rest of the heat which is not being used and currently is just released to the atmosphere.

In scenario 2, food waste is collected and used as a feedstock for the anaerobic digestion replacing maize/ grass silage and cattle slurry. The system boundaries considered are within the black lines in Figure 2.

<<INSERT FIGURES 1 AND 2>>

2.2 Life Cycle Inventory

In this section the inventory data utilised for the life cycle assessment are described as follows.

2.2.1 Baseline scenario: AD-Biogas using grass/maize silage and cattle manure as feedstock.

This is an AD facility using grass/maize silage and cattle slurry as feedstocks. The feedstock is stored in the designated area within the plant and then it is transported from the storage area to the feeding system using a tractor. The feeding system is a Trioliet® hopper and mixer with a maximum capacity of 100 m^3 of feedstock per day. The average operational data from January to April 2016 (actual dates from the 12th January to the 25th of April 2016) show a feedstock of 26.4 tonnes per day of cattle slurry and 19.8 tonne per day of maize/grass silage which is still under the total capacity of the plant (see Table 2). The feedstock goes through the digester feed and macerator and the solid feeding system (Trioliet®) before it is pumped into 2 anaerobic digester tanks of 2850 m^3 of capacity each one. Each digester has a roof mounted gas storage dome for 930 m^3 of biogas. The digesters are agitated and maintained at a temperature of 40°C (mesophilic regime). The average production of heat plus electricity is 17.9 MWh per day which is equivalent to a daily production of biogas of 3498 m^3. Looking at the 46.2 t of feedstock per day, this is translated into a biogas yield of 75.7 m^3 per tonne of feedstock. According to the daily data recorded in the SCADA of the AD plant, the average content of methane in the biogas produced is 51%. The methane yield is 38.6 m^3 per tonne of feedstock.

The digestate produced in the AD tanks is pumped out into a storage facility for being use in the farm as a fertiliser.

Biogas is transferred to the CHP unit which has a total capacity of 500 kW. According to the design specification, the electrical efficiency is 41.3% and the thermal efficiency 42.1%. The average total electricity produced per day is 8880 kWh with a daily export to the grid of 6560 kWh and the rest (2320 kWh/day) is used in the maintenance of the plant. This is equivalent to 74% of electricity output. There is an average daily heat production of 9052 kWh.

The AD plant is located 10 km away from the grass/maize silage production farm while cattle slurry is taken from a farm just beside the AD plant. The potential electrical output is 4.29 GWh per year and the potential heat output is 4.38 GWh per year according to the designer data, although looking at the average production during the evaluated months, it would be 2.4 GWh of electricity production per year and 2.2GWh of heat production per year. The lower performance may have been influenced by longer starting times because the plant had just gone on-line.

Data and assumptions summary

Data used in the model I, which comprises the AD of cattle slurry and silage and the production of electricity and heat in the CHP plant, are summarised in Table 2 below. The data used for the model are an average of the primary data recorded in the operational plant.

<<INSERT TABLE 2>>

2.2.2 Alternate Feedstock Scenario: substitution of the plant feedstock with food wastes

The Alternate Feedstock Scenario takes the existing operational facility and evaluates the impacts of substituting food wastes for grass/maize silage and cattle manure, taking into account estimates of biogas production from wastes taken from literature, which are set out in Table 3.

<<INSERT TABLE 3>>

From the summary of food waste studies provided in Table 3, a biogas yield of 120 m^3 per tonne of food waste was chosen for the baseline. Given the high levels of variability for the estimates of biogas yields from food waste, this was included as one of the sensitivity analysis.

The distance considered for the food waste to travel from the collection point to the AD plant is 100 km in the baseline scenario while another sensitivity analysis considers several distances as it will be shown in the correspond section. **2.2.3. Fossil fuel alternative**

The two production routes using different types of feedstocks, (a) maize/grass silage and cattle slurry and (b) food waste are compared against the impact of 1 MWh of electricity from the NI grid.

3. Life Cycle Impact Assessment results

The AD systems have been modelled using SimaPro LCA software, version 8.3 and the impacts estimated using the ReCiPe method, Midpoint Hierarchical V1.13. Several cases have been studied as presented in next sections.

3.1. Feedstock substitution option

The substitution of silage and cattle slurry by food waste collected in NI for the production of electricity through AD has been compared against the NI grid electricity.

Table 4 summarises the results from all the impact categories considered in the ReCiPe method in SimaPro. The ReCiPe method is the successor of the method Eco-indicator 99 and CML-IA (PRé, 2016). The purpose of this method was the integration of the ‘problem oriented approach’ of CML-IA method and the ‘damage oriented approach’ of the Eco-indicator 99 method. While the ‘problem oriented approach’ defines the impact categories at a midpoint level, the uncertainty of the results is relatively low due to the many different impact categories considered which makes the drawing of conclusions with the obtained results complex. Thus, the damage oriented approach of Eco-indicator 99 method results in only three impact categories which makes the interpretation of the results easier but at a higher uncertainty. The ReCiPe method implements both strategies and has both midpoint (problem oriented) and endpoint (damage oriented) impact categories. The midpoint characterization factors are multiplied by damage factors, to obtain the endpoint characterization values (PRé, 2016).

The ReCiPe method, at the midpoint level, was followed to estimate the 18 impact categories which are addressed as follows: climate change, ozone depletion, terrestrial acidification, fresh water eutrophication, marine eutrophication, human toxicity, photochemical oxidant formation, particulate matter formation, terrestrial ecotoxicity, freshwater ecotoxicity, marine ecotoxicity, ionising radiation, agricultural land occupation, urban land occupation, natural land transformation, water depletion, metal depletion and fossil depletion.

3.1.1. Climate Change

The characterization factor of climate change is the global warming potential (GWP) and the unit is kg CO_2 equivalents. Looking at Table 4, this means that the production of 1MWh of electricity injected into the grid, generates 302 kg of CO_2 eq if the feedstock is grass/maize silage and cattle slurry while the impact drastically decreased when using food waste (139 kg CO_2 eq). The electricity from the grid generates 597 kg of CO_2 eq. This means that the utilisation of electricity from silage and cattle waste could save 296 kg of CO_2 eq per MWh of electricity injected into the grid and 459 of CO_2 eq when using food waste.

The carbon footprint of electricity from silage and cattle slurry is due in a 40% to the production of grass silage, which is the major contributor, being the digestion of the feedstock a 5% of the total. In the food waste case, the impact is reduced because there is no need for the production of crops. On the other hand, the process with a higher contribution to the electricity from food waste is the transport of the food waste from the collection points (households/collection station) to the anaerobic digestion plant (42%). In this case, a value of 100 km distance has been applied which will be discussed further in a sensibility analysis. It can be said here that if the distance is not considered, the global warming potential is reduced to 53.6 kg of CO_2 eq per MWh of electricity injected into the grid.

The results of the impact assessment for GWP has been compared to other studies being difficult to fairly compare them as the feedstock used varies in all cases. For example Dressler et al studied biogas production from maize and its conversion to electricity obtaining emissions of 248 to 281 kg of CO_2 eq per MWh of electricity generated (Dressler et al., 2012) which are not far from the 302 kg of CO_2 eq per MWh of electricity in the case for silage and cattle slurry of our study. Studies performed in Italy for maize silage and pig slurry anaerobic digestion and electricity production showed values ranging from 294 to 350 kg CO_2 eq per MWh of electricity produced (J. Bacenetti, Negri, Fiala, & Gonzalez-Garcia, 2013) which is also ca. 302 kg CO_2 eq per MWh (Table 4).

3.1.2. Ozone depletion potential (ODP).

The characterization factor for ozone layer depletion accounts for the destruction of the stratospheric ozone layer by anthropogenic emissions of ozone depleting substances (ODS). The unit is kg CFC-11 equivalents. For the utilisation of GS + CS, the ozone depletion is 0.33 g of CFC-11 eq while for food waste is very low, being 0.02 of CFC-11 eq respectively.

The higher impact is for the AD of GS + CS utilisation for electricity production. This is caused by the release of halons such as trichloromethane (62%) and dichloromethane (4%) during the combustion of the biogas in the CHP plant (Whiting & Azapagic, 2014). The contribution of this chemicals can be seen in the process contribution graphs obtained from SimaPro 8.3. For the waste food and grid electricity scenarios, the ozone depletion is due to the combustion of fossil fuel in the transport of the food waste (64%) while for the electricity from the grid is seems to be due in a 40% to the natural gas contribution to the NI grid (Government, 2016).

3.1.3. Terrestrial acidification (Acidification Potential, AP)

The terrestrial acidification is measured in kg of SO_2 equivalents per MWh of electricity injected onto the grid and in this case, the utilisation of crops and cattle slurry has a higher impact due to the cultivation of silage (2.54 kg of SO_2 eq) while for food waste (0.53 kg of SO_2 eq) accounts 30% from the transport of the waste and 20% from the electricity production in the CHP plant itself, being the rest due to the digestate spreading considered in the food waste model as well. Electricity from the grid generates 2.75 kg of SO_2 eq per MWh due to the coal production used in the electricity grid mix.

3.1.4. Freshwater and marine eutrophication (Eutrophication potentials, EP).

Eutrophication potentials are measured as the environmental persistence (fate) of the emissions of P containing nutrients for freshwater and N for marine waters. The units are kg of P to freshwater equivalents and kg N to freshwater equivalents. The EPs of the grass/maize silage and cattle feedstock are 0.11 and 0.35 kg of P and N equivalents respectively while for food waste are 0.01 and 0.04 kg of P and N for each. These impacts are majorly due to the production of grass silage and the utilisation of pesticides.

<<INSERT TABLE 4>>

3.1.5. Human toxicity and ecotoxicities.

SimaPro calculates human toxicity and several ecotoxicities, which are terrestrial, freshwater and marine. The characterization factor of human toxicity and ecotoxicities accounts for the environmental persistence (fate) and accumulation in the human food chain (exposure) and toxicity (effect) of a chemical, being the unit used in the 4 cases, kg of 1, 4 - dichlorobenzene (1,4-DCB) equivalent. In this case, the scenario with higher toxicities values is the electricity production from the grid for all cases except the terrestrial ecotoxicity for which crops and cattle electricity is slightly higher. GS + CS (Table 4).

The human toxicity is calculated as 123, 106 and 21 kg of 1,4-DCB eq for grid electricity, GS + CS, and FW respectively. The main process contributor for the GS + CS usage is the utilisation of pesticides while for the other two feedstocks is due to the transport of the feedstocks. The ecotoxicities are all similar for the three scenarios being studied.

3.1.6. Photochemical oxidant formation.

The photochemical oxidant formation factor is defined as the marginal change in an average of 24 h for European concentration of ozone (dC O_3 in kg/m^3) due to a marginal change in emission of substance x (d M_x in kg/year). The unit used to evaluate it is kg NMVOC (Non-methane volatile organic compounds). The photochemical oxidant formation is of the same order for the 3 processes and presents the higher value, 1.52 kg NMVOC per MWh for crops and cattle slurry.

The contributors in this case are the harvesting of the grass/maize (12%), CHP (12%) and pesticide usage (7%) while the 0.63 kg of NMVOC from food waste electricity are majorly due to the transport of the waste (40%) and CHP (30%).

3.1.7. Particulate matter formation.

The particulate matter formation is explained as the intake fraction of PM10 and the unit used is kg PM10 equivalents. In the GS + CS electricity case, it presents the higher value, 1 kg PM10 eq per MWh of electricity injected into the grid and the process that contributes the most is the grass silage production (98%). Grid electricity accounts for 0.81 kg PM10 eq and FW for 0.25 kg PM10 eq per MWh of electricity having major contributions from the usage of coal in the electricity mix (55%) and transport of FW (28%) respectively.

3.1.8. Ionising Radiation.

The ionising radiation as the damage to human health related to the releases of radioactive material to the environment is measured in Becquerel emitted by Uranium 235 equivalent units. The values per MWh of electricity generated are for electricity from GS + CS, 40.8; from FW, 7.5 and from the grid 35 kBq U235 eq.

3.1.9. Agricultural and Urban Land Occupation

This factor measures the amount of either agricultural or urban land occupied by a certain period of time and the unit used to estimate is m^2*annum. In this case, the highest value for agricultural land occupation is for the electricity production from grass/maize silage and cattle slurry (1094 m^2*a) while for food waste is only 1.28 m^2*a and for electricity from the grid is 56 m^2*a. The main contributors are the production of silage (85%), garden waste (9%) as it was considered in a typical household waste mix (9%) and wood chips included in the NI grid mix (24%). For the urban land occupation, the 3 values were similar, 2.8, 3 and 4.6 m^2*a respectively and due to infrastructures created (14% and 85% for silage and cattle slurry and food waste) and due to coal mining (60%) for grid electricity.

3.1.10. Natural Land Transformation

The natural land transformation is the amount of natural land transformed and occupied and the unit is m^2. Table 4 shows how the values are very low for the 3 cases being all considered below 0.2 m^2. The reason for this is that we have not considered the processes to happen in areas considered natural protected parks or similar.

3.1.11. Water, metal and fossil depletion

Water depletion factor is the amount of water consumption and it is measured in m^3 while metal depletion is the decrease of the metal resources and the unit used is kg of Iron (Fe) equivalents. Fossil depletion is characterised by the amount of extracted fossil fuel extracted, based on the lower heating value with the units of kg of oil equivalent (1 kg of oil equivalent has a lower heating value of 42 MJ).

Utilisation of grid electricity and GS + GS electricity have similar values (1.5 vs 2) while FW electricity presents a lower value of 0.3 m^3. Metal depletion is higher for CS + GS electricity 19.6 kg Fe eq versus 4.4 and 4.8 for FW and grid electricity. Fossil depletion is higher 190 for GS + CS and 158 and 35 kg oil eq for grid electricity and FW respectively.

Figure 3 shows the most important environmental impacts of 1 MWh of electricity production into the grid from several sources: (a) grass/maize silage and cattle slurry, (b) food waste and (c) NI grid electricity as in Table 4.

It is clear that the UK biogas sector has an important contribution to waste management, renewable energy generation and nutrient recycling but it requires the cultivation of crops and digestate management (Styles, Dominguez, & Chadwick, 2016). These issues can be avoided if crops used are substituted by food waste and digestate is also utilised as a fertiliser for example (Parkes, Lettieri, & Bogle, 2015).

<<INSERT FIGURE 3>>

3.2. Landfilling of food waste

The environmental impact of landfilling the food waste has been studied in order to evaluate the emission savings of anaerobic digestion of food waste. In many countries biowaste is banned from landfilling being used in composting, incineration and/ or thermal gasification instead (EEA, 2011).

Table 5 summarised the result emission for the cases of (a) food waste anaerobic digestion, (b) landfilling of the food waste and (c) net savings from the usage of food waste for anaerobic digestion and electricity generation through CHP instead of landfilling the waste. To generate 1 MWh of electricity, 4.5 tonne of food waste are utilised so the comparison is done for the disposal to landfill of this amount of food waste.

It is to be mentioned that the disposal as landfilling or as another means of valorisation route for grass/maize silage and cattle slurry has not being considered in the LCA in case of food waste being anaerobically digested and vice versa. The landfilling of food waste was considered independently in contraposition to anaerobic digestion as food waste in Northern Ireland cannot be sent to landfill as a mandatory regulation introduced in the region from April 2016 (Ireland, 2015). In any case, both food waste and grass/maize silage are anaerobically digested in independent facilities as both biowastes need to be valorised.

In the most of the 18 impact categories considered, the anaerobic digestion of food waste has a lower impact. A comparison of both scenarios is shown in Figure 4 as percentage diagram.

The four categories where the savings are higher are global warming potential or climate change, human toxicity and freshwater and marine ecotoxicity. In the case of climate change, there are 139 kg CO_2 eq emitted per MWh of electricity injected into the grid from the AD of food waste. On the other hand, if the waste food is instead sent to landfill, the CO_2 eq emitted is 2290 kg of CO_2 eq for the same amount of waste needed to produce 1 MWh of electricity, this means the savings by producing electricity are 2151 kg of CO_2 eq. In fact, the savings are 478 kg of CO_2 eq per tonne of waste sent to landfill. In the case of human toxicity, 1985 kg of 1,4-DB are saved while for freshwater and marine ecotoxicities, the savings increase to 741 and 636 kg of 1,4-DB eq respectively.

<<INSERT TABLE 5>>

There are 3 categories where the impact of using the food waste to produce electricity through anaerobic digestion has a higher impact, these are ozone depletion and metal and fossil depletion. In a normalised graph like Figure 4 it can be seen that ozone depletion is 10% higher for AD of FW and post electricity production, while metal and fossil depletion are 17% and 0.9% higher.

In the rest of the cases, the landfilling of food waste is more contaminant (the % is more than 50%). As Figure 4 shows, for for freshwater and marine ecotoxicities the landfilling of FW is 99% more contaminant while or FW landfilling is 94% more pollutant for GWP category.

<<INSERT FIGURE 4>>

3.3.Electricity usage in the AD plant (parasitic load)

The plant being evaluated in this article uses part of the electricity and heat generated for self-consumption (parasitic load). A comparison has been done in order to evaluate the environmental impact in the hypothetical case where the plant was using electricity from the grid instead. Table 6 shows how by using the electricity produced in the AD-CHP plant instead of using grid electricity, there are 77 kg of CO_2 eq saved per MWh of electricity injected into the grid. For a production of 6.5 MWh per day as reported in Table 6, 500 kg of CO_2 eq can be saved per day which accounts for 167 tonne of CO_2 eq per year (333 working days per year). Figure 5 represents the percentage diagram for each impact category in both scenarios, where the plant uses the parasitic load from the own plant or where it is imported from the grid.

In the most of the impact categories, the utilisation of electricity from the grid has a higher impact than when electricity is produced in-house (the rate in the % diagram is higher). Only in the case of ozone depletion, marine eutrophication, terrestrial ecotoxicity, agricultural land occupation, natural land transformation and metal depletion, the utilisation of the electricity produced in the plant has a slightly higher impact.

Marine eutrophication and particulate matter formation are of the same order of magnitude. Agricultural land occupation is the category more affected negatively by the AD mainly because of the cultivation of crops.

Looking at Table 6 and Figure 5, the impacts that are higher when using electricity from the grid are the most of them. Being the most relevant the climate change, human toxicity and fossil depletion. Fossil depletion is mainly due to coal and gas contribution to the electricity from the grid fuel mix.

If reduction of carbon emissions is the main target, electricity generated in the AD-CHP plant shall be used. This should be noted as a good practice for policy makers and AD users.

<<INSERT TABLE 6>>

<<INSERT FIGURE 5>>

4. Sensitivity analysis results

Several sensitivity analyses have been done in order to study a few parameters with a high contribution to the environmental impacts. We have studied cases of interest for future studies:

(1) Biogas yield of the food waste.

(2) Utilisation of different rates of synthetic fertilisers and digestate produced in the plant.

(3) Distances considered in the food waste model.

1) Comparison of different biogas yields from food waste.

As summarised in Table 3, anaerobic digestion of food waste (FW) can have a wide range of yield to biogas production. A sensitivity analysis has been considered for a few yields from 90 to 150 m^3 of biogas per tonne of food waste. In the base scenario considered in section 3, 120 m^3 biogas/tonne of FW was considered.

As Table 7 and Figure 6 summarises, the environmental impact decreases when the biogas yield is higher in all the categories. This means that reaching a high performance of the AD process can help to increment the plant income due to electricity generation and posterior injection into the grid but it also better from the environmental point of view.

Biogas yields have been reported to increase with co-digestion of different substrates like crops, manures and food waste in different ratios. Lin and co-workers (Lin et al., 2011) reported a higher biogas production from the co-digestion of food and vegetable waste. Alatriste- Mondagrón (Alatriste-Mondragon, Samar, Cox, Ahring, & Iranpour, 2006) summarised the main advantages of co-digestion of bio-wastes as (1) increase in the methane production yield due to mixed supply of additional nutrients form co-substrates; (2) utilisation of equipment in a more efficient way; and (3) sharing of the costs by processing all waste streams in the same facility. Others have exposed the improvement in the biogas yield by using pre-treatments of the waste as ultrasonic systems (Castrillon, Fernandez-Nava, Ormaechea, & Maranon, 2011) (Zou, Wang, Chen, Wan, & Feng, 2016). However, utilisation of ultrasound or other systems is out of the scope of this work.

<<INSERT TABLE 7>>

<<INSERT FIGURE 6>>

2) Utilisation of different rates of synthetic fertilisers and digestate produced in the plant.

The cultivation of grass and maize silage requires the utilisation of fertilisers. In order to explore the effect of synthetic fertiliser utilisation, the proportion of fertiliser used with the replacement of digestate (produced in the AD plant) was studied as shown in Table 8 and Figure 7. The effect of using digestate instead of imported fertilisers affects the most over the climate change or global warming potential impact category. This is because of impact of the fertilisers on CO_2 emissions.

In Table 8 and Figure 7, there are 7 cases considered being (1) the case where there is not any fertiliser used, so 100% of the nutrients are provided by digestate utilisation. Case (2) is when a 5% of fertilisers is used; (3) means the utilisation of 10% of fertilisers and 90% of digestate; (4) 25% of fertilisers; (5) 50% fertilisers; (6) 75% fertilisers and case (7) only considers the utilisation of fertilisers in a 100%.

The baseline scenario considered in the general model (Table 4) was the case (4) where 25% of the nutrient required for the maize and grass cultivation is coming from imported fertilisers and the rest from digestate spreading. The digestate used is produced through the anaerobic digestion of grass/maize silage, cattle slurry or food wastes.

As Table 8 and Figure 7 show by using only digestate compared to the base scenario, 286 kg of CO_2 eq are being emitted compared to 302 which is a saving of 16 kg of CO_2 eq per MWh of electricity injected into the grid. The savings would arise to 106 kg of CO_2 eq for a day of operation in the plant and for 35 tonne of CO_2 eq per year. As it is summarised the impact category affected by differences in digestate/fertiliser rates is the global warming potential.

Digestate which represents the unconverted organic material remaining in the digester after AD is usually kept in liquid and solid storage tanks. These are covered in order to prevent emissions of greenhouse gases in the form of methane and ammonia. To use the digestate as a fertilizer, it has to satisfy the requirements from the PAS110 certificate. The digestate as a fertilizer has reduced number of pathogens, which will enhance the effectiveness of fertilization (Weiland 2010). Digestate can be a more economical and carbon-friendly alternative to synthetically produced fertilisers (Walsh, Jones et al. 2012). It also has an advantage over synthetic fertilizers in that it can improve soil quality and crop yields over the long term. A downside to using the digestate as a fertiliser is that the composition is variable whereas the mix of nutrients in artificial fertilisers can be predetermined and altered. If the digestate is landfilled it would be wasteful of the valuable components contained but in areas where there is a high risk of eutrophication, it could be a better option for the environment. It should be considered that additional charges would be made for the disposal of the digestate to landfill.

<<INSERT TABLE 8>>

<<INSERT FIGURE 7>>

3) Food waste model: distance of collection sensitivity analysis.

The process with higher environmental impact in the anaerobic digestion of food waste was in general the distance from the collection of food waste to the AD plant. For the baseline model, a distance of 100 km was assumed and it was though as a parameter to be studied further. The reasonable distance value for food transportation of the current case study is 100 km as NI is a small region and the AD plant can take the feed from all over it.

A sensitivity analysis has been considered for a range of distances starting for the 0 km case to 200 km. As Table 9 and Figure 8 summarises, and it would be though, environmental impact increases with distance for all the categories considered. The impact category affected in a higher percentage by the transport of the food waste is the GWP which for a distance of 0 km is 53 kg CO_2 eq rising to 225 kg of CO_2 eq per MWh of electricity injected into the grid for a FW transported 200 km. This shows the importance of consideration of location of the FW collection points and AD plants. Figure 9 plots a visual image of the GWP for several distances studied.

<<INSERT TABLE 9>>

<<INSERT FIGURE 8>>

<<INSERT FIGURE 9>>

5. Discussion and conclusions

In order to summarise the main results of the paper, Table 10 shows the global warming potential and the carbon savings for the main scenarios created using values from the UK Government GHG Conversion Factors. While the utilisation of grass/maize silage and cattle slurry through AD and CHP for electricity production would save 109 kg of CO_2 eq per MWh of electricity injected into the grid respect using grid electricity, the utilisation of food waste would save 272 kg of CO_2 eq. The utilisation of AD to produce electricity instead of the disposal to landfill can save up to 2151 kg of CO_2 eq per MWh of electricity injected into the grid which accounts for 478 kg of CO_2 eq per tonne of waste disposed. If the digestate is utilised for soil fertiliser, 65.45 kg of CO_2 eq per MWh of electricity injected into the grid can be saved. If we account for landfill plus fertiliser savings, they go up to 2216 kg of CO_2 eq per MWh of electricity.

<<INSERT TABLE 10>>

Ecoinvent data for Great Britain and Northern Ireland were used to calculate the GHG emission savings using a model in SimaPro 8.3 (Table 4). It is to note that if instead, the values from the UK Government GHG Conversion Factors (Table 10) are used to evaluate the carbon dioxide emissions the values for grid electricity are lower. This means that the savings by using AD of biogas to produce electricity are lower as well.

As set in Section 1, in common with many other European Countries and Regions, Northern Ireland has a subsidy framework for renewable energy, which includes electricity generation via biogas from anaerobic digestion, and this has stimulated the development of the AD sector in Northern Ireland. The results of this study have quantified the emissions from electricity produced from biogas from AD and the avoided GHG-eq emissions, relative to grid electricity, for traditional feedstocks and food waste.

This has demonstrated additional avoided GHG emissions from substituting traditional AD feedstocks with food waste (an increase of avoided GHG-eq emissions of 163.33 CO_2-eq), which supports the conclusions of other researchers studying GHG mitigation from slurry and food waste (Styles et al., 2015). Other benefits include a substantial reduction agricultural land occupation (from 1094.75 to 1.28 m^2a), and reductions in impacts across all other impact categories.

A note on estimates of UK grid electricity kg CO_2 eq per MWh.

The results presented in this paper for avoided GHG emissions have used the UK Governments ‘Greenhouse gas reporting – Conversion factors 2016’ as the baseline for the estimates (412.05 kg CO2 eq per MWh). However, the results presented in Table 4 for UK Grid GHG intensity are from the SimaPro model/Ecoinvent, which result in a substantially higher grid intensity of 597 kg CO_2 eq per MWh, an additional 185 kg CO_2 eq per MWh. The most obvious explanation for this is that the SimaPro models estimates include indirect GHG emissions (for example, embodied GHG’s in grid infrastructure), however, this is an area that requires further research to establish precisely why the estimates differ by such a substantial amount.

The analysis of the GHG mitigation benefits of resource management namely, the mandating of a ban on the landfilling of food wastes, has demonstrated the very substantial GHG emission reduction that can be achieved by the policy options – 2151.04 kg CO_2 eq per MWh relative to UK Grid. This is of an order of magnitude greater than the GHG mitigation achieved by the both renewable energy options. This emphasises the need for an integrated approach to policies on GHG reduction which includes resource management and agri-food, in addition to renewable energy (see below).

The analysis of the electricity usage in the plant (parasitic load) demonstrated that considerable GHG savings could be made from using electricity generated by the plant instead of grid electricity (-77.61 kg CO_2 eq per MWh), and this has important implications for policy makers and plant operators.

Sensitivity analysis.

The comparison of different biogas yield estimates for food waste taken from a range of sources highlights the very substantial variations in yield estimates made by different authors, an issue raised by other researchers looking at feedstocks for biogas production (Lijó, González-García, Bacenetti, & Moreira, 2017). This highlights the need for guidance from regulators and further research into the harmonisation of methods.

The comparison of different utilisation rates of synthetic fertilisers and digestate from the plant demonstrated potential savings of 65.45 kg CO_2 eq per MWh, although this was more limited at the operational facility, as substantial use was already being made of cattle slurry for nutrient management.

This would have greater relevance for countries or regions with low nutrient reserves, where high levels of synthetic fertiliser use is required. The environmental benefits of the variety of processing pathways for AD digestate is an area that has, to date, been comparatively under-researched, and we make specific recommendations for this area below.

The comparison of different transport distances for the food waste demonstrated the importance of taking into account regional/local issues when developing policies on renewable energy and resource management. Scenario 2 (transport distance 50 km) demonstrated 96.52 kg CO_2-eq per MWh emissions, very close to the reductions in emissions achieved by traditional grass silage and cattle slurry production (109.28). Scenario 4 (transport distance 200 km) demonstrated 225.27 kg CO_2-eq per MWh emissions, very close to the reductions in emissions achieved by food waste electricity generation. While this figure may appear unrealistic, consultations with the AD plant operator suggested that this usually depended on contractual and economic factors, and that some plants were already importing waste from the Republic of Ireland, with transport distances in excess of 200 km (Cromie, 2017).This is supported by the work of other researchers who have highlighted feedstock transport as a critical factor, particularly as plant sizes increase (Jacopo Bacenetti, Negri, Fiala, & González-García, 2013).

Summary

The overall aim of this study was to evaluate the life cycle environmental impacts of substituting food wastes for traditional anaerobic digestion feedstocks (traditional – maize and grass silage and cattle slurry; and alternative – food wastes), with the underlying objectives of integrated analysis of implications for policy development across the climate, renewable energy, resource management and bioeconomy nexus and to gain an understanding of the usefulness of life cycle analysis and make recommendations for future research priorities.

The evaluation of the impacts of substitution of food wastes for traditional feedstocks in an operational AD plant, has demonstrated that the application of policies that direct food wastes to AD like the policy introduced in Northern Ireland which banned all biowaste form being landfilled (Ireland, 2015), have demonstrated environmental benefits in terms of renewable energy and GHG mitigation. However, it also highlighted the need for an integrated approach to such analysis, to include the assessment of waste and resource management policies, as the largest savings in GHG emissions derived from avoided disposal of food wastes, rather than generation of renewable energy. One important area of uncertainty was the estimation of reductions in GHG emissions relative to UK grid electricity and this is addressed in below.

The sensitivity analysis of biogas yields highlighted the wide variations in yield estimates from the literature, while the analysis of digestate use again highlighted high levels of variation, depending largely on local/regional variations in synthetic fertiliser use. The analysis of transport distances supported the work of other researchers who have highlighted this as potentially significant.

Finally, we conclude that the research has demonstrated the benefits of using LCA modelling to underpin policy making in renewable energy, climate change and waste and resource management, and further, showed the need for such policies to evaluated in an integrated manner, if GHG mitigation and other wider environmental benefits are to be optimised. We believe the policies which ban the disposal of FW to landfill are important and are supported by studies like this one which verifies and confirm the lower emissions of pollutants from new FW valorisation options as AD. From this, we would set out the following recommendations for future research priorities, in this important and rapidly developing research area.

Recommendations for future research priorities

Research into the development of guidance for the design and evaluation of the environmental biogas/bioenergy systems, which includes:

- Feedstock transport distances; and
- Avoided waste/resource management impacts.

Research into digestate utilisation pathways and integrated/systems analysis of feedstock/bioenergy/biomaterial flows using the emerging anaerobic Biorefinery concept (R. Curry, Camacho, & Cromie, 2017); and

Research into synergies between feedstocks for AD and feedstocks for other bioeconomy processes, including gasification/pyrolysis, fermentation and algae.

The authors hope that the issues identified and discussed in this paper can provide insights for other researchers and help set out the priorities for research to support this important research and policy area.

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TABLES AND FIGURES

Table 1. Renewables Obligation Northern Ireland – current banding levels (2016).

Technology		Banding Level
Solar PV	< 50kW	4 ROCs
	50kW – 5MW	2 ROCs
Wind	< 250kW	4 ROCs
	250kW – 5MW	1 ROC
Hydro	< 20kW	4 ROCs
	20kW – 250kW	3 ROCs
	250kW – 1MW	2 ROCs
	1MW – 5MW	1 ROC
Biomass	< 50kW	2 ROCs
	50kW – 5MW	1.5 ROCs
Anaerobic Digestion	< 50kW	4 ROCs
	50kW – 500kW	4 ROCs
	500kW – 5MW	3 ROCs

Reproduced from http://greenbusinesswatch.co.uk/feed-in-tariff-in-northern-ireland-niro

Table 2. Summary of data and data sources for modelling scenario 1.

Data	Amount	Source
Inputs to AD plant		
Cattle slurry	26.4 tonne per day	AD plant owner
Maize/Grass silage	19.8 tonne per day	AD plant owner
Heat (from CHP)	3017 kWh per day	AD plant designer
Electricity (from CHP)	2320 kWh per day	AD plant owner
Outputs from AD plant/CHP plant		
Biogas	3498 m^3/day	AD plant owner
Digestate	5494.4 m^3 over 3.5 months	AD plant owner
Electricity total	8880 kWh per day	AD plant owner
Electricity to grid	6560 kWh per day	AD plant owner
Heat	9052 kWh per day	AD plant owner

Table 3. Estimates of biogas production from food waste from different sources.

No.	**Reference**	**Location**	**Biogas produced**
1	(Zhang et al., 2007)	USA	143.8 m^3/tonne feedstock
2	(Banks, Chesshire, & Stringfellow, 2008)	UK	140 m^3/tonne feedstock
3	(Pöschl, Ward, & Owende, 2010)	Germany	123.2 m^3/tonne feedstock
4	(Banks, Chesshire, Heaven, & Arnold, 2011)	UK	156 m^3/tonne feedstock
5	(Jin, Chen, Chen, & Yu, 2015)	China	44.8 m^3/tonne feedstock
Summary	**Range**	**N/A**	**44.8-156 m^3/tonne feedstock**

Table 4. Environmental Impacts of 1 MWh of electricity production into the grid from several sources: (a) Northern Ireland grid (NI Grid); (b) grass/maize silage (GS + CS) and cattle slurry; and (c) food waste (FW).

No.	Impact category	Unit	(a) NI Grid	(b) GS+CS	(c) FW
1	Climate change	kg CO_2 eq	597.11	302.77	139.44
2	Ozone depletion	kg CFC-11 eq	0.00001	0.00033	0.00002
3	Terrestrial acidification	kg SO_2 eq	2.75	2.54	0.53
4	Freshwater eutrophication	kg P eq	0.19	0.11	0.01
5	Marine eutrophication	kg N eq	0.09	0.35	0.04
6	Human toxicity	kg 1,4-DCB eq	123.73	106.12	21.64
7	Photochemical oxidant formation	kg NMVOC	1.23	1.52	0.63
8	Particulate matter formation	kg PM10 eq	0.80	1.00	0.25
9	Terrestrial ecotoxicity	kg 1,4-DCB eq	0.01	0.13	0.03
10	Freshwater ecotoxicity	kg 1,4-DCB eq	3.40	2.63	0.40
11	Marine ecotoxicity	kg 1,4-DCB eq	3.39	2.44	0.52
12	Ionising radiation	kBq U235 eq	35.71	40.80	7.57
13	Agricultural land occupation	m^2a	55.97	1094.75	1.28
14	Urban land occupation	m^2a	4.56	2.80	2.96
15	Natural land transformation	m^2	0.09	0.17	0.03
16	Water depletion	m^3	1.47	1.97	0.30
17	Metal depletion	kg Fe eq	4.79	19.64	4.44
18	Fossil depletion	kg oil eq	158.06	190.24	35.90

Table 5. Environmental Impacts of: (a) 1MWh of electricity production from food waste; (b) food waste landfilling; (c) net savings from (a) over (b) per MWh of electricity; and (d) net savings from (a) over (b) per tonne of food waste.

No.	Impact category	Unit	(a) AD of FW	(b) Landfill of FW	(c) Net savings AD of FW (per MWh of electricity).	(d) Net savings AD of FW (per tonne of waste)
1	Climate change	kg CO_2 eq	139.44	2290.48	-2151.04	-478.01
2	Ozone depletion	kg CFC-11 eq	0.000016	0.000014	0.000002	0.000000
3	Terrestrial acidification	kg SO_2 eq	0.53	1.15	-0.62	-0.14
4	Freshwater eutrophication	kg P eq	0.01	0.08	-0.07	-0.02
5	Marine eutrophication	kg N eq	0.04	12.73	-12.70	-2.82
6	Human toxicity	kg 1,4-DB eq	21.64	2006.83	-1985.18	-441.15
7	Photochemical oxidant formation	kg NMVOC	0.63	1.68	-1.05	-0.23
8	Particulate matter formation	kg PM10 eq	0.25	0.58	-0.33	-0.07
9	Terrestrial ecotoxicity	kg 1,4-DB eq	0.03	0.05	-0.02	-0.01
10	Freshwater ecotoxicity	kg 1,4-DB eq	0.40	741.40	-741.00	-164.67
11	Marine ecotoxicity	kg 1,4-DB eq	0.52	637.39	-636.88	-141.53
12	Ionising radiation	kBq U235 eq	7.57	10.38	-2.80	-0.62
13	Agricultural land occupation	m^2a	1.28	6.17	-4.89	-1.09
14	Urban land occupation	m^2a	2.96	17.34	-14.37	-3.19
15	Natural land transformation	m^2	0.03	0.19	-0.16	-0.04
16	Water depletion	m^3	0.30	1.52	-1.22	-0.27
17	Metal depletion	kg Fe eq	4.44	3.68	0.76	0.17
18	Fossil depletion	kg oil eq	35.90	35.58	0.32	0.07

Table 6. Environmental Impacts of: (a) 1 MWh of electricity production from GS + CS, (b) GS + CS using electricity from the grid and (c) net savings from (a) over (b).

No.	Impact category	Unit	(a) GS + CS	(b) GS + CS *Grid electricity	(c) Net savings
1	Climate change	kg CO_2 eq	302.77	380.38	-77.61
2	Ozone depletion	kg CFC-11 eq	0.00033	0.00030	0.00003
3	Terrestrial acidification	kg SO_2 eq	2.54	2.68	-0.15
4	Freshwater eutrophication	kg P eq	0.11	0.12	-0.01
5	Marine eutrophication	kg N eq	0.35	0.32	0.03
6	Human toxicity	kg 1,4-DB eq	106.12	112.96	-6.85
7	Photochemical oxidant formation	kg NMVOC	1.52	1.54	-0.02
8	Particulate matter formation	kg PM10 eq	1.00	1.01	-0.01
9	Terrestrial ecotoxicity	kg 1,4-DB eq	0.13	0.12	0.01
10	Freshwater ecotoxicity	kg 1,4-DB eq	2.63	2.91	-0.28
11	Marine ecotoxicity	kg 1,4-DB eq	2.44	2.66	-0.23
12	Ionising radiation	kBq U235 eq	40.80	66.12	-25.32
13	Agricultural land occupation	m^2a	1094.75	977.44	117.31
14	Urban land occupation	m^2a	2.80	3.06	-0.27
15	Natural land transformation	m^2	0.17	0.16	0.00
16	Water depletion	m^3	1.97	2.02	-0.05
17	Metal depletion	kg Fe eq	19.64	18.53	1.11
18	Fossil depletion	kg oil eq	190.24	201.43	-11.19

Table 7. Sensitivity analysis assuming different biogas yields.

No.	Impact category	Unit	1	2	3	4
1	Climate change	kg CO_2 eq	168.03	156.60	139.44	122.27
2	Ozone depletion	kg CFC-11 eq	0.00002	0.00002	0.00002	0.00001
3	Terrestrial acidification	kg SO_2 eq	0.67	0.61	0.53	0.45
4	Freshwater eutrophication	kg P eq	0.01	0.01	0.01	0.01
5	Marine eutrophication	kg N eq	0.05	0.04	0.04	0.03
6	Human toxicity	kg 1,4-DB eq	28.82	25.95	21.64	17.34
7	Photochemical oxidant formation	kg NMVOC	0.77	0.72	0.63	0.55
8	Particulate matter formation	kg PM10 eq	0.32	0.29	0.25	0.21
9	Terrestrial ecotoxicity	kg 1,4-DB eq	0.03	0.03	0.03	0.02
10	Freshwater ecotoxicity	kg 1,4-DB eq	0.53	0.48	0.40	0.32
11	Marine ecotoxicity	kg 1,4-DB eq	0.69	0.62	0.52	0.41
12	Ionising radiation	kBq U235 eq	9.88	8.96	7.57	6.19
13	Agricultural land occupation	m^2a	1.71	1.53	1.28	1.02
14	Urban land occupation	m^2a	3.95	3.56	2.96	2.37
15	Natural land transformation	m^2	0.04	0.04	0.03	0.03
16	Water depletion	m^3	0.38	0.35	0.30	0.24
17	Metal depletion	kg Fe eq	5.92	5.33	4.44	3.56
18	Fossil depletion	kg oil eq	45.98	41.95	35.90	29.86

(1) Yield: 90 m^3 of biogas produced per tonne of food waste

(2) Yield: 100 m^3 of biogas produced per tonne of food waste

(3) Yield: 120 m^3 of biogas produced per tonne of food waste

(4) Yield: 150 m^3 of biogas produced per tonne of food waste

Table 8. Sensitivity analysis assuming different fertiliser/digestate rate utilisation.

Impact category	Unit	1	2	3	4	5	6	7
Climate change	kg CO_2 eq	286.41	289.68	292.95	302.77	319.13	335.50	351.86
Ozone depletion	kg CFC-11 eq	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003
Terrestrial acidification	kg SO_2 eq	2.45	2.47	2.48	2.54	2.62	2.71	2.80
Freshwater eutrophication	kg P eq	0.10	0.10	0.10	0.11	0.11	0.12	0.12
Marine eutrophication	kg N eq	0.34	0.34	0.34	0.35	0.35	0.36	0.36
Human toxicity	kg 1,4-DB eq	100.65	101.74	102.84	106.12	111.58	117.05	122.51
Photochemical oxidant formation	kg NMVOC	1.48	1.49	1.50	1.52	1.56	1.60	1.65
Particulate matter formation	kg PM10 eq	0.97	0.97	0.98	1.00	1.03	1.06	1.10
Terrestrial ecotoxicity	kg 1,4-DB eq	0.10	0.11	0.11	0.13	0.15	0.18	0.20
Freshwater ecotoxicity	kg 1,4-DB eq	2.51	2.53	2.56	2.63	2.76	2.89	3.01
Marine ecotoxicity	kg 1,4-DB eq	2.31	2.34	2.36	2.44	2.56	2.69	2.81
Ionising radiation	kBq U235 eq	40.03	40.18	40.34	40.80	41.57	42.35	43.12
Agricultural land occupation	m^2a	1093.93	1094.09	1094.26	1094.75	1095.58	1096.41	1097.24
Urban land occupation	m^2a	2.47	2.53	2.60	2.80	3.12	3.45	3.78
Natural land transformation	m^2	0.16	0.16	0.17	0.17	0.17	0.17	0.18
Water depletion	m^3	1.72	1.77	1.82	1.97	2.23	2.48	2.74
Metal depletion	kg Fe eq	18.59	18.80	19.01	19.64	20.69	21.75	22.80
Fossil depletion	kg oil eq	187.19	187.80	188.41	190.24	193.29	196.35	199.40

(1) 0% of fertilisers and 100% of digestate used

(2) 5% of fertilisers and 95% of digestate used

(3) 10% of fertilisers and 90% of digestate used

(4) 25% of fertilisers and 75% of digestate used (baseline)

(5) 50% of fertilisers and 50% of digestate used

(6) 75% of fertilisers and 25% of digestate used

(7) 100% of fertilisers and 0% of digestate used

Table 9. Sensitivity analysis for different transport distances of the food waste.

No.	Impact category	Unit	1	2	3	4
1	Climate change	kg CO_2 eq	53.61	96.52	139.44	225.27
2	Ozone depletion	kg CFC-11 eq	0.000001	0.000008	0.000016	0.000031
3	Terrestrial acidification	kg SO_2 eq	0.21	0.37	0.53	0.85
4	Freshwater eutrophication	kg P eq	0.00	0.00	0.01	0.02
5	Marine eutrophication	kg N eq	0.02	0.03	0.04	0.05
6	Human toxicity	kg 1,4-DB eq	0.10	10.87	21.64	43.19
7	Photochemical oxidant formation	kg NMVOC	0.22	0.43	0.63	1.04
8	Particulate matter formation	kg PM10 eq	0.09	0.17	0.25	0.40
9	Terrestrial ecotoxicity	kg 1,4-DB eq	0.00	0.01	0.03	0.05
10	Freshwater ecotoxicity	kg 1,4-DB eq	0.00	0.20	0.40	0.80
11	Marine ecotoxicity	kg 1,4-DB eq	0.00	0.26	0.52	1.04
12	Ionising radiation	kBq U235 eq	0.64	4.11	7.57	14.51
13	Agricultural land occupation	m^2a	0.00	0.64	1.28	2.56
14	Urban land occupation	m^2a	0.00	1.48	2.96	5.93
15	Natural land transformation	m^2	0.00	0.02	0.03	0.06
16	Water depletion	m^3	0.03	0.16	0.30	0.56
17	Metal depletion	kg Fe eq	0.00	2.22	4.44	8.88
18	Fossil depletion	kg oil eq	5.67	20.79	35.90	66.14

(1) Distance from collection point to AD plant: 0 km.

(2) Distance from collection point to AD plant: 50 km

(3) Distance from collection point to AD plant: 100 km

(4) Distance from collection point to AD plant: 200 km

Table 10. Summary of main savings or avoided GHG emissions (UK Government GHG Conversion Factors).

	Summary	Avoided GHG emissions [kg CO_2 eq per MWh of electricity]
	UK Grid Electricity (Department for Business, 2016)	412.05
1	GS+CS Electricity	-109.28 (236.5 t CO_2 eq per year)
2	FW Electricity	-272.61 (590 t CO_2 eq per year)
2a	FW Electricity + Avoided Landfill of FW	-2151.04*
2b	FW Electricity + Avoided Landfill of FW + digestate spreading	-2216.49
3	Digestate spreading	-65.45

1, 2: Avoided GHG emissions respect the utilisation of grid electricity (412.05 kg CO_2 eq per MWh of electricity, calculation being (1) 302.77 – 412.05= -109.28 and (2) 139.44 – 412.05= - 272.61)

For a year: (1) 106.8*6.5*333= 236.5 t CO_2 eq and (2) 270.13*6.5*333= 590 t CO_2 eq.

2a: Landfill of food waste has a GWP of 2290.48 kg CO_2 eq per MWh of electricity (calculation is as follows: 139.44 – 2290.48 = - 2151.04)

* This corresponds to 478 kg CO_2 eq per tonne of waste→ similar to WRAP value of 523 kg of CO_2 per tonne of waste

2b: Calculation is: -2151.04 + (-65.45) = - 2216.49

3: Digestate spreading GHG savings have been assumed as the difference between 0% and 100% rate utilization of fertilisers in sensitivity analysis (section 4 of this research paper): 286.41 – 351.86 = - 65.45

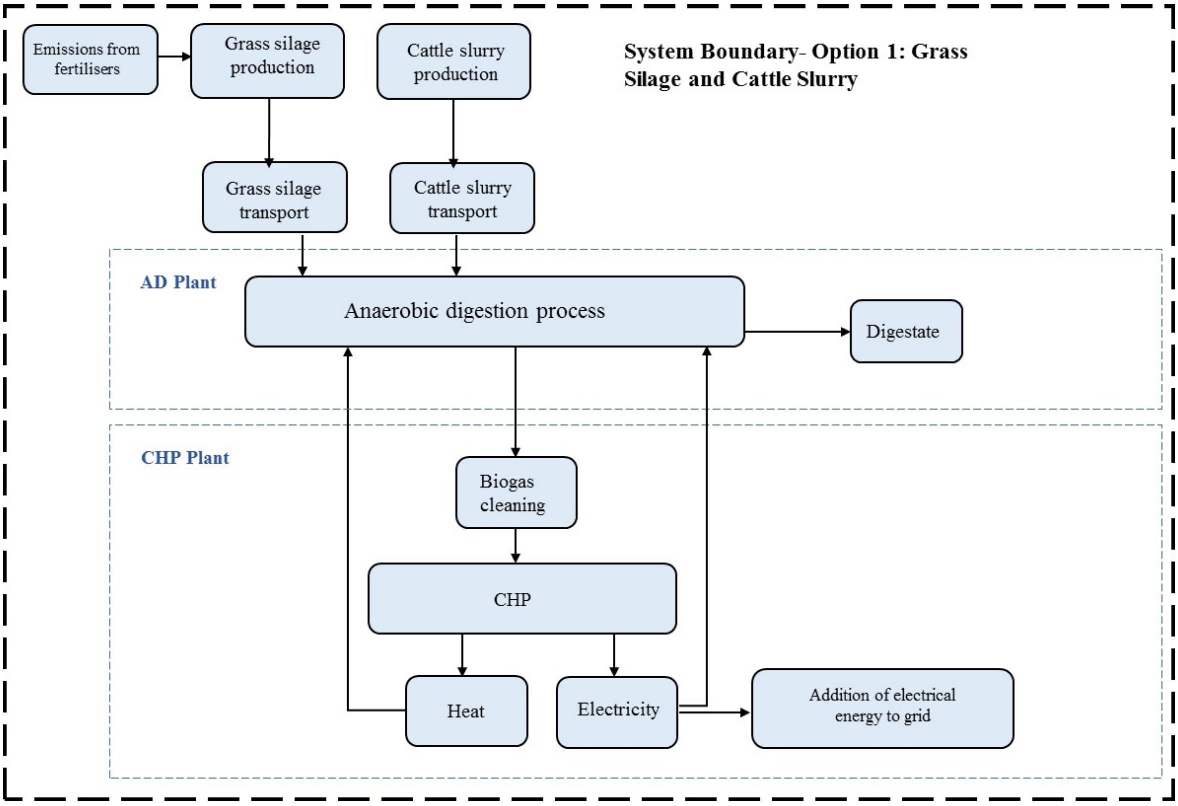

Figure 1. System boundary for baseline scenario

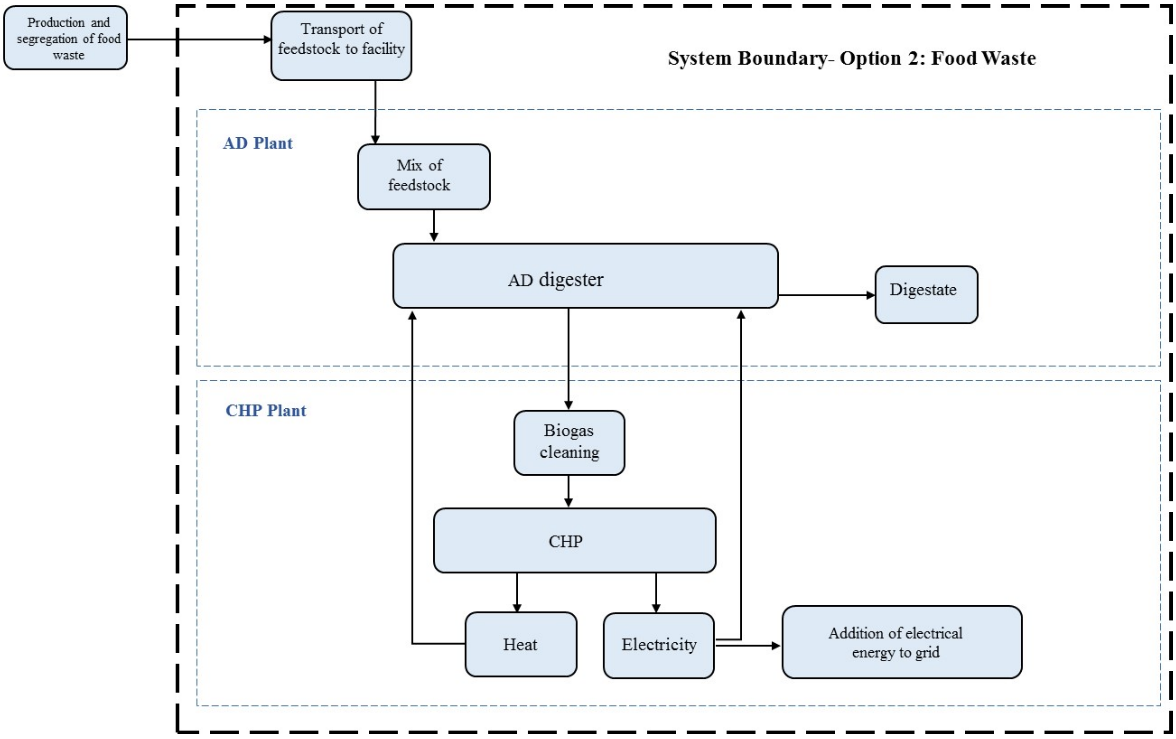

Figure 2. System boundary for alternate feedstock scenario.

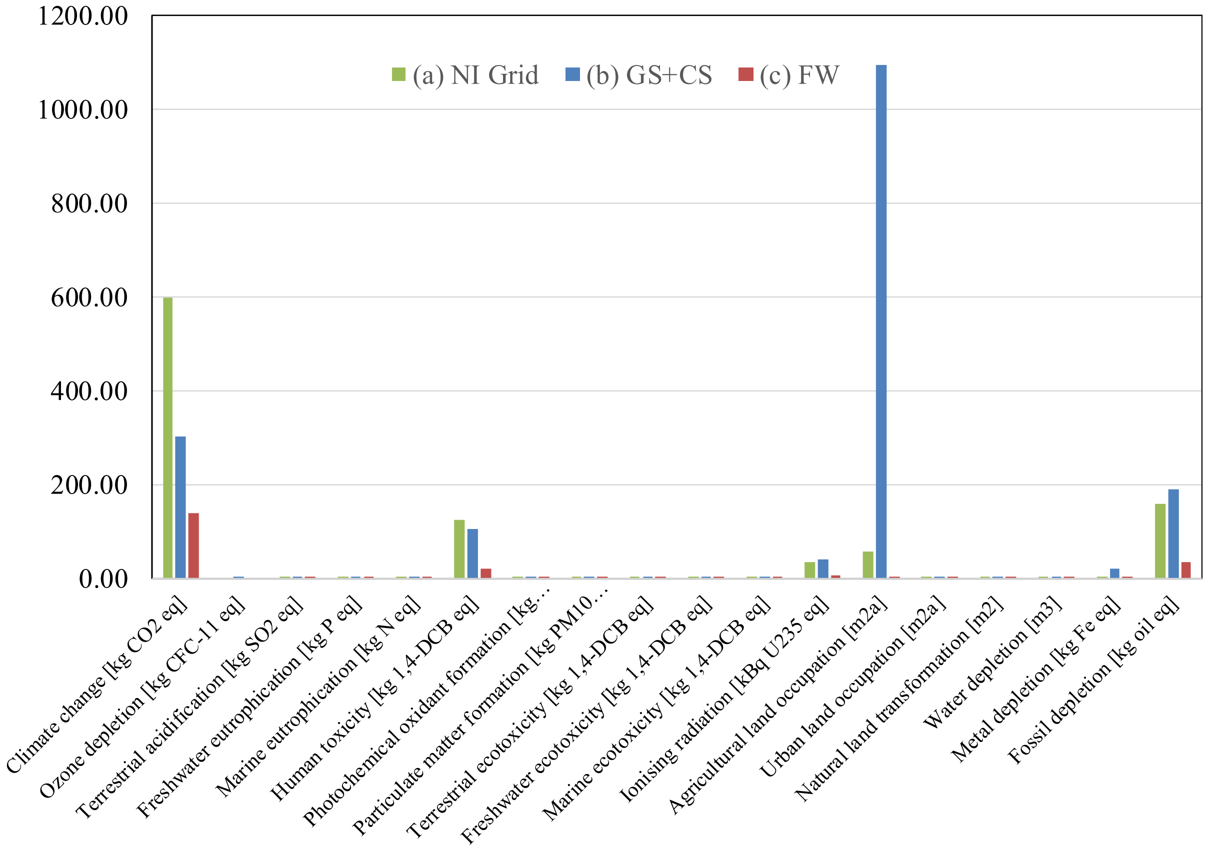

Figure 3. Environmental Impacts of 1 MWh of electricity production into the grid from several sources: (a) NI grid (🟩); (b) grass silage and cattle slurry (🟦); and (c) food waste (🟥).

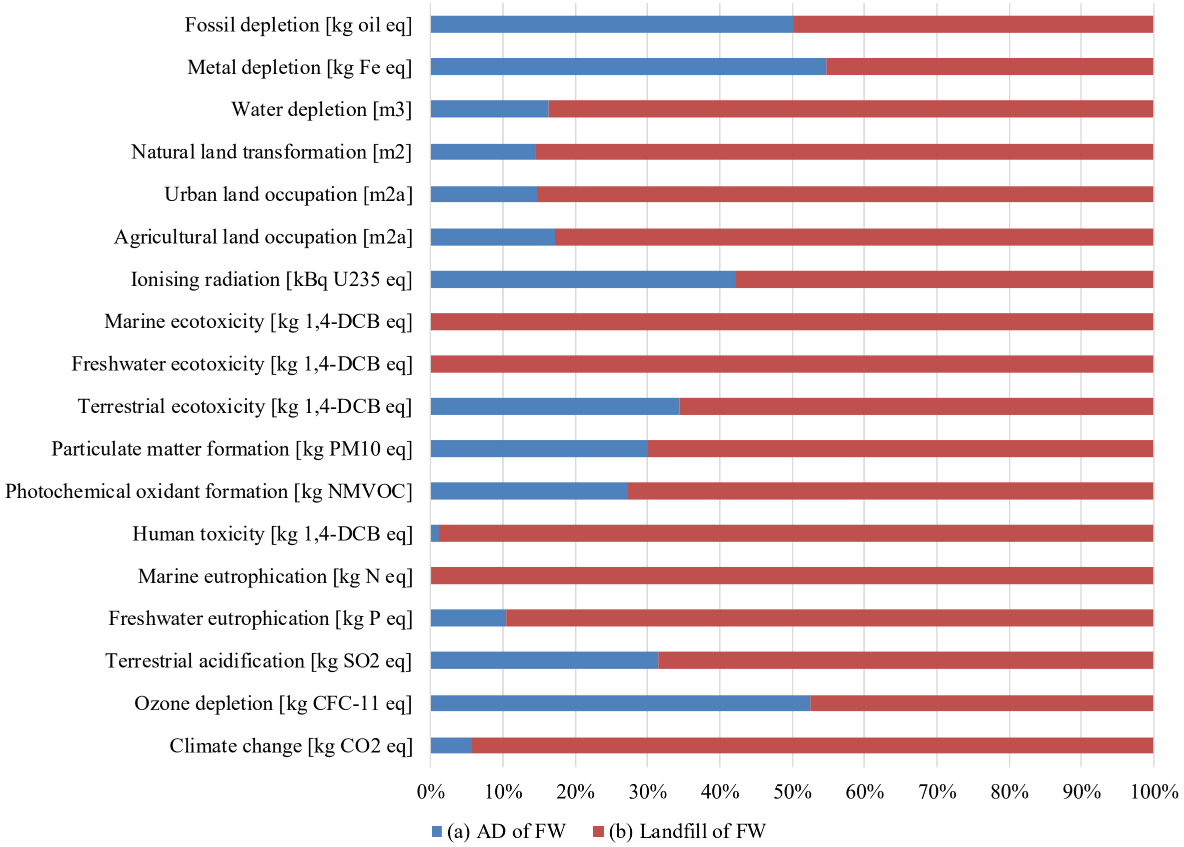

Figure 4. Environmental impact categories comparison in % for (🟦) anaerobic digestion of food waste and (🟥) landfill of food waste.

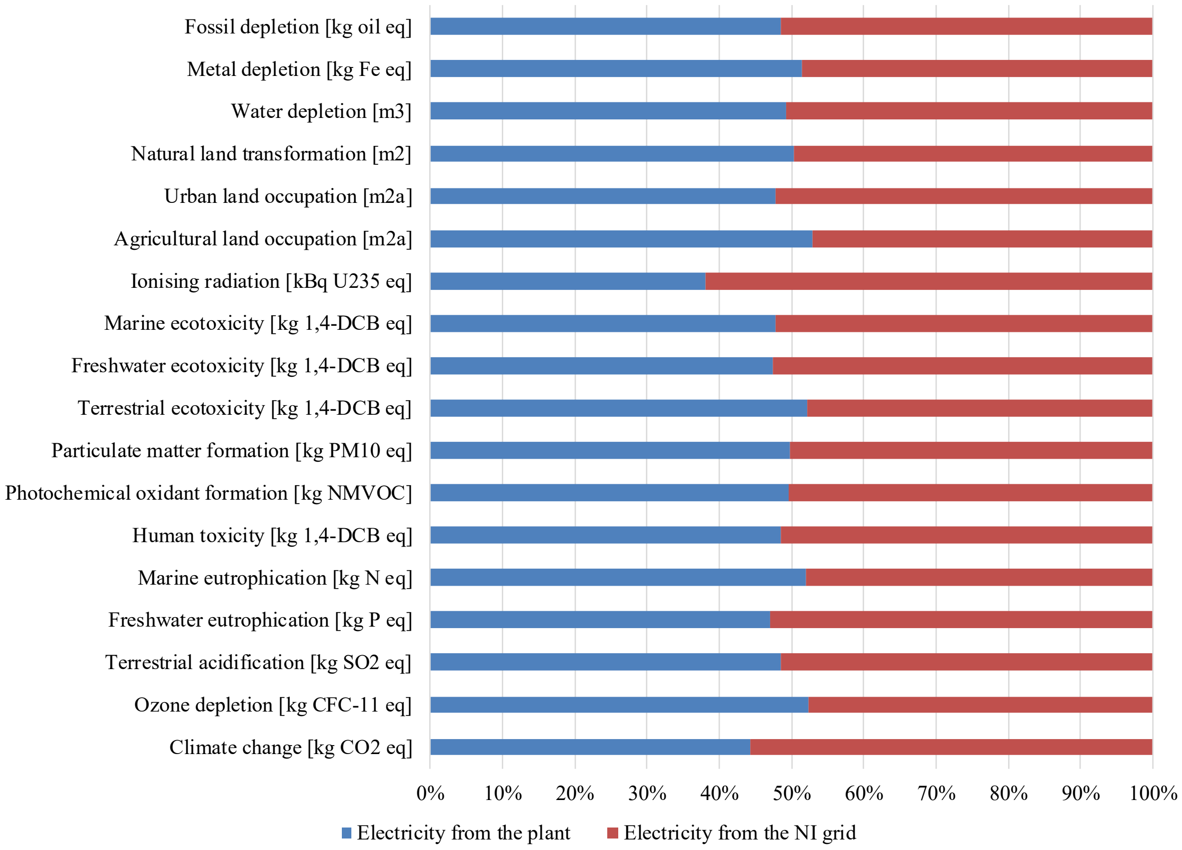

Figure 5. Environmental impact categories comparison in % for (🟦) utilisation of electricity from the plant and (🟥) utilisation of electricity from the NI grid.

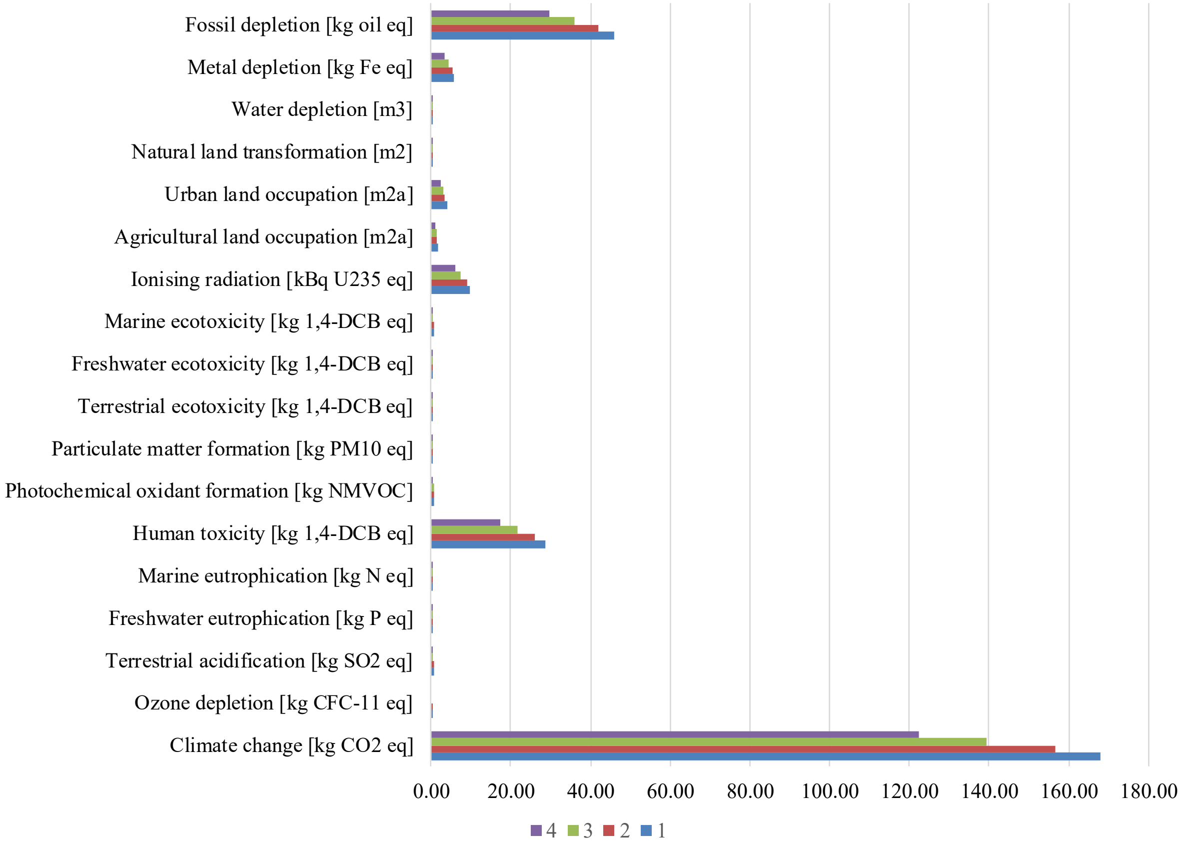

Figure 6. Sensitivity analysis assuming different biogas yields: 1 (🟦) 90 m^3 of biogas produced per tonne of food waste; 2 (🟥) 100 m^3 of biogas produced per tonne of food waste; 3 (🟩) 120 m^3 of biogas produced per tonne of food waste; 4 (🟪) 150 m^3 of biogas produced per tonne of food waste.

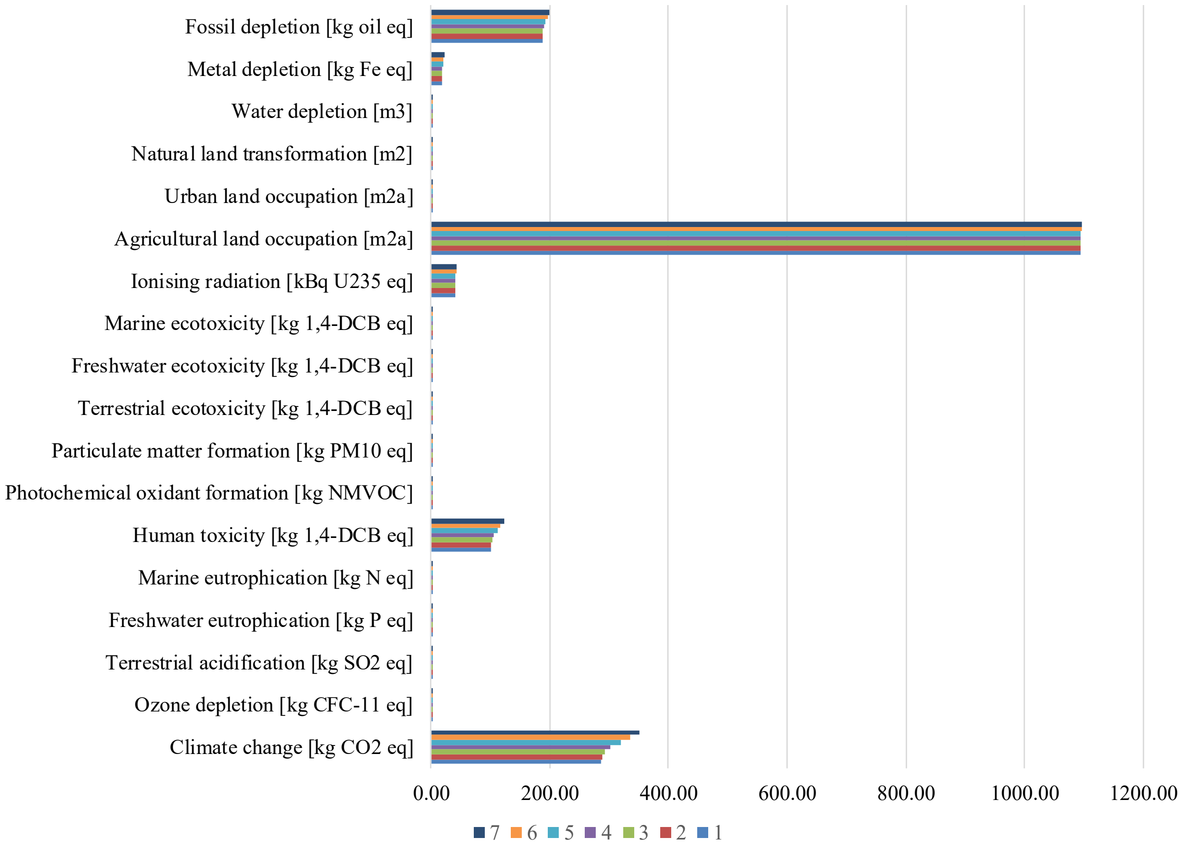

Figure 7. Sensitivity analysis assuming different fertiliser/digestate rate utilisation: 1 (🟦) 0% of fertilisers and 100% of digestate used; 2 (🟥) 5% of fertilisers and 95% of digestate used; 3 (🟩) 10% of fertilisers and 90% of digestate used; 4 (🟪) 25% of fertilisers and 75% of digestate used; 5 (🟦) 50% of fertilisers and 50% of digestate used; 6 (🟨) 75% of fertilisers and 25% of digestate used; 7 (🟦) 100% of fertilisers and 0% of digestate used.

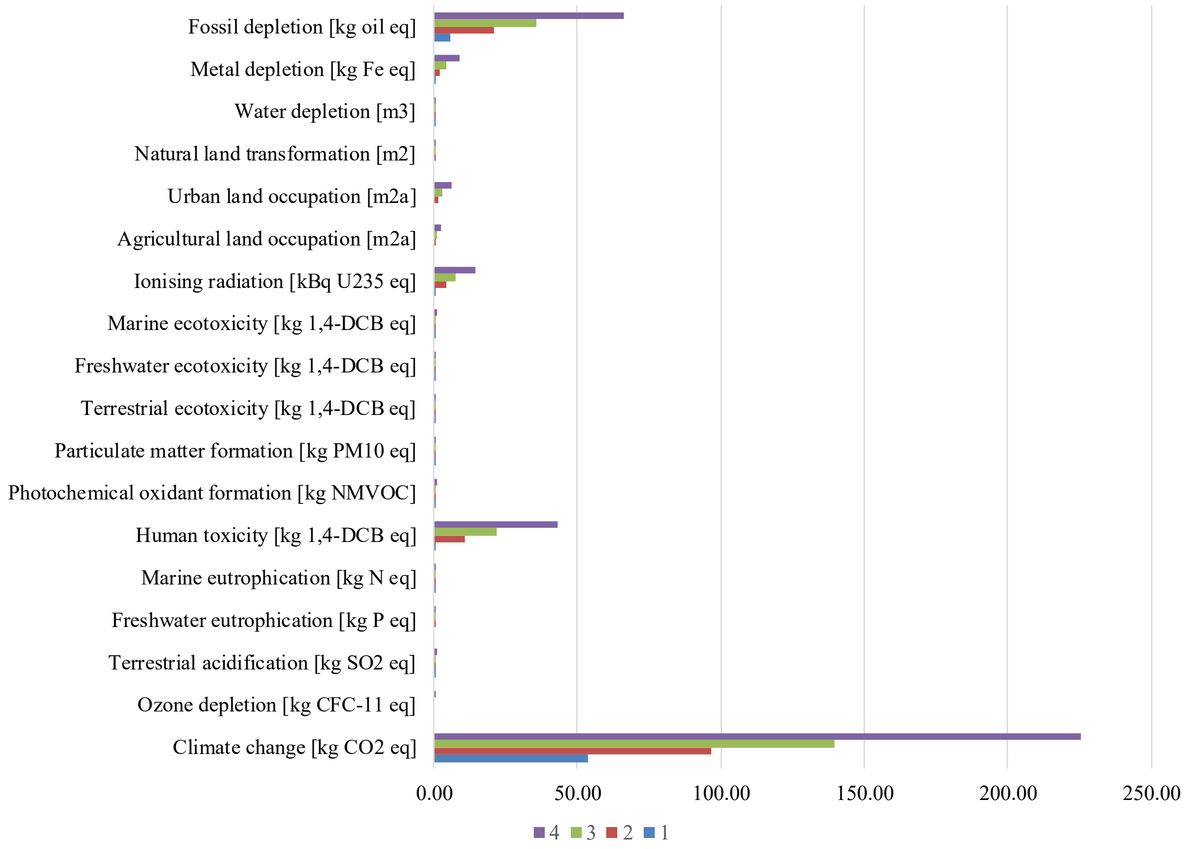

Figure 8. Sensitivity analysis for different transport distances of the food waste: 1 (🟦) distance from collection point to AD plant: 0 km; 2 (🟥) distance from collection point to AD plant: 50 km; 3 (🟩) distance from collection point to AD plant: 100 km; 4 (🟪) distance from collection point to AD plant: 200 km.

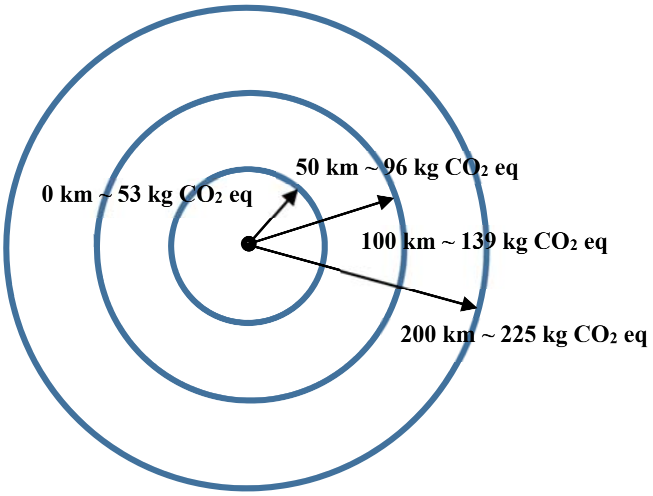

Figure 9. Representation of the distance transported for food waste and the GWP (kg CO_2 eq).