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Life Cycle Assessment of a Small-Scale Anaerobic Digestion Plant from Cattle Waste

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ABSTRACT

This paper outlines the results of a comprehensive life cycle study of the production of energy, in the form of biogas, using a small scale farm based cattle waste fed anaerobic digestion (AD) plant. The Life Cycle Assessment (LCA) shows that in terms of environmental and energy impact the plant manufacture contributes very little to the whole life cycle impacts. The results show that compared with alternative energy supply the production and use of biogas is beneficial in terms of greenhouse gases and fossil fuel use. This is mainly due to the replacement of the alternative, kerosene, and from fertiliser production from the AD process. However, these benefits come at a cost to ecosystem health and the production of respiratory inorganics. These were found to be a result of ammonia emissions during the production phase of the biogas. These damages can be significantly reduced if further emission control measures are undertaken.

KEYWORDS

Life Cycle Assessment, Biogas, Anaerobic Digestion

INTRODUCTION

The use of bioenergy may help meet our renewable energy and carbon reduction targets set by the Renewable Energy Directive [1] and Kyoto [2]. Bioenergy is of particular interest amongst renewable energy, as it doesn’t suffer from some of the intermittency or weather dependency that some other renewable technologies do, such as wind or solar. It is proposed by DECC that bioenergy might be able to produce half of our renewable energy target requirements by 2020 [3]. In addition, AD is useful to produce energy in remote areas, including farms, which in the UK are often off the main gas grid. This means that their energy production is often through the use of oil or kerosene boilers/burners that have higher impact in terms of greenhouse gas emissions and fossil fuel depletion than the use of, for example, natural gas.

However, studies of LCA for biogas production were found to be limited and incomplete within the literature [4-7]. Although there have been studies examining LCA of biogas, these do not always follow the methodology of standard LCA procedure [8,9]. LCA has been more widely used for other bioenergy techniques, rather than biogas production individually [10-13]. In addition, small farm operations do not always only use AD to produce energy, but it is one of many benefits associated with AD, including waste disposal and fertiliser production. It is of particular benefit in areas of nitrate vulnerability where manure spreading is limited.

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The majority of published biogas analyses focus on energy and carbon balances [4,5, 6] as opposed to a holistic environmental appraisal. Studies which did focus on wider environmental impacts suggested that emissions from the AD process can vary significantly depending on feedstock utilisation and end-use of biogas [5]. Other studies compared biogas against other transport fuels and showed that biogas from manure produced the largest reduction in greenhouse gas emissions [7]. However, biogas from maize silage offered the largest greenhouse gas reductions for heat and power [7]. A recent British study highlighted a detailed examination of the environmental impacts of a large-scale AD plant in the UK [15]. However, the study did not examine the environmental impacts in-line with the relevant ISO standards for LCA making this study difficult to interpret and compare against other future LCAs. Similarly, a number of the biogas LCA studies mentioned above have not clearly defined the study system boundaries.

As a result, it appeared that a detailed LCA study of UK biogas production had not been carried out. It was concluded that a holistic LCA of a UK biogas plant should be undertaken in order to model the environmental implications of using this technology. The plant reported in this paper is based on a farm in the UK. It is supplied with 100% dairy cattle waste from a herd of 130 cattle. Primary data was collected from site, and supplementary material data was obtained from LCA databases.

METHODOLOGY

Life Cycle Assessment methodology was followed in this study. The commonly accepted methodology for LCA was produced by the Society of Environmental Toxicology and Chemistry (SETAC) in the 1990's. This method has been adapted into an ISO series for LCA [8,9].

There are four main steps (shown in Figure 1): Goal definition is the stage in which the scope of the project is outlined. Here the study boundaries are established and the environmental issues that will be considered are identified. The inventory stage is where the bulk of the data collection is performed. This can be done via literature searches, practical data gathering or, most commonly, a combination of the two. Impact assessment is where the actual effects on the chosen environmental issues are assessed. This stage is further subdivided into three elements: classification, characterisation and valuation. The first two of these are fairly well established, although there is still ongoing research. However, the valuation stage is fairly subjective and still arouses debate in the literature.

Classification is where the data in the inventory is assigned to the environmental impact categories. In each class there will be several different emission types, all of which will have differing effects in terms of the impact category in question. A characterisation step is therefore undertaken to enable these emissions to be directly compared and added together. The characterisation stage yields a list of environmental impact categories to which a single number can be allocated. These impact categories are very difficult to compare directly and so the valuation stage is employed so that their relative contributions can be weighted. This is subjective and difficult to undertake and many studies omit this stage from their assessment. Instead they employ normalisation as an intermediate step. Improvement assessment is the final phase of an LCA in which areas for potential improvement are identified and implemented.

Many people employ the use of LCA software in order to help process inventory data. Software also often includes some life cycle inventory databases. In this study SimaPro[17] software was used, and numerous databases were employed. EcoInvent [18] is the primary database used, but where data were not available from this, other sources were obtained. There are also a number of commercially available impact assessment tools. These employ datasets, such as the IPCC data for greenhouse gases, in order to undertake the classification, characterisation, normalisation and valuation stages. For this study the EI 99 [19] method was adopted using the hierarchical data in the impact assessment.

GOAL AND SCOPE

The goal of this assessment was to examine and identify the life cycle environmental impacts from small-scale anaerobic digestion of cattle waste (AD). The objective was to identify the most important factors that affected the environmental load of a biogas generation plant. From these factors, the damages caused by the process were analysed, including the damages avoided from the displacement of a fossilised fuel. By determining the environmental load of biogas production from AD, it was possible to identify whether the process had beneficial or detrimental effects on the environment. This was assessed using a number of environmental impact categories, including damage to human health, damage to ecosystems and the depletion of global resources. The assessment examined the production, delivery and the use of the biogas (cradle to grave). The by-product of the AD process (the digestate), used as a source of natural fertiliser, was also examined as a displacement of mineral-based fertilisers. Throughout the assessment, the production of the plant was accounted for and linked to the biogas and natural fertiliser outputs. The environmental impacts were assessed using EI99 LCIA methodology. The plant assessed was based on a UK farm and was supplied with 100% dairy cattle waste from a herd of 130. The waste was collected during the winter months and during the milking period when the cows were indoors. The digester was 240m^3 and digested 653m^3 of cattle waste per annum (a mix of slurry and manure). The plant retention time (RT) was 20 days and the biogas production was measured hourly. On average approximately 8.9m^3 per hour of biogas was produced during RT. The feedstock intake rate was 12.5m^3/day.

FUNCTIONAL UNIT

The functional unit of the analysis was a cubic metre of biogas. As the methane-quality was known, this was easily converted to an equivalent cubic metre of methane. The process of AD was described to be a multi-output process; as a result, the second output (fertiliser) had a functional unit of mass (kilogram). This could be converted into a biogas equivalent as it was calculated that one cubic metre of biogas produced 58.47 kg of natural fertiliser (digestate). This was calculated from to the total annual biogas output and the total annual digestate output from the plant.

SYSTEM BOUNDARIES

The system boundary of the assessment is shown in Figure 2. The analysis system boundary commenced when the feedstock was collected from the cattle housing/milking parlour. The use of biogas was considered up to the point of use for heating energy. The boundaries did not consider the transport and spreading of the digestate as it was unclear as to how the digestate was distributed. Emissions associated with the AD plant construction were considered in terms of material use (mass) and some key manufacturing processes. The disposal of the plant was not considered, as the expected operational lifetime was unknown.

The biogas was understood to displace kerosene heating oil as a fuel, whilst the fertiliser was considered up to production and substitution of artificial fertiliser. The system boundary included the digestate as a potential artificial fertiliser replacement. The artificial fertiliser displacement was based on the available N, P_2O_5 and K_2O from the digestate.

LIFE CYCLE INVENTORY ANALYSIS

The direct inputs into the AD process were the feedstock material, the electricity use within the plant and the heat energy required to heat the feedstock. Indirect inputs included the energy consumed in the farming machinery. This was treated as on-site feedstock handling energy requirements. Other indirect inputs included the water consumption used to wash the milking parlours and cattle housing. This was carried out primarily for hygiene purposes, although the addition of water to the feedstock was beneficial to the AD process. However, it was considered outside the system boundaries, as the AD process did not affect the quantity of water used.

Under normal operating conditions, the plant produced 8.89m^3/hr of biogas. Of this, around 58-64% was methane (CH_4). Using an intake of 12.5m^3 per day of feedstock and knowing that the total annual feedstock input was 653 tonnes, resulted in a plant operational time of 52.24 days per year (1,253 hours per year). The findings suggested that the capacity factor of the AD plant was as low as 14%. This meant that the impacts of the manufacturing stage were distributed over a lower output of biogas. This resulted in a higher environmental impact per unit output of biogas from the plant manufacture emissions.

The feedstock used was a mix of farmyard manure (FYM) and cattle slurry. A ratio of 55:45 was chosen, in accordance with other UK studies [20,21]. This was denoted as ‘cattle waste’ within this study. The Total Solids (TS) and Volatile Solids (VS) of the waste were 8% and 85% respectively. Using data obtained from the site visit, it was calculated that for every 12.5m^3 of waste entering the plant; approximately 214m^3 of biogas was produced over a 24-hour period. Therefore, the biogas production rate was $17.1m^3_{biogas}/m^3_{waste}$.

ENVIRONMENTAL IMPACTS OF AD PLANT MANUFACTURE – CHARACTERISED RESULTS

The characterised results for the production of the plant only (therefore excluding use), is shown in Figure 3. The largest contributors towards the impact categories were the digester and digestate tank manufacturing. These two tanks made a relatively large contribution towards impact categories: carcinogens, respiratory inorganics, respiratory organics, climate change, radiation, ozone layer depletion, ecotoxicity, acidification & eutrophication, minerals and fossil fuel resources.

The reception tank was the third highest contributor (overall) towards the impact categories. As the construction materials for these three tanks were the same, this showed that a common material or manufacturing processes could be contributing towards the impact categories. The heat exchanger unit contributed towards all the impact categories, with a greater contribution towards ecotoxicity. Although 'miscellaneous pumps' and 'miscellaneous motors' represented 16 separate assemblies, the contribution towards the impact categories was insignificant.

The largest contributors to nearly all the impact categories were the largest sub-assemblies within the plant. Both of these assemblies had the highest material usage (a combined consumption of over 60 tonnes of steel). The impact on carcinogenic effects was affected greatly by the steel use within the plant. This was due to the disposal of dust by-products from steel production, which was assumed to be 100% virgin material. Other contributors to carcinogenic effects were due to the disposal of coal ash into landfill, which was used for electricity production. The emissions from iron ore extraction, used for steel production, affected the impact category of respiratory inorganics. This was due to the particulates emitted from the iron extraction process. Particulate matter can be generated by crushing, conveyance of crushed ore, blasting and transportation[22].

Finally, the impact category 'land use' was mostly contributed to by the transformation of the land (around 700m^2) into industrial land. The land was assumed to be converted from normal grazing land for cattle to industrial land. This caused damage to ecosystems, because of the change in land use. The unit for measuring the effects of land-use was the potential disappeared fraction of a species on land per year per square metre (PDF*m^{2}yr).

Whilst the characterised data shows the relative contribution of the stages of the LCA to it doesn't show the relative significance of the impacts. In order to show this a normalisation step was undertaken, the result of which are shown in Figure 4. The most significant impacting categories are shown to be respiratory inorganics and fossil fuel resource depletion. These were nearly three times greater when combined than the other impact categories. Respiratory organics, carcinogens, radiation, ozone layer depletion and acidification/eutrophication were considered to have minimal impact compared to the other categories.

Depletion in fossil fuel resources occurred through the use of heavy oils, natural gas and hard coal consumed for electricity production. These resources were also used for heat generation, for manufacturing of steel components and transportation requirements. These processes were considered necessary within the manufacturing of the AD plant. However, efficiency implementations, such as using recycled steel, reducing overall steel use, minimising transport distances etc. could reduce the impact on fossil fuel depletion.

The use of insulation material within the digester (polyurethane) was also found to have an impact on the depletion of fossil fuels, although does play a key part in the process. It was estimated that the plant used over 600 kg of polyurethane. If other materials were used such as cork or sheep's wool (organic materials), the fossil fuel consumption in the digester tank may have been reduced by over 70%. Polyurethane requires 85.2 MJ/kg of fossil fuels, whilst sheep wool and cork require around 20MJ/kg of material.

Damages to human respiratory systems can be caused through the emissions of a number of inorganic substances. In this study these were found to include particulate matter (PM), nitrate and sulphate, sulphur trioxide (SO_3), ozone (O_3), carbon monoxide (CO) and nitrous oxide (NO_x). These substances were found to cause chronic health effects and mortality. The majority of the contribution towards respiratory inorganics during the plant manufacture was due to the initial stages of steel manufacture. When obtaining iron ore, blasting techniques were used in order to separate the ore from the original source. The blasting created particulates of 2.5-10 µm in diameter. This particle size is sufficiently small to penetrate the human respiratory system and bring about serious health effects. Diesel combustion was also found to generate particulates, which may have led to similar health effects.

ENVIRONMENTAL IMPACTS OF THE AD PLANT USE PHASE – BIOGAS PRODUCTION

As there were two outputs from the plant an allocation process was undertaken. Over all, using an economic allocation 12% of the impacts were allocated to the biogas production. Using a mass allocation 40% of the results were allocated to the biogas production [4]. The results from this with an additional unallocated (total impact) impact are shown in Figure 5.

The allocation methodology was found to have a very large effect on the scale of the environmental impacts for biogas production. For some impact categories such as respiratory inorganics, the difference in allocation percentage had a significant effect on the damage towards that impact category. The most significant environmental impact from the normalised results was the effect on respiratory inorganic from biogas production. Over 70% of the total impact was contributed by the biogas production and the remaining 29% affected by the plant manufacture. The emissions contributing towards respiratory inorganics were primarily found to be a result of the air emissions from the digestate storage. Other emissions from kerosene combustion at start-up, diesel and biogas combustion for digester heating, also contributed to this impact category. Emissions such as particulates and sulphur dioxide contributed towards the high impact on respiratory inorganics.

The production of biogas showed a negative effect on the impact category of climate change. This was due to the potential carbon dioxide emissions sequestered from the organic matter. The CO_2 fixation was accounted for as a consumption of the CO_2 resource. This theory assumed that carbon dioxide was consumed to generate the feedstock (animal feedstock production) and therefore was required within the plant. The CO_2 is stored within the biogas in the form of CH_4 (and some CO_2) until the biogas is combusted.

Another area in which the production of biogas contributed significantly towards the environment was through the detrimental effect on fossil fuel reserves. This was due to the depletion of kerosene and diesel fuel used in the process**.**

WHOLE LIFE CYCLE IMPACT ASSESSMENT

For the whole life impact assessment a mass based allocation has been selected. This is because during the 25 year operational life of the system the mass will not fluctuate, whereas the economics may fluctuate significantly. Figure 6 shows that over the whole life of biogas production, the emissions from the plant use contributed the most towards three environmental impact categories: respiratory inorganics, acidification/eutrophication and fossil fuel resource depletion. The plant construction was also found to have insignificant contributions towards the environmental impacts, when compared to the use phase of the AD plant. These emissions were produced only once within the lifetime of the plant, whilst plant use had reoccurring emissions.

The most significant result came from the consequential displacement of the kerosene production, using biogas. The energy equivalent of kerosene showed a significant reduction in fossil fuel resource depletion over the life of the AD process. Additionally, savings in CO_2 emissions also contributed towards a reduction in climate change impact, giving the plant an overall (net) negative output on climate change.

Figure 7 shows the whole life normalised environmental impacts for the digestate output of the AD process. These results also highlighted that the AD plant use phase contributed significantly towards respiratory inorganics, acidification/eutrophication and fossil fuels resource depletion. However, due to the mass allocation, the emissions allocated towards the digestate production were higher. As a result, the overall contribution of the emissions towards these environmental impact categories was more significant. Over the life of the plant the emissions associated with the plant construction had minimal contribution towards the environmental impact categories, which was similar to the biogas production lifecycle.

The most significant contribution towards the whole-life cycle of the digestate output from AD was the consequential savings in displacing inorganic fertiliser. Based on the same quantity of fertiliser (in terms of N, P_2O_5 and K_2O properties) the displacement of inorganic fertiliser resulted in a significant reduction in impacts towards four main environmental impact categories: carcinogenic effects, respiratory inorganics, climate change and fossil fuel resource depletion.

Overall the key benefits from digestate displacing inorganic fertiliser were savings in fossil resources which also led to a reduction in carbon emissions (and a lower impact on climate change). Additionally, other smaller benefits across most of the environmental impacts were also seen.

The common factor between both lifecycles (Figures 6 & 7) was the high emissions contributing towards respiratory inorganics and acidification/eutrophication. These emissions, produced during the use phase of the AD plant, could have a detrimental impact towards human health and ecosystem quality. It also appeared that although there were savings in kerosene and inorganic fertilisers, these impact categories were still significant.

The emissions leading to respiratory inorganics were from the digestate storage, the combustion of kerosene, diesel and biogas. These emissions can cause smog leading to respiratory effects such as asthma, chest infections and bronchitis amongst other chronic obstructive pulmonary disorders. As a result, these emissions could have potentially serious effects on human health. This was primarily due to the ammonia emissions during the production phase of biogas, the diesel and kerosene combustion and emissions from the biogas combustion (used for the production of further biogas). Ammonia release was especially significant as it contributed towards both impact categories. These emissions could have been avoided if ammonia filters were put in place such as the ANAStrip process [23]. This could significantly reduce the impact of these environmental concerns, as it eliminates traces of ammonia within the process. Another technique would be to prolong the digestion period so that less ammonia is emitted during the digestate stage. A final recommendation would be to create a cover over the digestate tank in order to trap the post digestion emissions. This would not only reduce air emissions but also recover some of the remaining biogas.

Acidification can have an impact on ecosystems through the increase in the pH acidity of waters and soils. Air emissions can also lead to acid rain which can have detrimental effects especially on vegetation (for example conifer trees can deteriorate in health through acid rain). Eutrophication can lead to an abnormal increase in nutrient concentration over specific soil or water volume. The increase in nutrient availability increases the growth of aquatic plants and algae. An overproduction of algae and blooms causes an increase of plant life on the water surface, which can lead to reduced sunlight and oxygen penetrating the top layer of water. Increased nutrients in soil can lead to leaching into water streams causing eutrophication of lakes, rivers or bathing waters [24].

This shows how emissions from an industrial process such as AD could have detrimental impacts on the delicate balance of natural species and also human health. The detrimental environmental impacts affected by the use of AD can have direct or indirect impacts towards human health and ecosystem quality. Measures should be taken to minimise the emissions within the AD process. Reducing emissions via a desulphurisation plant could minimise the overall environmental impact of the AD process, which is significant if the technology were to be used on a large scale. This would eliminate the hydrogen sulphide within the biogas and subsequently eliminate the sulphur dioxide emissions from hydrogen sulphide combustion. These systems can range from very crude devices such as a container of iron filings acting as a filter for the biogas to pass through; to more expensive computer controlled gas cleaning processes [25].

CONCLUDING REMARKS

The study analysed the environmental impacts of biogas production and utilisation through the technique of life cycle assessment (LCA). LCA enabled an understanding of the factors which contributed most towards detrimental impacts on the environment, during the life cycle of biogas production. The study also examined the environmental benefits of using biogas as a domestic heat source, subsequently displacing the use of domestic heating kerosene fuel. The key findings from the LCA results can be summarised:

- The emissions created from the plant manufacture contributed very little towards the whole life cycle environmental impacts. This would have been further reduced if a higher operating capacity factor were obtainable.
- The use phase of the AD plant created emissions which appeared to have significant impacts towards human respiratory systems and acidification/eutrophication issues within ecosystems.
  - The impacts were a result of emissions such as ammonia from the digestate storage, sulphur dioxide, nitrous oxide and particulates from the combustion of biogas, kerosene or diesel.
- The production of biogas and fertiliser both created significant impacts towards fossil fuel depletion due to the use of diesel and kerosene. However, over the whole life cycle, the consequential displacement of kerosene as an end-use energy source and inorganic fertilisers, showed a net-benefit in fossil fuel depletion.
- The study concluded that it is essential to cover the digestate storage tank as biological reactions are still occurring thus emitting, methane, ammonia and carbon dioxide. Globally a number of AD units do not cover the digestate storage.
- Desulphurisation and ammonia removal processes were also considered to be crucial within the AD system in order to remove these emissions either entering the atmosphere directly or undergoing the combustion process.
- Ammonia is also released during the spreading of digestate. However, as the lifecycle system boundary terminated at the fertiliser production stage, this was not included. This could however be included as a further analysis.

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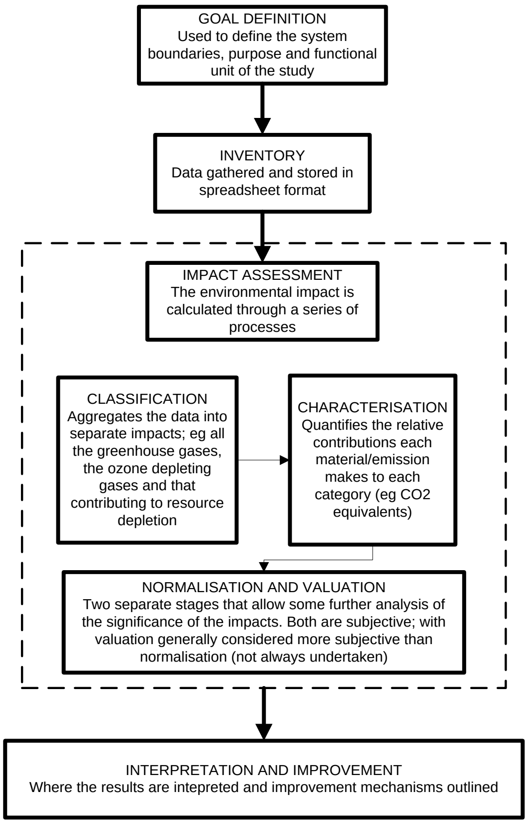
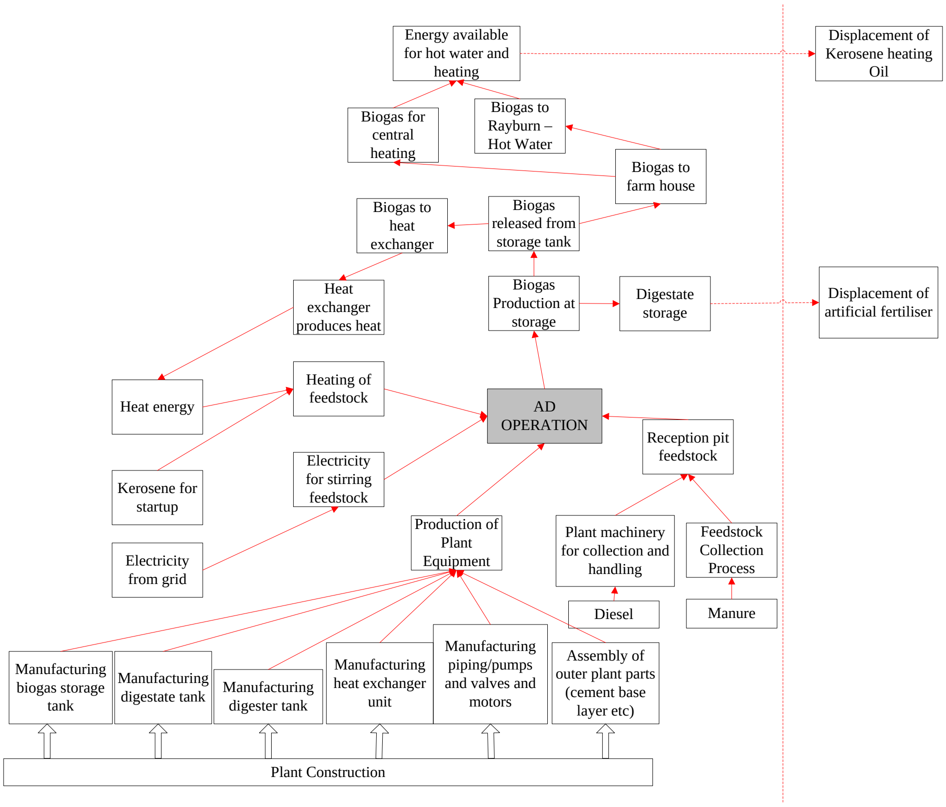
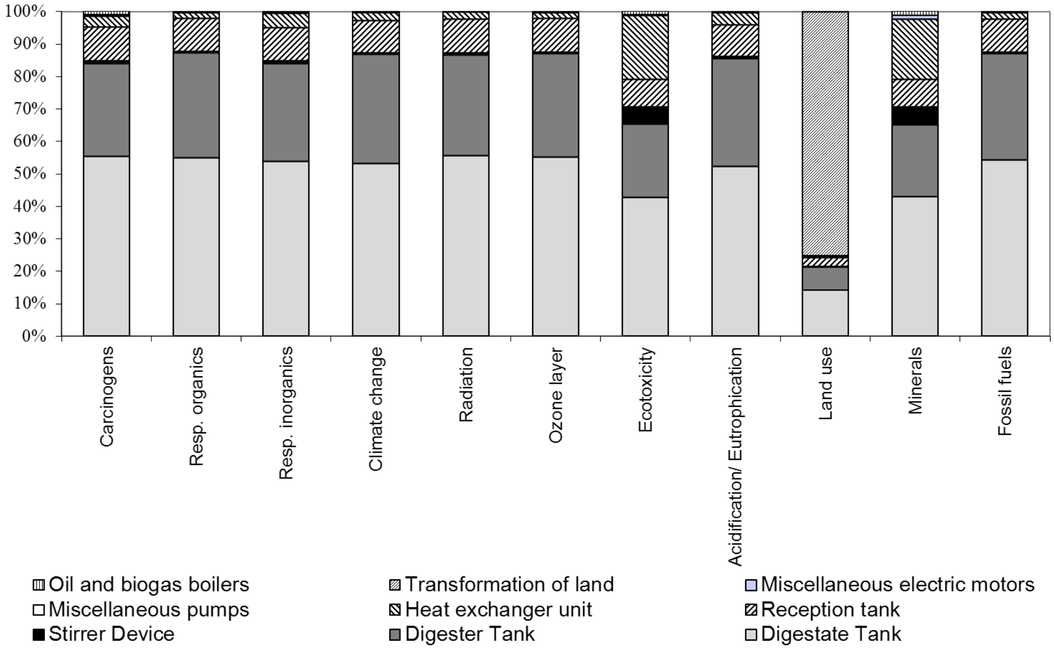
List of Figures


GOAL DEFINITION
Used to define the system boundaries, purpose and functional unit of the study
INVENTORY
Data gathered and stored in spreadsheet format
IMPACT ASSESSMENT
The environmental impact is calculated through a series of processes
CLASSIFICATION
Aggregates the data into separate impacts; eg all the greenhouse gases, the ozone depleting gases and that contributing to resource depletion
CHARACTERISATION
Quantifies the relative contributions each material/emission makes to each category (eg CO2 equivalents)
NORMALISATION AND VALUATION
Two separate stages that allow some further analysis of the significance of the impacts. Both are subjective; with valuation generally considered more subjective than normalisation (not always undertaken)
INTERPRETATION AND IMPROVEMENT
Where the results are intepreted and improvement mechanisms outlined


Energy available for hot water and heating
Displacement of Kerosene heating Oil
Biogas for central heating
Biogas to Rayburn – Hot Water
Biogas to farm house
Biogas to heat exchanger
Biogas released from storage tank
Heat exchanger produces heat
Biogas Production at storage
Digestate storage
Displacement of artificial fertiliser
Heat energy
Heating of feedstock
AD OPERATION
Reception pit feedstock
Kerosene for startup
Electricity for stirring feedstock
Electricity from grid
Production of Plant Equipment
Plant machinery for collection and handling
Feedstock Collection Process
Diesel
Manure
Manufacturing biogas storage tank
Manufacturing digestate tank
Manufacturing digester tank
Manufacturing heat exchanger unit
Manufacturing piping/pumps and valves and motors
Assembly of outer plant parts (cement base layer etc)
Plant Construction


100%
90%
80%
70%
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20%
10%
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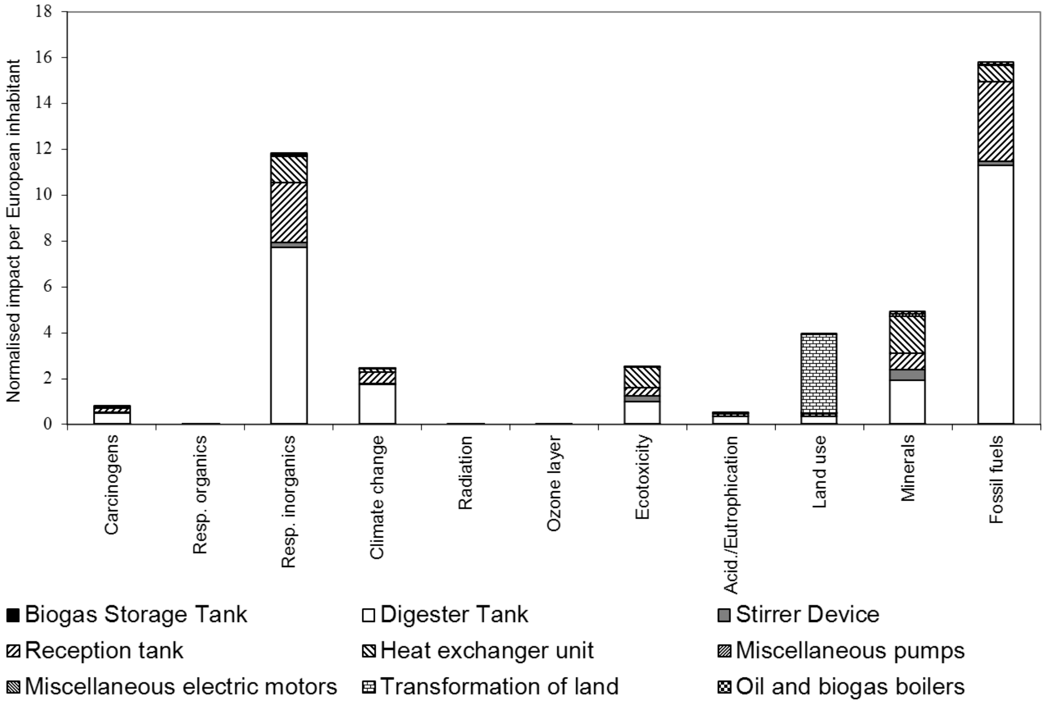
Carcinogens
Resp. organics
Resp. inorganics
Climate change
Radiation
Ozone layer
Ecotoxicity
Acidification/ Eutrophication
Land use
Minerals
Fossil fuels
Oil and biogas boilers
Transformation of land
Miscellaneous electric motors
Miscellaneous pumps
Heat exchanger unit
Reception tank
Stirrer Device
Digester Tank
Digestate Tank


Normalised impact per European inhabitant
0
2
4
6
8
10
12
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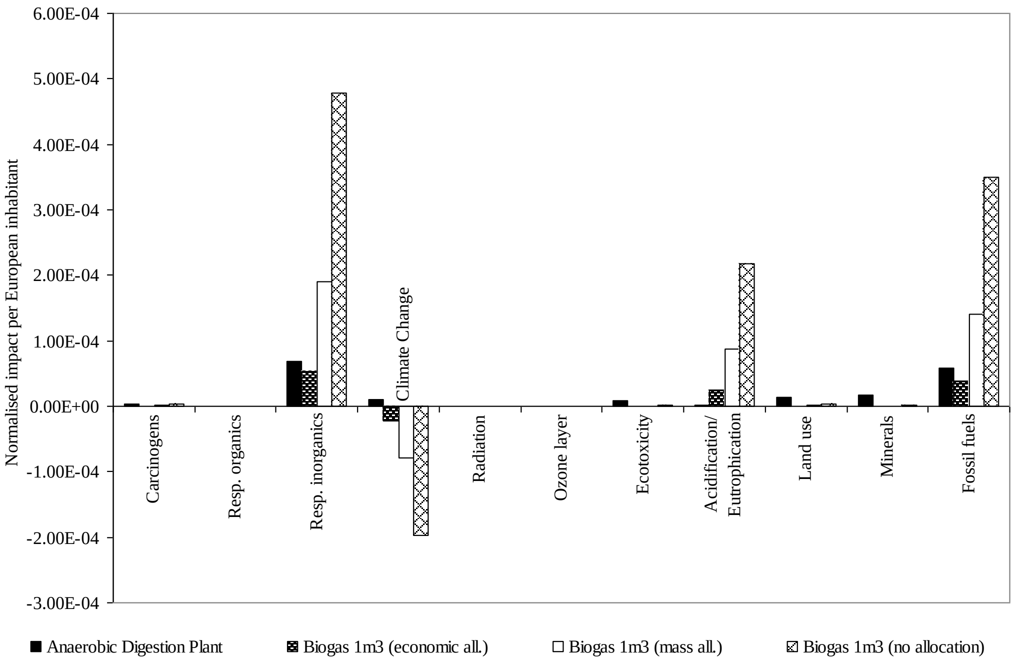
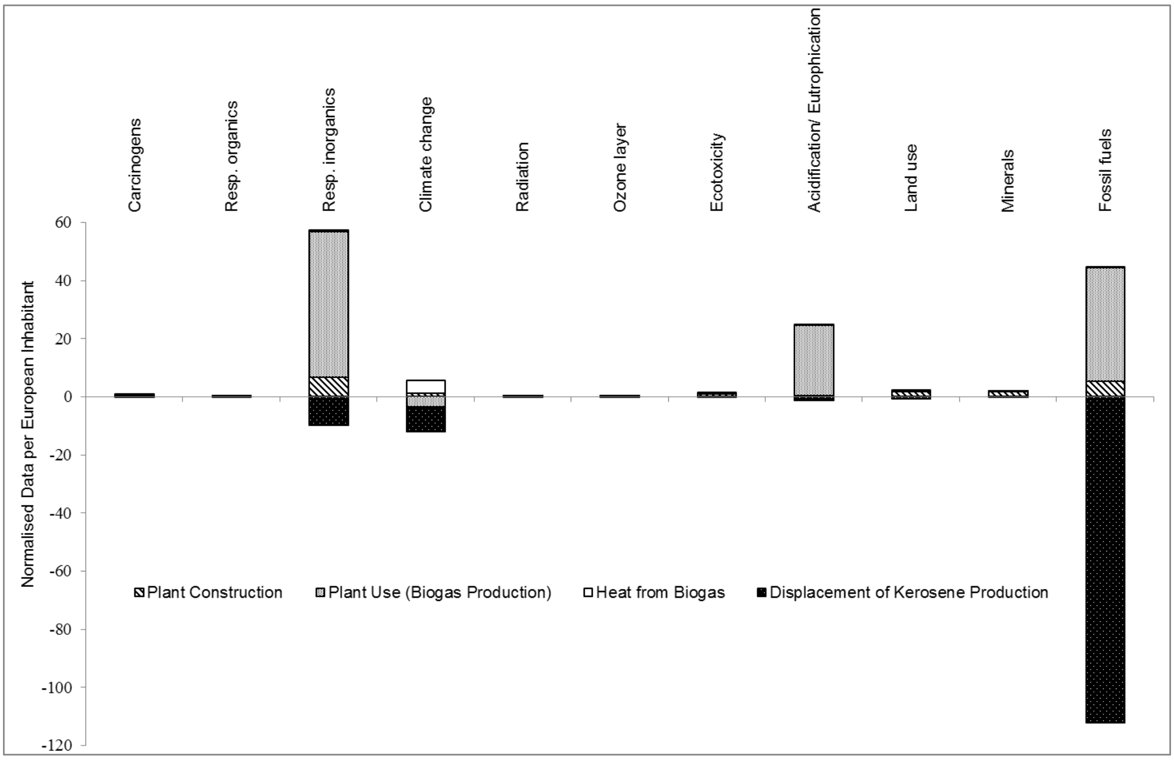
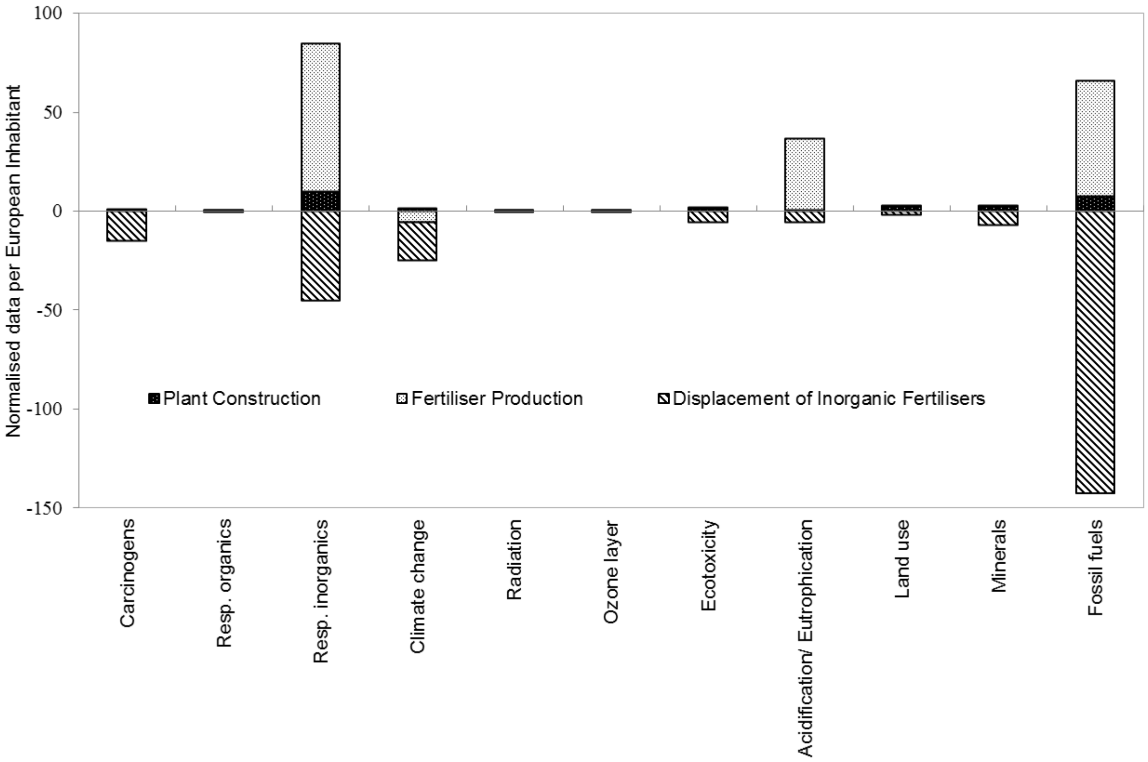
16
18
Carcinogens
Resp. organics
Resp. inorganics
Climate change
Radiation
Ozone layer
Ecotoxicity
Acid./Eutrophication
Land use
Minerals
Fossil fuels
■ Biogas Storage Tank
□ Digester Tank
Stirrer Device
▨ Reception tank
▧ Heat exchanger unit
▨ Miscellaneous pumps
▧ Miscellaneous electric motors
⊞ Transformation of land
⊠ Oil and biogas boilers


Normalised impact per European inhabitant
6.00E-04
5.00E-04
4.00E-04
3.00E-04
2.00E-04
1.00E-04
0.00E+00
-1.00E-04
-2.00E-04
-3.00E-04
Carcinogens
Resp. organics
Resp. inorganics
Climate Change
Radiation
Ozone layer
Ecotoxicity
Acidification/ Europhication
Land use
Minerals
Fossil fuels
Anaerobic Digestion Plant
Biogas 1m3 (economic all.)
Biogas 1m3 (mass all.)
Biogas 1m3 (no allocation)


Carcinogens
Resp. organics
Resp. inorganics
Climate change
Radiation
Ozone layer
Ecotoxicity
Acidification/ Eutrophication
Land use
Minerals
Fossil fuels
Normalised Data per European Inhabitant
60
40
20
0
-20
-40
-60
-80
-100
-120
▧ Plant Construction
▨ Plant Use (Biogas Production)
☐ Heat from Biogas
■ Displacement of Kerosene Production


100
50
0
-50
-100
-150
Normalised data per European Inhabitant
Plant Construction
Fertiliser Production
Displacement of Inorganic Fertilisers
Carcinogens
Resp. organics
Resp. inorganics
Climate change
Radiation
Ozone layer
Ecotoxicity
Acidification/ Eutrophication
Land use
Minerals
Fossil fuels