Life Cycle Assessment of Anaerobic Digestion of Cattle Manure

by

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Thesis presented in partial fulfilment
of the requirements for the Degree

of

MASTER OF ENGINEERING
(CHEMICAL ENGINEERING)

in the Faculty of Engineering
at Stellenbosch University

Supervisor
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April 2019

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ABSTRACT

The pressure on energy resources worldwide combined with the awareness of the major impact industrial processes have on the environment, triggers the development of alternative energy sources and methods to reduce waste. Anaerobic digestion of waste addresses both these criteria by simultaneously supplying energy and reducing waste that would otherwise have to be stored or burned.

This study focuses on the anaerobic digestion of cattle manure and the processes associated with the products downstream of the digester that can potentially replace current sources of energy and nutrients. A pilot anaerobic digester at Stellenbosch University (SU) is used as the base for the mass balance but the process data used is obtained from literature.

Six different sets of processes (scenarios) were evaluated based on the possible uses of the biogas and digestate outflows from the digester. Ecoinvent's database together with GreenDelta as Life Cycle Assessment software provider was used to determine the life cycle assessment (LCA) of each scenario. The CML impact assessment method was used as it concentrates on the LCA categories as per the scope of this study. LCA is the methodology for determining relative environmental impacts of a process from cradle to grave. The CML environmental categories are acidification potential, climate change, ozone depletion potential, photochemical oxidation, terrestrial ecotoxicity, human toxicity, depletion of abiotic resources, aquatic toxicity and eutrophication.

The results of each scenario are compared to a base case consisting of the normal operation of a milk cow stall, combined with offset processes for the six scenarios. In scenario 1 and 2 the biogas is used to heat SU's indoor swimming pool while the digestate is either applied to fields as nutrient source or cleaned via pasteurisation for domestic use. Scenario 3 uses the digestate as nutrient supply while biogas is scrubbed and bottled for cooking. Scenario 4 converts the digestate solids into fertilizer pellets while a portion of the biogas is used for generating electricity. Scenario 5 and 6 both involve the cleaning and bottling of biogas for cooking. In scenario 5 the digestate solids are mixed with limestone for fertilizer production. The liquid phase is used for irrigation. Scenario 6 uses the liquid digestate as nutrient source in a photo bioreactor cultivating algae. The bio-oil produced is converted into biodiesel. The solid digestate is applied to agricultural fields as nutrient source.

After normalizing the LCA results of the scenarios against the results of the base case, it was found that the application of digestate without phase separation has a lower environmental impact than digestate converted into fertilizer. Biogas used for heating and power generation has lower impacts on the environmental categories than biogas scrubbed and bottled for cooking. The impacts from the base case are higher than the impacts of an anaerobic digester combined with processes utilizing biogas and digestate in their raw states. Processes from the different scenarios were mixed to create an optimum scenario with even lower impacts, but scenario 4's impacts remained the lowest overall.

Operating an anaerobic digester fed with cattle manure will improve the environmental impacts of a cattle stall significantly. The application of biogas and digestate on the farm adds financial benefits for the farmer while the whole operation is more environmentally friendly.

ABSTRAK

Die druk op energiehulpbronne wêreldwyd, gekombineer met die bewustheid van die groot impak wat industriële prosesse op die omgewing het, gee aanleiding tot die ontwikkeling van alternatiewe energiebronne en metodes om afval te verminder. Anaërobiese vertering van afval spreek beide hierdie kriteria aan deur gelyktydig energie te verskaf en afval te verminder wat andersins gestoor of gebrand moet word.

Hierdie studie het op die anaërobiese vertering van beesmis gefokus en op die prosesse geassosieer met die verteerder se produkte stroomaf wat potensieel die huidige bronne van energie en voedingstowwe kan vervang. ’n Loods anaërobiese verteerder is by die Universiteit van Stellenbosch gebruik as die basis vir die massabalans. Die data wat gebruik is, is uit literatuur verkry.

Ses verskillende stelle prosesse (scenario’s) is geëvalueer gebaseer op die moontlike gebruike van die biogas en oorskot uitvloeisels vanaf die verteerder. Ecoinvent databasis met GreenDelta as LSA sagteware verskaffer, is gebruik om die lewensiklus assessering (LSA) van elke scenario vas te stel. Die CML impak assesseringsmetode is gekies omdat dit fokus op die LSA kategorieë volgens die raamwerk van hierdie studie. LSA is die relatiewe metodologie om omgewingsimpak van ’n proses van wieg tot graf vas te stel. Die CML omgewing kategorieë is aansuring potensiaal, klimaatverandering, osoon uitputting potensiaal, fotochemiese oksidasie, aard-ekotoksisiteit, menslike toksisiteit, uitputting van abiotiese hulpbronne, water toksisiteit en eutrofisering.

Die resultate van elke scenario is vergelyk met die basisgeval wat bestaan uit die normale werking van ’n melkkoeistal, gekombineer met teenstelling prosesse vir die ses scenario’s. In scenario 1 en 2 is die biogas gebruik om die binnehuise swembad van die Universiteit van Stellenbosch te verhit terwyl die oorskot op die velde aangewend is as voedingsbron, of skoongemaak is via pasteurisasie vir huishoudelike gebruik. Scenario 3 het die oorskot as voedingstof voorsiening gebruik terwyl biogas geskrop en gebottel is om mee te kook. Scenario 4 het die vaste oorskot in kunsmiskorrels omgesit, terwyl ’n gedeelte van die biogas gebruik is vir die opwekking van elektrisiteit. Scenario 5 en 6 het beide die skoonmaak en bottelering van biogas om mee te kook, behels. In scenario 5 was die vaste oorskot met kalkklip gemeng vir kunsmis produksie. Die vloeistoffase is gebruik vir besproeiing. Scenario 6 het die vloeibare oorskot as voedingsbron gebruik in ’n foto bioreaktor wat alge kweek. Die bio-olie wat vervaardig is, is omgesit na biodiesel. Die vaste oorskot is op landbouvelde as voedingsbron aangewend.

Nadat die LSA resultate genormaliseer is deur dit te vergelyk met die resultate van die basisgeval, is dit gevind dat die toepassing van oorskot sonder fase skeiding ’n laer omgewingsimpak het as ’n oorskot omgesit na kunsmis. Biogas wat gebruik is vir verhitting en kragopwekking het ’n laer impak op die omgewingskategorieë as biogas wat geskrop en gebottel is om mee te kook. Die impak van die basisgeval was hoër as die impak van ’n anaërobiese verteerder gekombineer met prosesse wat biogas en oorskot in hul rou toestand gebruik. Prosesse van verskillende scenario’s is gemeng om ’n optimale scenario te skep met selfs ’n laer impak, maar scenario 4 se impak bly oor die algeheel die laagste. Deur koeimis in ’n anaërobiese verteerder te gebruik, sal die omgewingsimpak van ’n koeistal aansienlik verbeter. Die toepassing van biogas en verwerking op die plaas hou finansiële voordele vir die boer in, terwyl die hele bedryf meer omgewingsvriendelik is.

ACKNOWLEDGEMENTS

I would like to acknowledge:

1. My supervisor, Dr Tobi Louw, for his guidance, time and dedication throughout the three-year period I worked on this thesis.

2. My family who supported my decision to take on this project and allowed me the time and opportunity to complete it successfully.

3. The University personnel who assisted with registration and support throughout the time, successfully overcoming the long distance between me and Stellenbosch.

4. My Lord, Jesus Christ without whom I would not have been able to take on this project.

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LIST OF ABBREVIATIONS

Abbreviations	Detail
LCA	Life Cycle Assessment
AD	Anaerobic Digestion
CHP	Combined heat and power
NPK	Nitrogen-Phosphate-Potassium
UV	Ultraviolet
RO	Reverse Osmosis
SRF	Solid recovered fuel
RDF	Refuge derived fuel
PEF	Process engineered fuel
MSW	Municipal solid waste
ISO	International Standards Organisation
LCIA	Life cycle impact assessment
eq	equivalent
VOCs	Volatile organic compounds
PAN	Peroxy-acetyl-nitrate
SU	Stellenbosch University
HRT	Hydraulic retention time
SANS	South African National Standards
Cp	Specific heat
LPG	Liquid petroleum gas
EDTA	Ethylenediamine tetra acetic acid
DCB	Dichloro-benzene
EU	European Union
HPWS	High pressure water scrubbing
AwR	Alkaline with regeneration
BABIU	Bottom ash upgrading
CFC	Chlorofluorocarbon
COD	Chemical oxygen demand
CCS	Capture carbon and storage
FPCM	Fat and protein corrected milk

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1 INTRODUCTION AND BACKGROUND

Anaerobic digestion processes have been around since the 19th century when it was discovered that combustible gas can be produced from the digestion of wastes in the absence of air. England and India used the energy from this process for lighting before the start of the 20th century (Klinkner 2014). In the past few decades, the need for cleaner energy sources worldwide and the urgency to reduce waste generated by various processes in households, farms and industry resulted in more research undertaken to develop different sources of energy and methods to reduce waste. Different types of anaerobic digesters and different conditions are designed and trialled to increase the application possibilities. Anaerobic digestion reduces the carbon footprint and allows the direct application of ammonia that would otherwise have required costly energy to be produced from nitrogen (Van Der Weerden et al. 2014).

Different types of wastes, such as municipal waste, organic material, manure and effluent water can be fed to an anaerobic digester system operating at a specific temperature and pH. The anaerobic digester produces two main products, biogas and slurry digestate. The actual composition of the biogas and digestate will vary according to the type of waste input. Biogas consists mostly of methane and is recognised as a source of energy. The digestate slurry contains mainly phosphate, potassium and nitrogen and is a useful substitute for fertilizer (Klinkner 2014).

Cattle manure is one possible source of waste fed to an anaerobic digester for producing biogas and digestate. This study focuses on the information gathered from a cattle stall with 60 cows operating at the Welgevallen experimental farm at Stellenbosch University (SU). The stall is potentially operated in combination with an anaerobic digester fed with the manure from the stall. The environmental impacts of the anaerobic digester fed with the manure from the cattle stall are investigated as well as the impacts from the processes downstream of the digester. The parameters and dimensions of the digester at SU were used to compile the mass and energy balances of this study.

The environmental impacts of the conventional cattle stall and the traditional way of handling the effluent from the stall by applying it to nearby agricultural fields were compared to the impacts of an operation including an anaerobic digester fed with the manure slurry from the cattle stall.

The two outputs of the anaerobic digester (biogas and digestate) can be utilised in various processes to benefit from the energy and nutrients available. Biogas can be scrubbed of water, carbon dioxide and hydrogen sulphide for use as vehicle fuel, generation of electricity, cooking and heating. The digestate can be used as is or separated into solid and liquid phases. The liquid phase can be used for irrigation and the solids converted into different types of fertilizers. The digestate can also act as nutrient supply to a photo bioreactor cultivating algae for biodiesel production.

Six scenarios were created, all including the basic stall operation and an anaerobic digester. A different set of processes utilising the main products of the anaerobic digester are combined in each scenario. Each of the created scenarios associated with the products of the anaerobic digester have environmental impacts. The "Life cycle assessment" (LCA) methodology was used to determine the environmental impacts of the cattle stall (base case) and compared to the impacts of the different scenarios. LCA methodology is governed by the International

Standards Organisation (ISO) and considers all impacts of a product from cradle to grave. According to ISO 14044, the method consists of four steps: The goal and scope definition, the development of an inventory of products and processes involved (LCI), the impact assessment (LCIA) and the interpretation step (ISO 14044 (2006), Switzerland).

The CML impact assessment method chosen, consists of 10 environmental impact categories (Menoufi 2011) namely:

- acidification potential
- climate change
- terrestrial ecotoxicity
- aquatic ecotoxicity (freshwater and marine)
- depletion of abiotic resources
- photochemical oxidation
- human toxicity
- eutrophication
- ozone depletion

Various databases are available to assist industry and researchers in calculating the environmental impacts of processes. The "Ecoinvent" database was chosen as tool for this study as it is recognised worldwide in the industry, free of charge for research purposes by institutions such as SU, it is relatively user-friendly for new users and has efficient online support. The environmental impacts of the anaerobic digester and the associated processes were determined by either selecting known processes in the database or by creating processes based on the mass balance generated previously. The impacts of the individual processes are combined per scenario and compared to the impacts of the base case. The base case consists of the stall operation, the application of the stall effluent to nearby fields as well as the processes that offset the chosen processes in the 6 scenarios. The results from the database for each scenario are normalised to allow a comparison between the impacts of the scenarios and structuring a final conclusion.

This study is justified as it wants to investigate the different processes associated with the products from anaerobic digestion and their impacts on the environment. Anaerobic digestion has the potential to reduce the volume of waste and pollutants that are generated daily by industrial and agricultural processes. Waste from packaging, excess materials and organic waste would otherwise have to go to either landfill sites or be incinerated while causing various forms of pollution. The downstream processes of the digester can add to the benefits of AD but the environmental impacts of these processes need to be determined and considered. AD uses different types of equipment and is already recognised in several countries as a source of energy and nutrients in processes such as those that will be considered in this study.

The objectives of this study are to:

1. Identify different scenarios for the uses of the products from anaerobic digestion on a cattle farm.
2. Analyse the environmental impacts of these scenarios with the help of life cycle assessment methodology and the "Ecoinvent" database.
3. Compare the results for the various scenarios with each other as well as the results obtained for the environmental impacts of the cattle stall scenario (base case).

4. From the results of the life cycle assessment, make recommendations to the farmer on the advantages of anaerobic digestion and the products of the system. These recommendations include both benefits for environmental aspects as well as energy and nutrient savings for the farmer.

In the next chapter a literature overview is given on anaerobic digestion, life cycle assessment, different processes associated with biogas and digestate applications and a brief explanation of the various environmental categories investigated.

After the methodology is explained in chapter 3, the results are presented in chapter 4 with graphs, tables and discussions. The conclusion and recommendations follow in chapter 5. Appendix A contains information on the mass balance performed for the compilation of the life cycle inventory of the study. The inventory processes are outlined in Appendix B. Appendix C consists of three tables showing the details of the contributors to the impacts on the environmental categories studied.

2 LITERATURE OVERVIEW

The worldwide drive towards successful anaerobic digestion (AD) processes is two-fold. Firstly, a more environmentally friendly fuel/power source is found and secondly, the waste generated by mankind in massive volumes can be changed into useful products. The use of the biogas produced during AD as a fuel for heating or cooking is considered more environmentally friendly than traditional fuels such as wood or coal (Sacher et al. 2014).

2.1 ANAEROBIC DIGESTION

2.1.1 Processes, feeds and products associated with Anaerobic Digestion

Anaerobic digestion (AD) consists of 4 processes: hydrolysis, acidogenesis, acetogenesis, and methanogenesis. The first step converts carbohydrates, proteins and fats into smaller compounds such as sugars, amino acids, and fatty acids. Volatile fatty acids are formed during acidogenesis, thereafter acetic acid and hydrogen gas (H_2) are produced during acetogenesis. Lastly, methanogens consume acetic acid or H_2 to produce bio-methane (CH_4) (de Mes et al. 2003). See Figure 2.1 below for a basic anaerobic digester flow diagram (Mitchell et al. 2015)

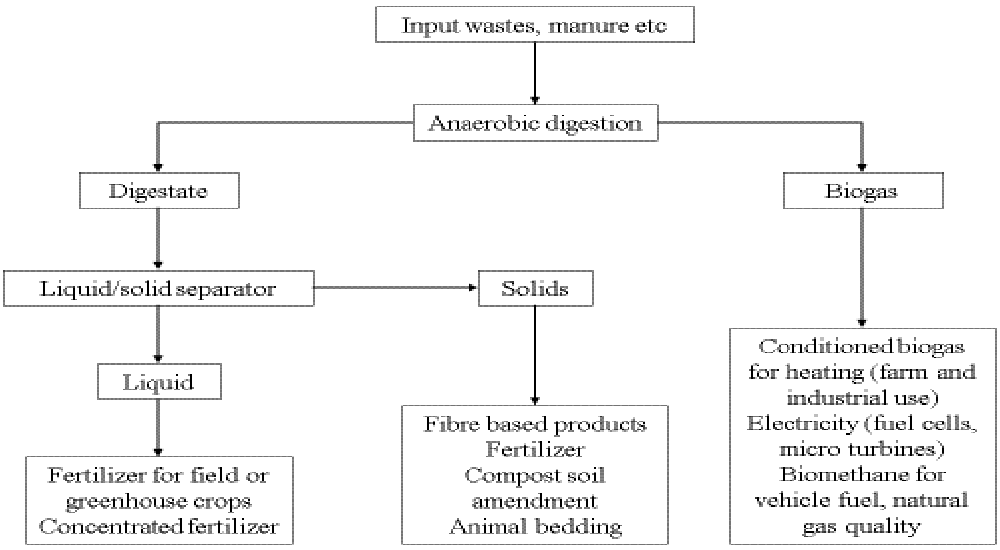

Figure 2-1 Schematic flow diagram of a basic anaerobic digester system

Different wastes can be used to power an anaerobic digester. Municipal wastes, faecal wastes, animal manure, wood and paper pulp are some of the popular feeds to anaerobic digesters. Mixed wastes are quite common too (Cherubini & Strømman 2011). This study only focuses on cattle manure slurry as feed for anaerobic digestion. See Table 2.1 for the composition of cattle manure used for feeding the anaerobic digester in this study.

Table 2-1 Composition of cattle manure (Lorimor et al. 2008)

	Total manure	Solid fraction	Liquid fraction
Nitrogen kg/day	12.36	6.18	6.18
Phosphate kg/day	4.08	3.26	0.816
Potassium kg/day	8.94	1.79	7.152
Water kg/day	2900.8	290.08	2610.72
Carbon kg/day	148.32	88.99	59.33
Sulphur kg/day	3.24	1.62	1.62

The nitrogen levels shown in the cattle manure input to the digester, are not significantly changed during anaerobic digestion. Relatively high levels of nitrogen are found in both the solid and liquid phases of the digester. The conditions inside the digester keep the nitrate and nitrite levels low, but nitrogen, ammonia and ammonium are found and measured as Kjeldahl nitrogen (Mitchell et al. 2015).

The major product of AD is biogas that can be used to generate electricity and/or heat. The composition of biogas is 55 -75% CH_4, 25 - 45% CO_2, 0 – 1.5% H_2S and 0 – 0.05% NH_3. The gas is saturated with water vapour (de Mes et al. 2003). The slurry effluent stream may contain solid fibre depending on the sources of waste fed to the anaerobic digester. The slurry effluent, especially the liquid phase, contains nitrogen and phosphate that can be applied to agricultural soils (Mitchell et al. 2015).

2.1.2 Conditions inside the Anaerobic Digester

Temperature, pH and organic feed rate to the digester are important parameters for the process to run continuous and need to be as constant as possible. These conditions are required to ensure that the specific anaerobic micro-organism community exists to produce maximum methane volumes. A pH of between 7 and 8 is optimum and a temperature close to 35°C is commonly used for mesophilic conditions. The concentration of ammonia formed during the process needs to be kept low to prevent the process from stopping or slowing down. The process can be run as a batch for a few days or as a continuous process where gas is being removed constantly after a certain retention time is reached and waste is continuously fed to the digester at a steady rate (de Mes et al. 2003). Retention time varies mainly between 10 and 30 days depending on the type of waste fed to the digester (Mitchell et al. 2015).

Cobalt and nickel supplementation assist anaerobic digestion stability, the production of biogas and optimal utilisation of the substrate as feed to the digester (Gustavsson 2012). The levels of cobalt, nickel and other metals such as beryllium, copper and zinc have an impact on freshwater aquatic ecotoxicity. The levels of nickel in cow manure is approximately 0.13% but the contents vary considerably as different locations and animal sources are examined (Adesoye et al. 2014)

To ensure the anaerobic digestion process is optimised, the feedstock, process and digestate components need to be controlled. Therefore, the selection and exclusion of unsuitable waste loads need to be checked to prevent potential hazardous feed products into the system. The process needs to be monitored through periodical sampling and analyses of the biomass and digestate (Holm-Nielsen et al. 2009).

2.1.3 Types of Anaerobic Digesters

Different types of anaerobic digesters are used worldwide on small and large scale such as mixed plug flow reactor, covered lagoon and complete mixed reactor. Other systems are also gaining interest like the up flow anaerobic sludge blanket and the sequential batch reactor (Mitchell et al. 2015). The major cost for an anaerobic digester is the initial capital cost for the manufacturing of the plant and equipment. Once the capital cost is laid out, day to day maintenance and operational costs will be incurred (Holm-Nielsen et al. 2009).

2.1.4 Processes and products downstream of Anaerobic Digestion

There are various possible biogas utilization purposes. In the simplest process, H_2S is removed and the biogas dried. Thereafter, it can be used to produce heat and power (combined heat and power) or vehicle fuel, fuel cells and chemicals. Another advantage of biogas is the fact that it can be produced when waste is available and then stored easily for use when required (Holm-Nielsen et al. 2009).

The digestate resulting from the anaerobic digester can be separated into a solid and liquid phase. The dry matter content of the solid fraction is normally about 30%. 60-80% of the dry matter and phosphorus presents itself in the solid fraction. Only 20-25% of the nitrogen and 10-15% of the potassium ends up in the solid phase. Recyclable products such as clean water, fibre products and fertilizers can be recovered from the digestate (Holm-Nielsen et al. 2009).

It is useful to integrate the digestate with the agricultural fields in the vicinity of the anaerobic digester or have fixed arrangements in place for the transportation of the digestate. (Holm-Nielsen et al. 2009).

There are many possible uses for biogas and digestate, some of these were researched to find the most relevant options for use in this study. See Table 2.2 for a summary of the most probable uses of biogas and digestate.

These uses of biogas and digestate from anaerobic digestion were evaluated and some of them were combined into 6 scenarios for this study. The theory of some of these processes is discussed below.

2.2 Discussion of processes downstream of anaerobic digestion

2.2.1 Water purification

The liquid leaving the anaerobic digester can be filtered and cleaned to the quality of potable water. There are several well-known processes available for water purification. A number of methods and steps are required to produce water of drinkable quality.

Carbon filtration removes organic contaminants that may be present in the water. Ultraviolet disinfection is a very strong sterilizing agent. It kills the genetic material of any bacteria, viruses and other microbiological contaminants present in the water by using a particular wavelength, making sure there is no risk of viral or bacterial reproduction. Micro filtration is required to remove the residue of the organisms after ultraviolet treatment (Oram 2014c).

Reverse Osmosis (RO) is a very effective method for the removal of viruses, metals and chemicals by forcing water through a semi-permeable synthetic membrane. Up to 98% of the impurities can be removed (Williams 2015). Even twenty layers of membranes may be used to remove up to 99.5% of dissolved impurities in the water. If water is not used soon after purification, it may breed bacteria again and require additional treatment before consumption. The waste water contains a high concentration of impurities and can thus not be distributed until further purified. The membrane used needs to be replaced regularly (Williams 2015).

De-nitrification of the water is required as the water leaving the anaerobic digester will contain nitrogen as well as nitrates and ammonia. Eutrophication is an environmental impact caused by high concentrations of macronutrients such as nitrogen and phosphorus in water. A higher concentration of these nutrients causes certain types of species to increase unnaturally and an imbalance occurs in aquatic ecosystems (Guinee 2002). The high concentration of nitrates leaving the digester slurry, enhances algae growing in the water which in turn reduces the oxygen content of the water. During de-nitrification, nitrates (NO_3) are converted to inert nitrogen gas (N_2) (Wahal 2010).

Chlorine is widely used as an efficient disinfectant, especially in municipal potable water supplies. Chlorine kills organisms such as viruses and bacteria. It is important to have some excess chlorine in the water to provide residual disinfection. Levels of 0.3 to 0.5 mg/l of free chlorine are ideal. Low water temperature and high pH conditions will require additional contact time between chlorine and water (Oram 2014a). Other methods of disinfection were developed such as ozonation, chloramination and UV radiation. Ozone has a better disinfection ability than chlorine. While ozone kills bacteria and viruses, it also oxidises manganese, iron and sulphur that are soluble in water. The raw water runs through a Venturi and while a vacuum is created, the ozone pulls into the water to quickly react with the metals and microbiological organisms. Filtration is required after ozonation. Ozone is less soluble in water than chlorine (Oram 2014b).

Water pasteurisation is commonly used in rural areas where chemicals and modern equipment are not readily available and diarrhoea is often caused by contaminated water especially in young children. Heating water to 65°C for 6 minutes will kill parasites, bacteria and viruses. A brackish taste of water will not be removed by pasteurisation but the water will be safe to drink. Much less fuel is required for pasteurisation compared to what is required to boil water at sea level. To boil 1 kg of water from 25°C, 2570 kJ of heat energy is required while only 167.5 kJ is required to heat water from 25 to 65°C (Dale 1994). Pasteurisation does not treat any chemical contaminants in the water (Williams 2015).

Table 2-2 Summary of uses for products from anaerobic digestion

Product and application	Advantages	Disadvantages	Used to date	Status of development	References
Biogas					
Biogas for electricity and heat for boiler combined heat and power Gas turbines for generating electricity	Fights environmental pollution Meets renewal energy standards Cleaner exhaust gas than other fuel sources Reduces household energy consumption Replacing coal Reduced GHG Electricity can be sold to grid Overcomes seasonal supply of power from wind and sun	Impurities especially sulphur can lead to corrosion of equipment Biogas can be explosive when coming into contact with air in ratio of 1:8-10 Sometimes treatment of biogas required to remove H_2S, moisture and particles Biogas has lower calorific value than other fuels, more biogas will be required for heating or to produce steam.	30 MW power per day by Fluence Corporation, Italy Natural gas turbines are widely used Birra Peroni Group produces thermal energy for factory boiler Use of steam to run adsorption refrigeration systems	In South Africa the first biogas to electricity plant, was launched in Oct 2007 Situated near Mossel Bay and utilises process wastewater generated during the operation of PetroSA's gas to liquid plant at Duinzicht as the substrate for anaerobic digestion output of plant a total 4.2 MW Quota/green certificate system for supply of renewable energy in countries such as Sweden, Norway, Belgium, Poland, Rumania	(Mitchell et al. 2015) (Holm-Nielsen et al. 2009) (Zafar Ilyas 2006) (Sacher et al. 2014) (GmbH 2016) (GmbH 2016) (Holm-Nielsen et al. 2009)

Product and application	Advantages	Disadvantages	Used to date	Status of development	References
Biogas used to produce solid oxide fuel cells	Clean process Waste is reduced		Biogas reforming and their ensuing effects on solid-oxide fuel cell performance are explored Phosphoric acid fuel cell in Japan brewery Solid oxide fuel cells on farm scale	Using biogas tri-reforming and Solid Oxide Fuel Cell is promising for application in small and medium sized stationary power systems Direct Fuel cell plants generate up to 5.1 x 10^6 MWh of clean electricity as of September 2016	(Lo Faro et al. 2013) (de Mes et al. 2003)
A biogas-powered train or biomethane for vehicle fuel	Cleaner exhaust gases and reduction of waste. Lower noise levels than diesel heavy vehicles.	Must be compressed or liquified Biogas has lower calorific value and higher volumes are required	Biogaståget Amanda (The Biogas Train Amanda), has been in service in Sweden since 2005 Germany increased the portion of biomethane in fuel to 10% by 2013 80 municipalities in Germany use natural gas fuel buses Pure biomethane available at 180 filling stations in Germany. Sweden, the Czech Republic, France, the USA and New Zealand.	15000 vehicles driving on upgraded biogas gas in Sweden, and the forecast is of 70000 vehicles, running on biogas supplied from 500 filling stations, by year 2010-2012 Swedish program now aims for commercial expansion of vehicle	(Neal & Wilkie 2014) (GmbH 2016) (Holm-Nielsen et al. 2009) (Underwood & Tomich 2013)

Product and application	**Advantages**	**Disadvantages**	**Used to date**	**Status of development**	**References**
			EU had 459facilities for production and upgrading of biogas to transport fuel in 2015 The Netherlands high values of electricity from AD of animal manure, household waste etc	fleets and infrastructure for (upgraded) biogas refuelling stations TABLE 5. Indicative gas quality requirements for various applications TABLE 6. Overview of techniques used for biogas treatment	(Scarlat et al. 2018) (de Mes et al. 2003) (de Mes et al. 2003)
Biogas for cooking, lighting and space or water heating	Less smoke causing eye infection and lung diseases Protecting the environment by cutting off less trees No need to buy fossil fuel sources for household use	Modify LP gas systems as biogas needs less air to burn Specially designed biogas burners or modified appliances needed	Households in Africa and Asia Replaces kerosene lamp	Fully incorporated in many poor areas in Africa and Asia	(Sacher et al., 2014)
Upgrading and injection biogas into the natural gas grids	Biogas is much easier to produce than the extraction of natural gas	Production of biogas does not necessary take place close to natural gas pipe systems	Stockholm Vatten AB plant is running since early 2016, cleaning waste water, producing biogas for upgrading to methane	Bioferm energy systems report in 2016 on various plants where biogas is renewed for use to generate electricity or heat	(Mitchell et al. 2015) (Holm-Nielsen et al. 2009) (Krayl 2015)

Product and application	**Advantages**	**Disadvantages**	**Used to date**	**Status of development**	**References**
Digestate					
Nutrient rich liquid for agricultural soils Digestate replacing fertilizer NPK	Lower pathogen concentrations. Improve crops for selling and use. Reduced usage of mineral fertilizer. Reduction of water pollution. Economical advantages for farmers.	Different crops need different nutrients, digestate cannot automatically apply to any soils or plants		Short term studies done with good results compared to commercial fertilizers	(Mitchell et al. 2015) (Kirk, DM. Gould 2012) (Rigby & Smith 2011)
Anaerobic digestion solids can be made into organic fertilizer pellets using digestate and limestone	The nutrients such as nitrogen, phosphorus and potassium are already mineralized and can be used by plants more effectively. Granules are easier to store, transport and there is no run off during application.	Strength of granules depends on many parameters	Anaerobic digestion liquor together with limestone for granulation		(Voća et al. 2005) (Mangwandi et al. 2013)
Compost soil amendment from solid and liquid effluent	Improved utilization of plant nutrients	Inappropriate application to soils can cause: ammonia emissions, nitrate leaching and overloading of phosphorus			(Holm-Nielsen et al. 2009)

Product and application	**Advantages**	**Disadvantages**	**Used to date**	**Status of development**	**References**
Purification water treatment processes AD digestate into clean water for reuse	Reuse of water possible Waste water is cleaned while source of energy is created	Concentrated effluents to be treated Expensive processes	Ion Exchange, carbon filters, ozone, UV, ceramic filters, copper zinc systems, reverse osmosis Only on pilot and laboratory scale by 2011	Well entrenched processes in many applications. Technology is available but the use thereof is still limited to some European countries and other first world countries.	(Williams 2015) (Holm-Nielsen et al. 2009) (Christenson & Sims 2011)
Producing biodiesel while cleaning waste water using microalgae AD nutrient outflow as feed for algae that can be source of biodiesel	Reducing waste while obtaining useful product. Digestate contains the nitrogen and CO_2 required by algae			Some parts of South Africa (e.g. in the Upington area, N Cape and near Messina (Limpopo) have ideal conditions for growth of high-oil content algae: long sunlight hours during summer, relatively high temperatures. South Africa also has more open land (compared to Europe), and a relative large demand for transport fuels such as diesel (8.7 billion litres used in 2006)	(Burton et al. 2009)

Product and application	**Advantages**	**Disadvantages**	**Used to date**	**Status of development**	**References**
				Several saline waste-water streams relating to the mining and desalination industries could also potentially be used by salt tolerant algal species, supplemented by seawater in coastal areas. South Africa does not have significant large-scale algal farming experience. The biofuels industry in South Africa is also still in the formative stage.	
AD effluent for cow fodder	Increase cow's milk that can be sold		Households in Africa and Asia		(de Mes et al. 2003)
AD solids into livestock bedding	Animal bedding from digestate does not contain pathogens that cause diseases in the animals	Intensive management necessary to ensure a healthy environment, with low pathogen concentrations	The digestate gets separated from the solid content of the manure, it can be dried and be used for bedding		(Kirk & Gould 2012)
AD solids into fuel pellets	Fuel can be available close to the anaerobic digester location	Low calorific value of digestate compared to wood	Fuel pellets are made of digestate. The ash from the combustion contains N, P, K that can be applied to soil	Studies are done since 2010	(Kirk & Gould 2012) (Kratzeisen et al. 2010)

Product and application	**Advantages**	**Disadvantages**	**Used to date**	**Status of development**	**References**
AD solids into construction material (medium density fibreboard and fibre/plastic composite materials	Fibres of animal manure is strong enough to produce medium density fibreboards and wood plastic composites. Less nuisance from odours and flies. Digestate solids contain higher concentrations of plant-available nitrogen and phosphorus compared to as-excreted manure. High carbon content of digestate solids adds organic matter to the soil and improves the water holding capacity of the soil.	Other waste sources from AD may not contain fibres that are strong enough		Animal manure fibre panels have adequate bending strength, stiffness and internal strength. Painting of these fibreboards still needs to be investigated and expanded to a larger scale	(Kirk & Gould 2012) (Rigby & Smith 2011)
By-products of biodiesel production are soaps, glycerol	Available in high volumes. Many applications		Glycerol can be used in food industry: sweetener in drinks, moistening agent for baked goods, prevent sugar crystallisation. Solvent for food colourings. Preservative, anti- freeze, personal care products. Tablet holding agent and raw material in petrochemical industry.		(Wen 2013) (Bonotto 1988)

Product and application	**Advantages**	**Disadvantages**	**Used to date**	**Status of development**	**References**
Producing pigments and chemicals from microalgae	Artificial colourants can be replaced		Dunaliella is cultivated in Israel, the United States and Australia for use as natural colourants. Spirulina is marketed as a nutritional supplement.		(Bonotto 1988) (Cho et al. 2002)

2.2.2 Algae Bio-oil as feed for Biodiesel production

The anaerobic digester slurry contains sufficient nutrients to sustain the growth of algae. Algae contain a much higher percentage of oil than terrestrial crops such as sunflowers or soya beans. Algae grow fast but needs to be kept in suspension. Sunlight and carbon dioxide (CO_2) are required for photosynthesis and reproduction. Open or enclosed photo-bioreactors are used and both types have advantages and disadvantages. Open photo-bioreactors are more susceptible to the environmental conditions but cheaper to operate while closed systems can be controlled better but involve higher operating costs (Halim et al. 2012). The oil is separated from the solid biomass by solvent extraction using hexane. The oil (triglycerides) can be transformed into biodiesel (Wen 2013).

Biodiesel is mainly produced using base catalysed trans-esterification. The process does not require high temperature or pressure and conversion yields are 98%. The triglyceride (oil) from the algae is reacted with an alcohol to form glycerol and an ester. During the esterification process, a strong alkaline such as sodium hydroxide is used as a catalyst. A mono-alkyl ester or biodiesel is produced with crude glycerol as by-product (Christenson & Sims 2011).

Algae biomass can also be converted into bio-oil, bio-char or gas via pyrolysis where the solid biomass is liquefied at elevated temperatures of up to 700°C in the absence of oxygen. The bio-oil produced can be refined for the production of heating oil and fuels for vehicles. The benefit lies in pollution reduction when compared to incineration. Alternatively, biomass can be partially combusted to produce syngas and ash at temperatures higher than 800°C in the presence of steam or air to generate a syngas mixture of CO, H_2, CO_2 and CH_4 with some light hydrocarbons. The syngas can be used for providing heat, generating electricity and chemical synthesis (Chen et al. 2016).

Algae biomass can also be converted into bio-ethanol as well as many non-fuel applications such as bio-plastics, paints, fertilizer, pharmaceutics, colorants and lubricants. The application is determined by the cost of the algae biomass as there is competition for the use of algae in the production of biodiesel, especially biomass grown on waste-water. Thermo-chemical liquefaction may lead to the conversion of low oil content algae into high energy density transportation fuels (Chen et al. 2016).

2.2.3 Generation of electricity using a gas turbine

Similar to natural gas, biogas (consisting of approximately 65% methane) is applied widely after clean-up (removal of H_2S and CO_2) for generation of electricity and heat, so-called "combined heat and power" or "CHP". The calorific value of 1 m^3 of biogas have the potential of generating 6 kWh of electricity using a gas turbine but efficiencies are generally low at 30 - 40 % for small applications with a methane content of 60 – 70%. (Yingjian et al. 2011).

Internal combustion engines are most commonly used for power generation and all size engines are in use. Biogas can be combined with diesel or plant oil injection in dual engines or else spark ignition engines are used. The biogas will need to be stored as it is produced to keep the power generation equipment running as continuously as possible. See Figure 2.2 for the main components in the biogas production system and CHP generation (Salman 2015b).

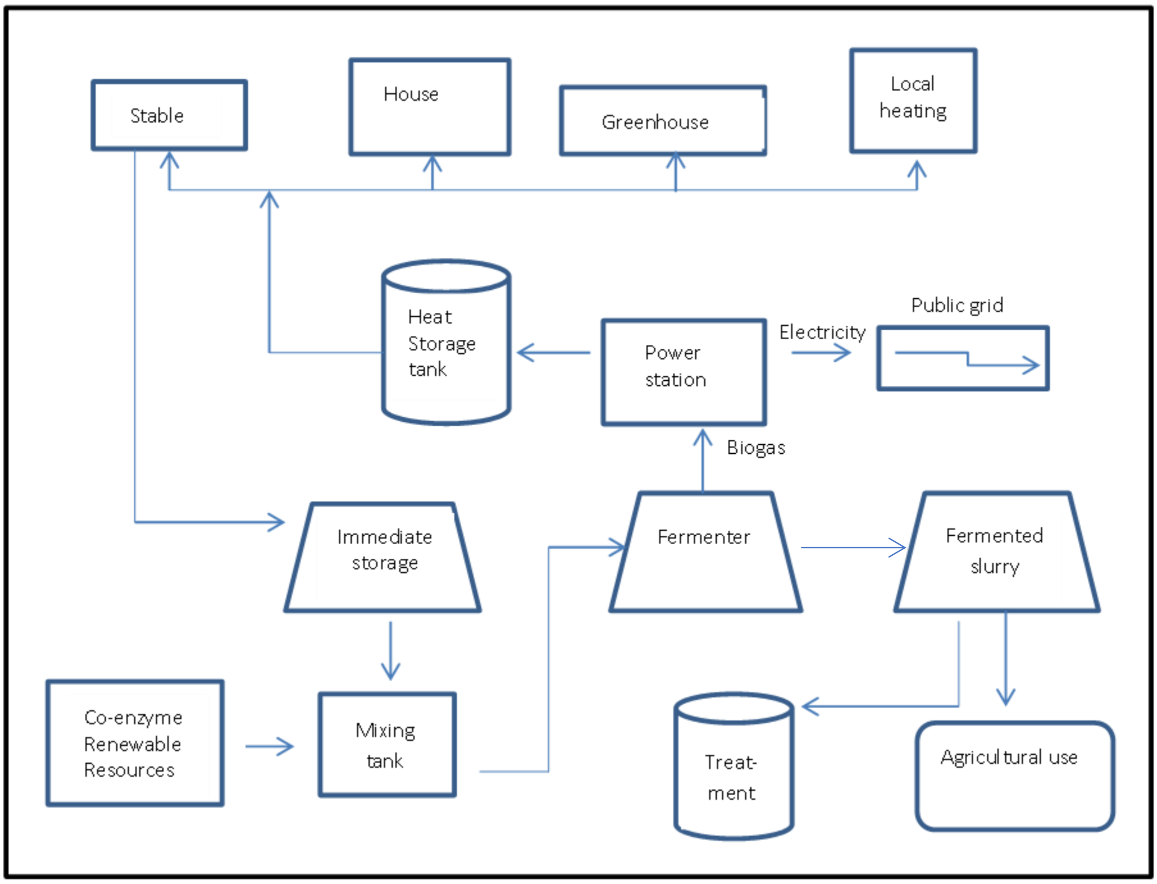

Figure 2-2 Anaerobic digestion process with application on small scale

2.2.4 Pelletized fuel or fertilizer from digester solids

Pelletizing of solid waste requires different processes and equipment for segregation, crushing, and solidifying before fuel pellets can be produced. These products are also known as Solid Recovered Fuel (SRF), Refuse Derived Fuel (RDF) or Process Engineered Fuel (PEF) (Salman 2015a).

The physical appearance of the digester outlet is changed and additives or binder materials are used while producing the pellets. The calorific value of the pellets is much higher than that of the initial slurry outlet due to the removal of the inorganic materials and moisture. The pellets can be used for the generation of electricity or heating of equipment such as boilers (Salman, 2015a).

The calorific value of raw municipal solid waste (MSW) is around 1000 kcal/kg while that of fuel pellets is 4000 kcal/kg. On an average, about 15–20 tons of fuel pellets can be produced after treatment of 100 tons of raw garbage. Since pelletizing enriches the organic content of the waste through removal of inorganic materials and moisture, it can be a very effective method for preparing an enriched fuel feed for other thermo-chemical processes like pyrolysis/gasification, apart from incineration. By transforming the solid digestate into fuel pellets, the disposal of waste to landfill areas is prevented. This fuel source has superior emission characteristics compared to the exhaust gases of coal or wood burning.

This is a renewable energy source considered with other sources such as wind, solar and biomass (Salman 2015a).

The digestate can also be successfully turned into fertilizer granules by adding very small particles of limestone (50 microns) to the slurry that is mainly liquid (90%). Different granulation times, speeds and solid-to-liquid ratios have been tried. As in all fertilizer granulation processes, the granule strength is of utmost importance to ensure the particle is still intact after drying, packaging and transportation to the area intended for application (Mangwandi et al. 2013).

It is important to ensure the safety of both people and animals when fertilizer from anaerobic digestate is applied to crops or plants. The composition of the bacteria must be checked for pathogenic bacteria before application. The digestate from anaerobic digestion normally contains enough nitrogen and phosphorus but additional potassium is required for the correct N:P:K nutrient ratios required by different plants. The nutrients in the digestate are much easier absorbed by plants than commercial fertilizers as the anaerobic digestion transforms the nitrogen into ammonia. If different feed materials are used for the anaerobic digestion process, other important nutrients such as magnesium will also be available to the plants through the digestate-fertilizer, while heavy metals should be minimized to prevent them from ending up in water sources (Voća et al. 2005).

2.3 LIFE CYCLE ASSESSMENT

Anaerobic digestion and the uses of the products from this process have environmental impacts that may determine the viability of the processes as possible energy and nutrient sources. These impacts need to be compared to current processes using fossil fuels and other energy sources. The impacts of current waste handling processes or the lack of it, also need to be investigated. An acceptable methodology for determining the impact on environmental categories by anaerobic digestion and the processes discussed above, is required. Life cycle assessment (LCA) is an internationally acceptable method for this purpose and defined by ISO standards (Heijungs et al. 2009). LCA through CML impact assessment methodology is used in this research study to determine the environmental impacts of the anaerobic digester together with the processes associated with its products as well as the impacts of a conventional milk cow stall operation. More information about the LCA methodology is now discussed.

2.3.1 Definition and history

Products and services are used and/or created while following a cycle from cradle to grave having environmental impacts that need to be measured. Products are normally first designed, manufactured from raw materials sourced from the earth and its surroundings, then used and finally follow a route of either reuse, disposal or recycling. During any product’s existence, the environment is affected by possible emissions and use of resources (Rebitzer et al. 2004).

The SETAC (Society of Environmental Toxicology and Chemistry) triangle was developed to illustrate the components of Life cycle assessment. See Figure 2.3 illustrating the “SETAC triangle” (Klopffer 1997).

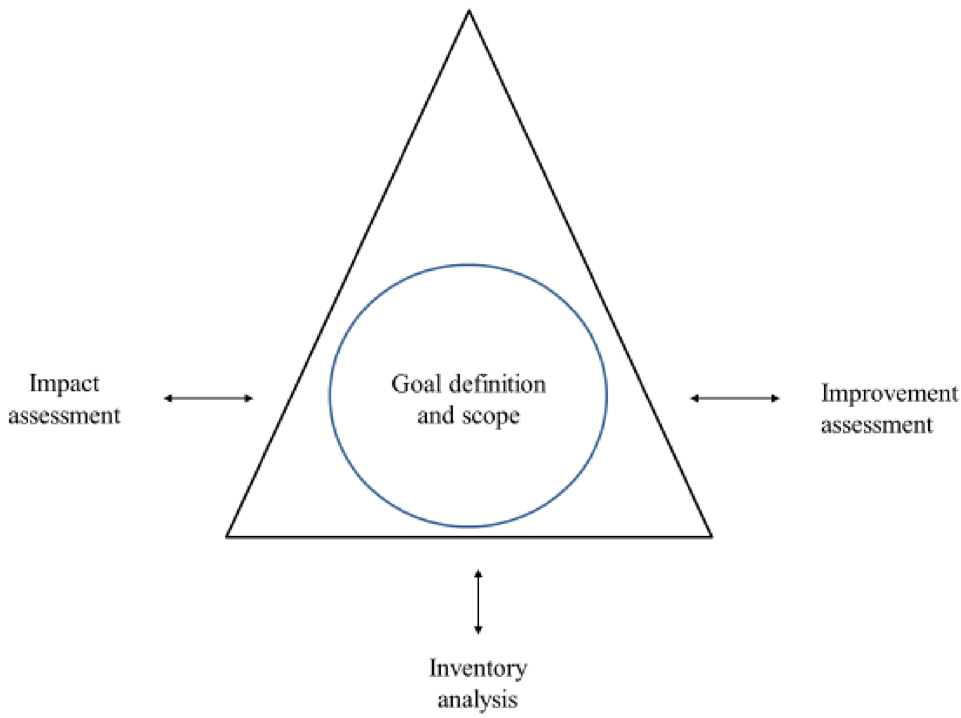

Figure 2-3 The "SETAC triangle"

Today, the ISO 14044 standard provides the guidelines for LCA execution. The standard defines an LCA as "addressing the environmental aspects as well as potential environmental impacts through the use of resources and environmental consequences of releases throughout a product's life cycle from raw material acquisition through production, use, end-of-life treatment, recycling and final disposal (i.e. cradle-to-grave)" (ISO 14044 (2006), Switzerland).

The uses of an LCA varies from sector driven to global exploration and comparative studies disclosed to the public (Guinee, 2002).

Under ISO 14044 the "improvement assessment" component was replaced by "interpretation"(Klopffer 1997). ISO 14044 together with ISO 14040(2006), cancelled and replaced ISO 14040 (1997) that contained the standards on principles and framework as well as ISO 14041 (1998) on the goal and scope definition details, ISO 14042 (2000) that covered the details on life cycle impact assessment and lastly ISO 14043 (2000) on the standards for life cycle interpretation (Rebitzer et al., 2004).

2.3.2 The components of LCA

"Goal and scope definition" entail a description of the product system with the boundaries defined, the intended use of the study also needs to be determined. A functional unit needs to be defined for the study to allow comparisons of results with other systems and products. The study needs to have boundaries set between the studied system and the environment as well as between the studied system and other product systems (Klopffer 1997). Another source distinguishes between three different types of system boundaries. They are boundaries between the "technical system and the environment", between "significant and insignificant systems" and between different "technological systems" (Guinee 2002). The anticipated use for the LCA plays an important role in the approach to the impact assessment. Any limitations identified during the development of the scope needs to be carefully recorded. The details of the decision makers need to be known when the results of the study are compiled and presented and interactive communication with them is encouraged (Miettinen 1997).

Geography and time can be defined as boundaries in certain scenarios while the ISO standard defines all raw material inputs where no human interaction has played a role as "elementary flows" with emissions going back to nature. A time dimension can be brought into the study but where landfill sites are involved, emissions can take place over a long period of time. The products emitted can also change over time if released at a low rate. Short and long-term impacts are often reported separately. LCAs are sometimes only relevant to a specific technological system, a specific time period or a geographical area. Allocation of the environmental impact of a system with many functions or processes is one of the most difficult aspects of this type of study and the outcome of the study is highly dependent on the decisions made in this regard. Often processes are sub-divided into smaller systems and their impacts determined individually. The ISO standard contains some guidelines on allocation (Heijungs et al. 2009).

The "Inventory" (LCI) step involves the determination of all inputs and outputs for all stages of the product life that cross the system boundary. It is a "material and energy balance" indicating all emissions, resources used, co-products produced, energy and waste flows to water, air and soil. Specific and generic data can be presented in data format and needs to be collected from real processes as far as possible (Klopffer 1997). This data inventory can be referred to as the material and energy balance, the inventory table, or the eco-balance of the product.

"Life cycle impact assessment" (LCIA) involves 4 steps, i.e. classification, characterisation, normalization and weighting or valuation. This stage transforms the data from the inventory phase into data for potential environmental impacts. The data is interpreted according to the environmental impact and relevant social implications or preferences. During the characterisation step, the actual modelling results are concluded. The final stage is the weighting of category impact results and possible preferences to the various impact categories proposed (Guinee 2002). Accurate models are needed and are continuously developed and improved for use by those who need to do life cycle assessments. The result of the LCIA stage is often dependent on the choices and assumptions made with regards to boundaries and processes included during the LCI phase (Rebitzer et al. 2004).

Different sets of databases are used such as public regional or national databases, industry and consultant databases. "Ecoinvent" and "US NREL" have the facility to compile inventories of unit processes selecting the relevant inputs and outputs. Many industry based databases have already aggregated datasets for all the outputs to the environment (Heijungs et al. 2009). More information about the database selected and used will be discussed in chapter 3.3.1.

During the LCIA stage, the categories impacted by the product system are determined and then quantified. The total impact on each category from each stage of the system is calculated by adding all the individual impacts together. The importance of the various category impacts is considered and depend on the purpose of the LCA. Sometimes normalizing and weighting are used to assist with the interpretation of the study results although valuation is mostly subjective (Miettinen 1997).

The severity of the impacts on the various categories depend on the properties of the substance emitted, the type of receiving environment as well as the quantities and characteristics of the product released. Impact categories that are classified as global such as ozone depletion or climate change are impacted independent of where the substance was released. For the regional or local environmental categories, the global impacts are less significant. The sensitivity of the receiving environment often plays a major role in the final outcome of the LCA and decisions made from the results (Heijungs et al. 2009).

"Interpretation" is the final stage where the results of the LCIA are summarized and discussed to present conclusions and recommendations for decision-making purposes according to the goal and scope definition of the LCA (ISO 14044 (2006), Switzerland).

Weighting is normally divided into two methods, i.e. panel discussion or monetisation where values are expressed in terms of money. The reliability of the results of the LCA depends strongly on the uncertainties of the inputs to the study such as the completeness and accuracy of the data, choices made related to the goal and scope, accuracy and completeness of relations (Heijungs et al. 2009). See Figure 2.4 for a diagram on the 4 stages of an LCA (Technical Committee ISO/TC 207, Environmental management & SC 5 2006).

2.3.3 Applications of LCA

LCA is a method to determine the environmental impact of a product from cradle to grave on categories such as marine aquatic ecotoxicity, ozone layer depletion and acidification potential. A life cycle assessment can serve different purposes and be executed by different types of institutions or professionals.

It may be executed before a new product is introduced by a company or an upgrade of a system is planned. Governments, research facilities or entrepreneurs may be the initiators of the process. When support for the development of environmental regulations is required, a public LCA study may be done by government. The same may be required to give consumers of a product peace of mind or when new standards need to be implemented. The private sector will also apply this methodology to create environmental sensitivity with consumers or to market a new product. The results of such a study should always motivate manufacturers to reduce the environmental impact of the product during production, use and disposal stages (Rebitzer et al. 2004).

Two types of LCA studies are being performed; the first is the descriptive method where a process is evaluated solely on the existing parameters and information available. The second type is a comparative study where scenarios are compared with each other or step changes are simulated and the impacts calculated for each situation. LCAs can also be either simplified or detailed. The potential interest and impact of the process and its products will determine to what extend the LCA needs to be done (Guinee 2002). The two types of Life cycle assessments are also known as attributional (descriptive) and consequential (comparative). Attributional is a study of a product system as is while the consequential study is executed with expected consequences of a change in mind (Rebitzer et al. 2004).

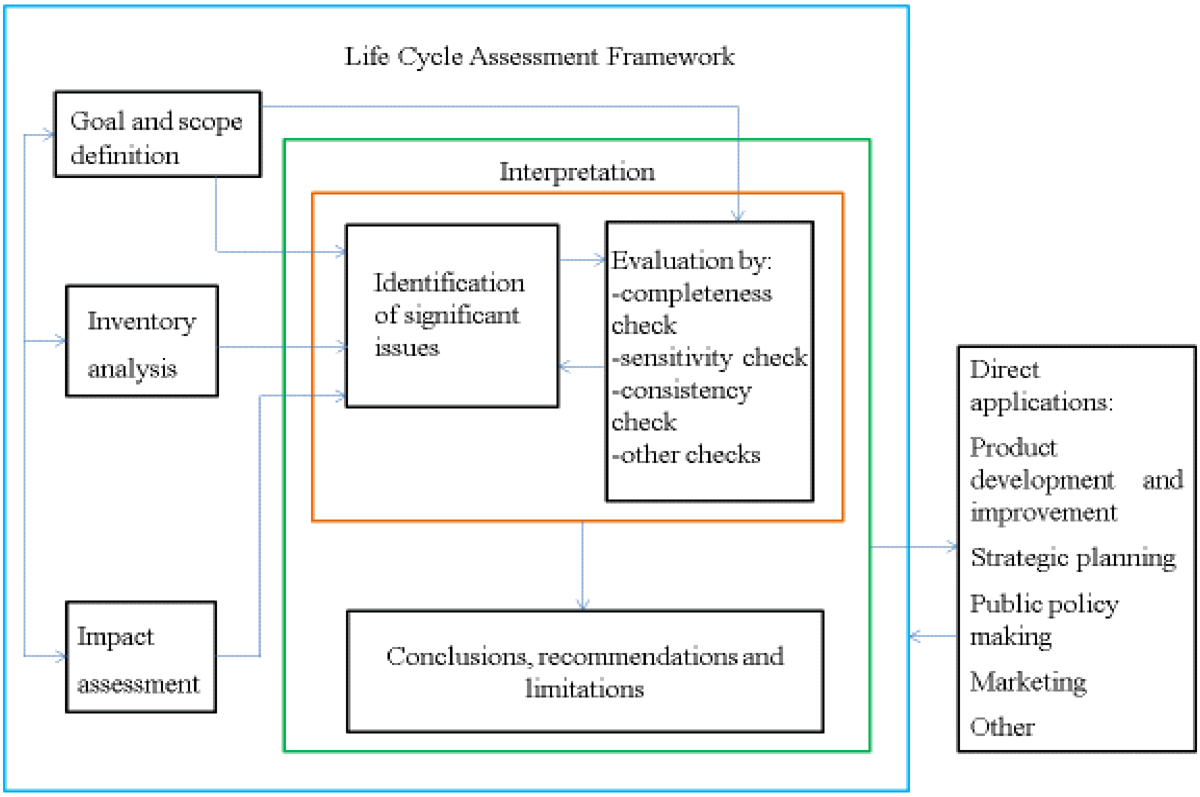

Figure 2-4 Relationships between elements within the interpretation phase with the other phases of LCA (Technical Committee ISO/TC 207, Environmental management & SC 5 2006)

See Table 2.3 for a list of the possible impact categories.

Table 2-3 List of CML and other impact categories (Guinee 2002)

Impact Category		
A. CML impact categories	**B. Study-specific impact categories**	**C. Other impact categories**
Depletion of abiotic resources Impacts of land use land competition Climate change Stratospheric ozone depletion Human toxicity Ecotoxicity freshwater aquatic marine aquatic terrestrial Photo-oxidant formation Acidification Eutrophication	Impacts on land use loss of life support function loss of biodiversity Ecotoxicity freshwater sediment marine sediment Impacts of ionising radiation Odour malodourous air Noise Waste heat Casualties	Depletion of biotic resources Desiccation Odour malodourous water

2.3.4 Description of the CML impact categories (Guinee 2002)

2.3.4.1 Depletion of abiotic resources

Non-living resources found naturally are classified as abiotic resources. Examples are minerals and sources of energy such as wind. This category is often impacted by processes and is split into 2 sub-categories by the database used in this study, i.e. "depletion of abiotic resources such as elements and ultimate reserves" and "depletion of abiotic resources such as fossil fuels". The unit of measurement is kg (antimony eq).

2.3.4.2 Climate change

Climate change is measured by the heat radiation absorbed by the atmosphere. This radiation is caused by emissions from human processes. There can be negative impacts on the health of humans and the ecosystems. The effect of the absorbed radiation is a rise in temperature of the earth's surface or the so called "greenhouse effect". The unit of measurement is kg (carbon dioxide eq).

2.3.4.3 Stratospheric ozone depletion

Pollution from human processes can cause the stratospheric ozone layer to become thinner and then allowing more solar UV-β radiation to penetrate the ozone layer and reach the earth's surface. This radiation can be potentially dangerous to the health of animals, humans, land and water ecosystems. The unit of measurement is kg (CFC-11 eq).

2.3.4.4 Human toxicity

The impact of toxic substances on human health is checked by this impact category. These impacts can originate from toxic substances in air, water or soil. The unit of measurement is kg (1,4 – dichlorobenzene eq).

2.3.4.5 Freshwater aquatic ecotoxicity

The impacts of toxic substances on various forms of freshwater aquatic ecosystems are measured. The unit of measurement is kg (1,4 – dichlorobenzene eq).

2.3.4.6 Marine aquatic ecotoxicity

The marine aquatic ecosystems are monitored for the impacts from toxic substances. The unit of measurement is also kg (1,4 -dichlorobenzene eq).

2.3.4.7 Terrestrial ecotoxicity

The impacts of toxic substances on terrestrial ecosystems are determined. The unit of measurement is kg (1, 4 dichlorobenzene eq).

2.3.4.8 Photo oxidant formation/photo chemical oxidation

When primary air pollutants such as "volatile organic compounds" (VOCs), sulphur and carbon monoxide react with sunlight, reactive chemical substances e.g. ozone and peroxy-acetyl-nitrate (PAN) can be formed and cause harm to human health in the form of coughing and bronchial irritation. It is also dangerous to ecosystems and plants. The unit of measurement is kg (ethylene eq).

2.3.4.9 Acidification potential

Sulphur dioxide, NO_x and NH_x are the main acidifying pollutants that can potentially cause harm to organisms, materials and ecosystems in groundwater, surface waters and soil. Fish populations and impacts on forests are two examples of this impact. The unit of measurement is kg (SO_2 eq).

2.3.4.10 Eutrophication

An excessive increase in macronutrients and especially nitrogen and phosphorus can cause harm to the environment. The higher levels of macronutrients can cause an increase in the population of certain species and biomass in water and on land that will result in an imbalance inside ecosystems. Surface water may become unfit for use as drinking water and lower levels of oxygen will be available in aquatic water systems due to the consumption of oxygen by the decomposition of biomass. The emissions caused by the degrading of organic substances also form part of this impact category. The unit of measurement is kg (PO_4 eq).

2.4 SUMMARY OF LITERATURE OVERVIEW

Anaerobic digestion of different types of waste, consists of a 4-stage process and two main products result from the process, biogas and digestate. Several processes have been developed to utilise biogas as energy source and digestate as source of nutrients such as nitrogen, phosphate and potassium. Without an anaerobic digester, the farmer can spread cattle manure over agricultural fields but no form of energy can be obtained from a conventional stall of milk cows. This conventional process has certain environmental impacts and so does anaerobic digestion and the processes that follow the production of biogas and digestate from the digester.

Life cycle assessment is a method to determine environmental impacts of processes from cradle to grave and is guided by ISO 14044. The results of the impacts on the impact categories (calculated by CML methodology in this study) can be compared with each other to determine what processes are more environmentally friendly than others. The “Ecoinvent” database used, is one of several databases that already have aggregated datasets for most of the outputs to the environment.

3 METHODOLOGY

3.1 Anaerobic Digester Setup at Stellenbosch University

The setup at Welgevallen experimental farm (Stellenbosch University, SU) was used as basis for this study. A photo of the anaerobic digester at SU before commissioning is shown in Figure 3.1.

Figure 3-1 Photo of the Anaerobic digester at Stellenbosch University before commissioning

See table 3.1 for a description of the setup of the anaerobic digester in this study.

Table 3-1 Description of the setup of the Anaerobic Digester

Description	**Number**	**Reference**
No of cows in stall	60	
Average manure produced per cow per day	36 kg	ASAE 2005
Total manure produced per day at stall	2160 kg	
Water content in manure	88%	
Water used to wash manure into digester per day	1000 litre	
Total volume fed to digester per day	3.17 m^3	
Temperature inside digester for mesophilic conditions	35°C	Dennis & Burke 2001
Average ambient temperature in Stellenbosch for past 30 years	20.59°C	NASA 2016
Total solids in manure slurry per cow	4.18 kg/day	Fisheries 2015
Total solids in manure for this stall	250.8 kg/day	

Description	Number	Reference
Volatile solids in manure per cow	3.56 kg/day	Fisheries 2015
Total volatile solids in manure for this stall	213.6 kg/day	Fisheries 2015
Composition of solids fed to digester (C:N = 12)	0.08% N 0.03% P 0.06% K 51.9% C	Lorimor & Powers 2004
Yield of biogas from volatile solids	40%	Dennis & Burke 2001
Raw biogas produced	85.1 Nm^3/day	

More details about the mass balance for the system are shown in Appendix A.

The functional unit selected for this study is 1 day's operation of the stall of 60 cows and all the outflows from there to the anaerobic digester. The average figure for milk production per cow worldwide is 15 litres per day (Compassion in world farming 2012). The volume manure produced in 1 day is fed to the anaerobic digester and related volumes of biogas and digestate are produced. These products are applied in various combinations to form scenarios that are compared on their environmental impacts using the Life cycle assessment methodology. See Figure 3.2 for a diagram of the basic anaerobic digestion process chosen with influents and effluents.

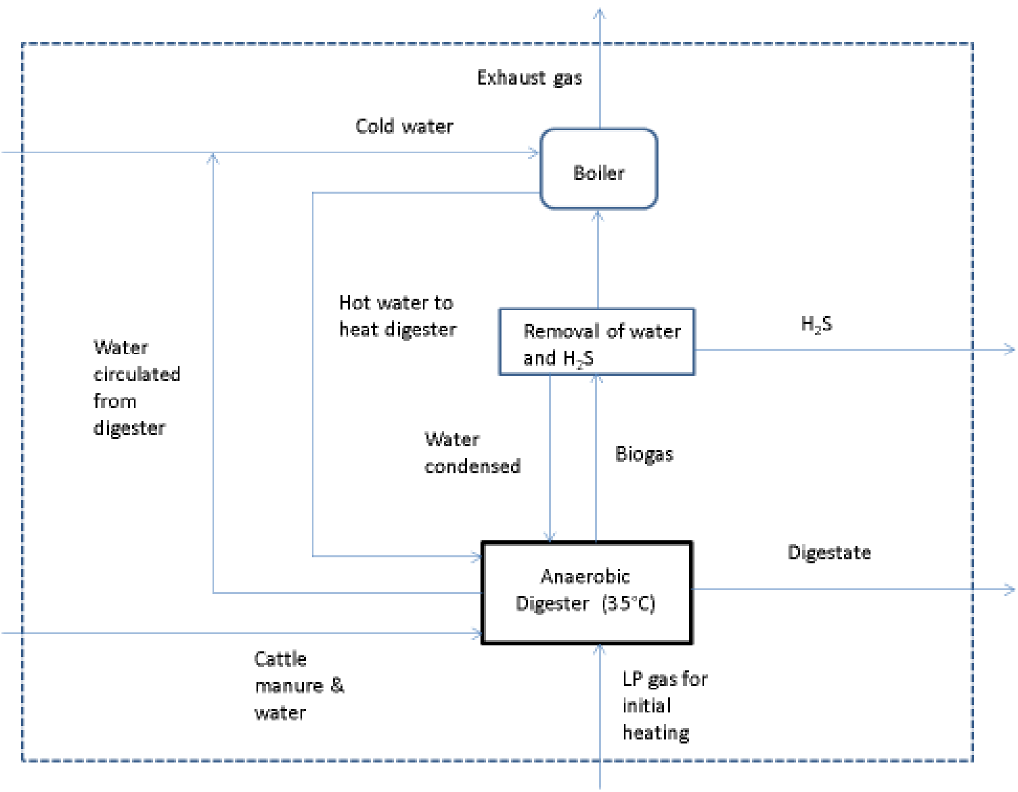

Figure 3-2 Diagram of Anaerobic digestion of cattle manure showing influents and effluents

The typical composition of the biogas produced in the digester from animal waste is given in Table 3-2 (Mitchell et al. 2015).

Table 3-2 Typical composition of biogas from animal manure

Components	Formula	Typical range	Figure used
Methane	CH_4	60 – 75%	65%
Carbon dioxide	CO_2	19 – 33%	28%
Nitrogen (including ammonia)	N_2	0 – 1%	1%
Hydrogen	H_2	0 - 1%	1%
Hydrogen sulphide	H_2S	0.3 – 1%	1%
Oxygen	O_2	0 – 0.5%	0.5%
Water	H_2O	0 - 6%	3.5%

From the drawings of the digester unit (Sustainable engineering solutions 2016), the following dimensions of the digester were obtained and presented in Table 3-3.

Table 3-3 Dimensions of the digester

	Length (mm)	Width (mm)	Height (mm)	Volume (m^3)
Top section per compartment	2500	2200	750	4.125
Bottom section per compartment	2500	2200	2500	13.75
Total for 3 compartments in bottom section				41.25

The hydraulic retention time (HRT) of the digester is calculated by dividing the volume of the unit by the daily flow. For this digester, the HRT is calculated as 13 days. This agrees with the range found in literature of 10 to 30 days for this type of reaction (Mitchell et al. 2015).

The specific heat (Cp) of dairy cattle manure corresponding with a high water content such as 88% in this case, equals 3.606 kJ/kg°C (Nayyeri et al. 2009). The energy required to heat the cattle manure slurry from ambient temperature to 35°C is calculated as 163.7 MJ/day. The digester is made of concrete and mostly buried underground with a heat transfer coefficient of approximately 1.2 W/m^2°C (Fulton et al. 2001). The heat loss through the walls of the digester adds up to 270.15 MJ/day. Thus, the total energy requirement for the contents of the digester to stay at 35°C, is 433.8 MJ/day. This energy needs to be supplied by burning LP (liquified petroleum) gas for the first 13 days until the digester starts producing biogas as energy source.

LP gas has a calorific value of 25 MJ/litre (Hahn 2010). To keep the digester at 35°C, 10.06 kg/day of LP gas is required. As the LP gas is burnt, 30.19 kg/day of CO_2 gas is released.

The slurry residue leaving the digester is called the digestate and contains nutrients such as nitrogen, potassium, phosphate, carbon and sulphates. More than 90% of the effluent is water because the solid content of the digester influent was reduced by 35 - 50% during the digestion process. The solid content of the digestate is 5.5 – 8.5% according to literature (Moore 2008).

The total mass of the digestate flow is calculated as 3064 kg/day. The composition of the digestate from the mass balance is shown in Table 3-4. Details of the mass balance are found in Appendix A.

Table 3-4 Calculated composition of the digestate

Components	Percentage
Nitrogen as ammonia	0.37%
Phosphate	0.13%
Potassium	0.29%
Sulphate	0.07%
Carbon as COD	3.55%
Water	94.61%
Other nutrients	0.98%

The calorific value of biogas is 22 MJ/Nm^3 (de Mes et al. 2003). It is assumed that 80% of the water in the raw biogas (85.1 Nm^3/day) is removed by condensing it and all the H_2S gas scrubbed to prevent corrosion inside the boiler, leaving 81.87 Nm^3/day of biogas. The total energy available per day is 1801 MJ in this scrubbed biogas flow.

3.2 Life cycle inventory for the various scenarios

Six different scenarios were created and investigated where biogas and digester effluent were utilized in different ways. All the scenarios contain the same anaerobic digester process that includes all cattle manure handling and upstream storage processes and concludes with the products from the digester. A base case is created with the standard operation of the cattle stall containing 60 milk cows where after the manure from the stall is applied to the nearby fields while gas produced by the animals and housing activities are vented to the atmosphere. All the environmental impacts of the stall, digester, manure and downstream processes are accounted for. The milk stall process was amended for the six scenarios to prevent double accounting of the manure's impacts by both the stall and digester processes. Offset processes for the 6 scenarios are added to the base case and where applicable in the various scenarios to normalise the results.

3.2.1 Base case scenario

The base case is firstly defined as the normal operation of a cattle stall with 60 milk cows. The database process is based on the production of milk per cow per day and includes all activities and emissions associated with this operation. The milk production is calculated according to the "fat and protein corrected milk" formula from the International Dairy Federation in equation 1 using 4% fat and 3.3% true protein found in the database (GreenDelta 2016).

$$\text{FPCM} = \text{Prod x } [(0.1226 \text{ x fat\%}) + (0.0776 \text{ x protein\%}) + 0.2534] \qquad (1)$$

where FPCM (kg/year) is "fat and protein corrected milk" production in 1 year and Prod (kg/year) is actual production of milk in 1 year. The calculations were converted to obtain a useful figure for the stall of 60 cows for 1 day as it is the functional unit of this LCA. This equation is an indication of the conversion efficiency of dairy cows' feed into useful products for human consumption (Shirley 2006).

The processes involving the application of manure (solid and liquid) to the nearby agricultural fields are added to the base case as they are not part of the cattle stall operation process in the database. See more processes included in the base case scenario in paragraph 3.2.8 to offset the processes included in the various scenarios.

3.2.2 Scenario 1: Heating pool/split digestate application

After 80% of the water vapour and all the H_2S is removed from the biogas produced during anaerobic digestion, the biogas enters the boiler to produce warm water for heating the digester as well as the sport facility's indoor swimming pool. Of the 1801.05 MJ/day of energy available in the biogas, 433.8 MJ/day is used to keep the digester at 35°C continuously.

The digestate sludge is filtered where after the solid fraction is send through a filter press to reduce the liquid content to a maximum of 12%. The solids fraction is sent to a dryer to reduce the moisture to < 10% (Bolzonella et al. 2017). To evaporate water from the digestate 1.1 MWh of energy per ton of water is required supplied by the biogas (Bolzonella et al. 2017). At a dryer efficiency of 80%, 58.4 MJ/day of biogas energy will be required to dry the digestate. The hot air can be recirculated over the dryer to optimise energy efficiency. The dry product (124 kg/day) is used as compost at nearby agricultural fields. The liquid fraction together with the liquid from the filter press and the dryer (total of 2935 kg/day) are used for irrigation of the sports facilities' lawn.

The composition and masses of the liquid and solid fractions of the digestate after filtration, are found in table 3-5. These figures are important for calculating the impacts of the different applications of the two phases in the various scenarios.

Table 3-5 Calculated composition of the digestate fractions

	Digestate leaving digester, kg/day	**Solid fraction, 35% solids kg/day**	**Liquid fraction, kg/day**
Total mass	3064	355	2709
Solids	165	124	41
P	4.08	3.06	1.02
N	11.4	2.8	8.6
K	8.9	1.3	7.6
C	109	82	27
Water	2900	230	2670
S	2	1.6	0.4
Other nutrients	30	24	6

After heating the digester and the digester solids, the remaining energy available from the biogas is used to heat the indoor swimming pool at the nearby sport facilities. The swimming pool is 50 m long, 20 m wide and 2 m deep. The temperature should be maintained at 27°C during training sessions and events for a period assumed to be a maximum of 10 hours per day.

The temperature of the air inside the building is maintained at 24°C. The temperature of the water drops to 24°C during the non-heating period. The heat loss from the surface of the water is calculated as 643 MJ/h using the following formula in equation 2 (Lund 2000).

$$q = Us(Twf - Ta) \tag{2}$$

where q is the heat loss from pool surface (kW), U is the heat transfer coefficient (kJ/s m^2 °C), s is the surface area (m^2) and T_{wf} and T_a are the temperatures of the water and ambient air respectively (°C). The remaining energy from the biogas after heating the digester and supplying energy for the dryer is 1367 MJ/day. This energy will only be sufficient to replace the energy loss from the swimming pool's water for 2 hours and save that equivalent of power supplied by the National supplier. See Figure 3-3 for a diagram of scenario 1.

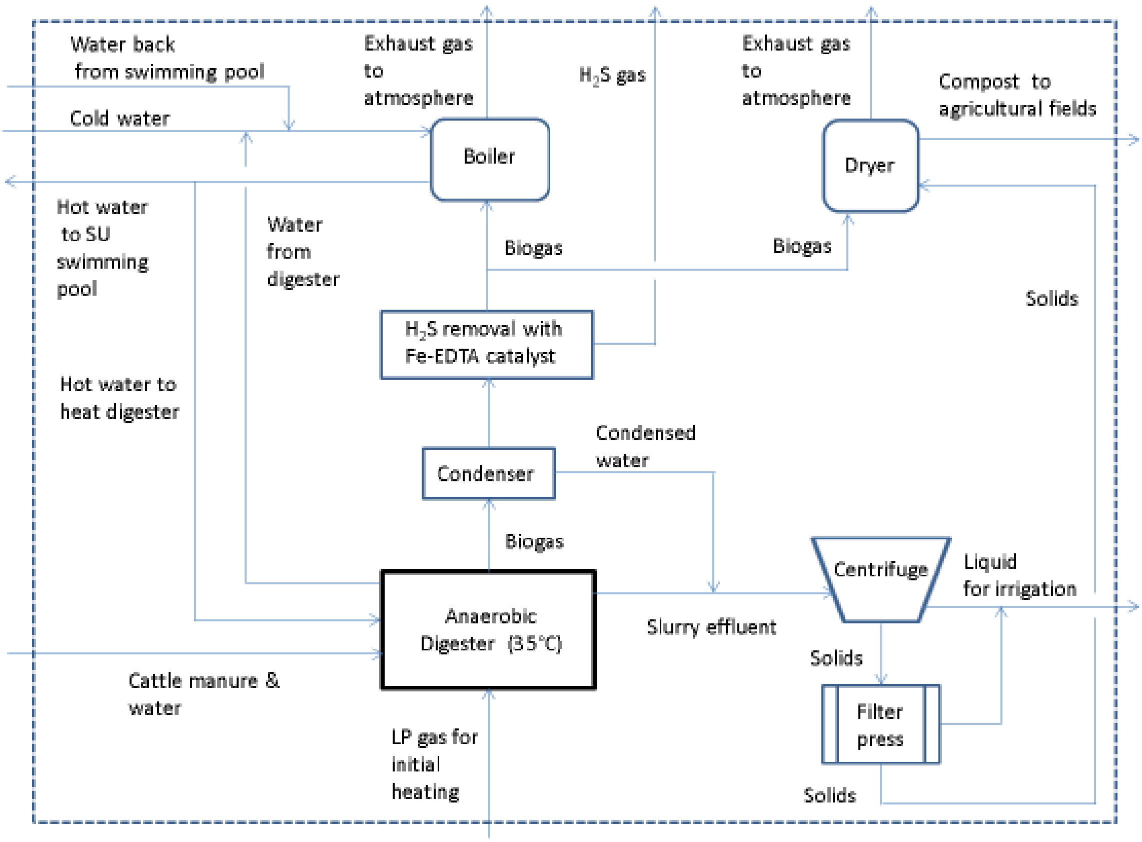

Figure 3-3 Flow diagram of Scenario 1

3.2.3 Scenario 2: Heating pool/pasteurised water for domestic use

Scenario 2 is similar to scenario 1 in all aspects except for the way the liquid fraction of the digestate is utilized. In this scenario, after filtration of the digestate, the liquid fraction is pasteurised by heating it to 65°C for 6 minutes to kill all bacteria, viruses and parasites (Dale 1994).

The energy required to heat the 2935 kg/day of liquid to 65°C is 368.7 MJ/day. The energy available in the biogas produced during anaerobic digestion is sufficient to keep the digester at 35°C (433.8 MJ/day), dry the digestate solids (58.4 MJ/day) and pasteurise the liquid phase.

There is 940.2 MJ/day of energy available to keep the water of the indoor swimming pool at 27°C and save electricity that is normally bought from the national supplier. The energy will only be enough to replace the heat loss from the pool for almost 1.5 hours. See Figure 3-4 for a diagram of scenario 2.

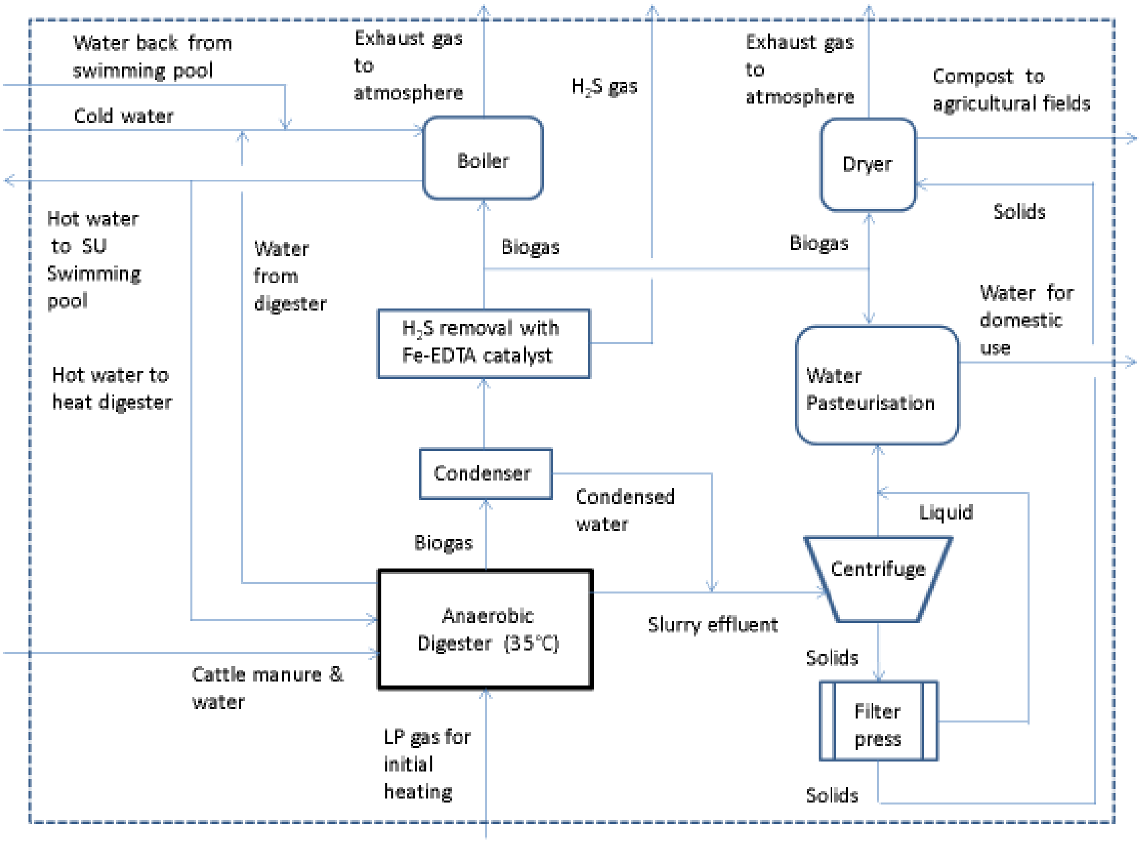

Figure 3-4 Flow diagram of Scenario 2

3.2.4 Scenario 3: Bottling biogas/full digestate as nutrient supply

In scenario 3, energy from the biogas is firstly used to keep the digester at 35°C before the rest of the gas is scrubbed of CO_2 for bottling under pressure into 9 kg cylinders for use by the community as energy source for cooking or heating. The scrubbed biogas is almost pure methane used for bottling. If 9 kg cylinders are used, 4 units can be filled per day if energy for pressurizing is obtained from the national supplier. The bottling is done at 10 000 kPa and requires approximately 275 MJ/day (Zafar Ilyas 2006). The energy available per 9kg cylinder is 495 MJ and consists of 13.5 Nm^3. To heat water from 25 to 100°C at sea level, 314 kJ of energy is required. A cylinder of 9 kg methane can heat 1576 litres of water while a cylinder of 9 kg biogas can heat only 963 litres of water. The environmental impact of bottling and burning methane is included in the LCA. The bottled biogas supplies 2197 MJ/day of energy that a community member can use for cooking or heating instead of obtaining the energy from the national supplier or burning fossil fuels. All the digestate from the digester, 3064 kg/day is used for irrigation and nutrient supply to the nearby agricultural fields. See Figure 3-5 for a diagram of scenario 3.

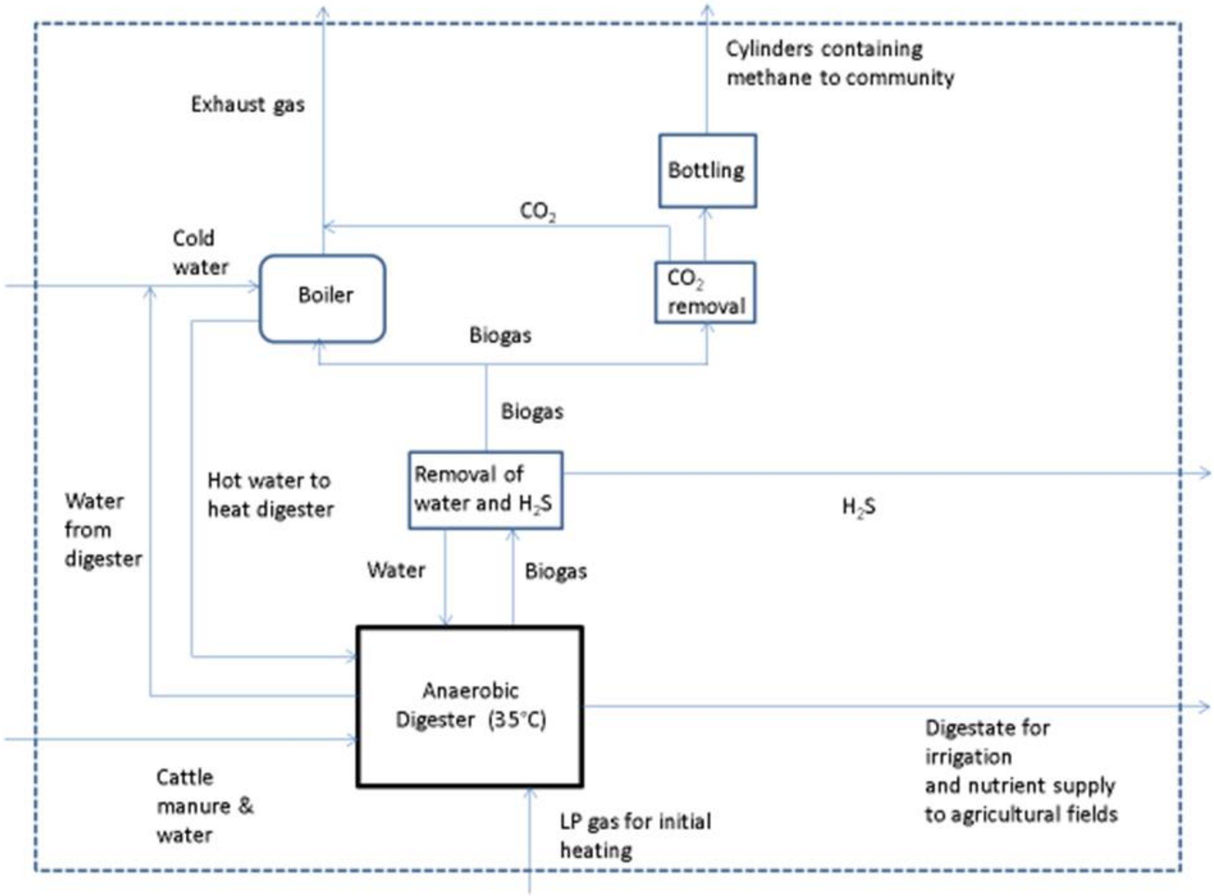

Figure 3-5 Flow diagram of Scenario 3

3.2.5 Scenario 4: Power generation/fertilizer pellets

The digestate from the digester is split into liquid (to irrigate fields or greenhouse crops) and solid fractions. The solids are converted into fertilizer pellets. The biogas from the digester is used for the supply of energy to the digester, pelletiser, dryer and the balance for generation of electricity that can be sold into the national grid.

As for scenario 3, this scenario also requires a smaller boiler/geyser than in scenario 1 and 2 as water only needs to be heated to maintain the digester temperature at 35°C. The digestate (3064 kg/day) produced during anaerobic digestion is filtered and the liquid fraction together with the condensate from the condenser is used for irrigation of greenhouse crops. The total solid fraction of 124 kg/day solids, is dried and pelletised into fertilizer pellets. The water removed from the solid fraction is calculated as 224 kg/day requiring 896 MJ/day of energy for the drying process. Biogas (50.9 Nm^3/day) is used as energy source at 80% efficiency in a direct fire dryer (Zlokarnik 2012). After the drying step, 118 kg/day of material is fed to the pelletiser. The energy requirement for the pelletising process is 12.73 MJ/day of heat for the mass of material available (Girovich 1996). Energy used at the boiler, dryer and pelletiser steps, equals 1567 MJ/day with 10.6 Nm^3/day of biogas remaining for power generation. This volume of biogas is scrubbed with water to remove the CO_2 to ensure equipment runs optimally during power generation. The LCA includes the environmental impact of this process. Power generation of 7 kWh/day from biogas is possible at an electrical efficiency of 28% (Yingjian et al. 2011). This can offset the same amount of power used by the University from the National supplier. See Figure 3-6 for a diagram of scenario 4.

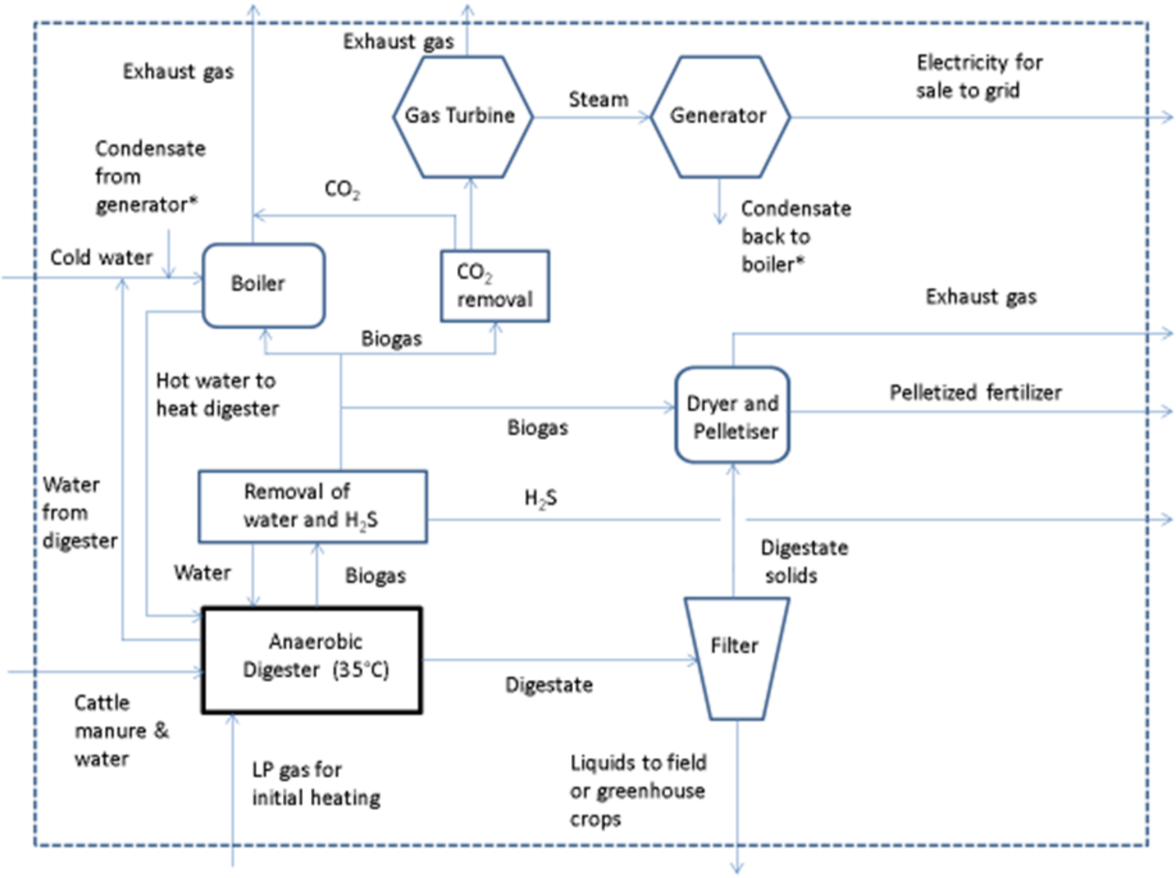

Figure 3-6 Flow diagram of Scenario 4

3.2.6 Scenario 5: Bottling biogas/NPK fertilizer pellets

In scenario 5, the digestate is filtered and the solids sent to a granulator where limestone is added for the manufacturing of fertilizer (NPK) granules. The biogas remaining after heating the digester, is cleaned and bottled into 9 kg cylinders like in scenario 3. The boundary for biogas, is the cylinders with biogas made available to local community members for cooking.

Limestone is added to the solid fraction containing phosphate, nitrogen and potassium to produce NPK fertilizer pellets in a granulator (Mangwandi et al. 2013). This product can replace some of the NPK fertilizers available on the market. Every 28000 ton of digestate can be changed into 9200 ton of fertilizer (Drosg et al. 2015). Potentially 198 kg/day of fertilizer can be produced from the 602 kg/day of filtered digestate. Granules of 2-4 mm are produced with a water content of 4%. At 60% efficiency, 119 kg/day of granules can be expected from the process. An experimental efficiency of 46% was improved by optimising the parameters of the granulator such as the impeller speed, the ratio of feed to product as well as the ratio between solids and liquid (Mangwandi et al. 2013). The ratio of N:P:K for this pellet composition is approximately 3:1:2. The liquid fraction of the digestate is used nearby for irrigation. Warm water is only required to keep the digester at a constant temperature. The remaining biogas (105.4 kg/day) is scrubbed for bottling. See description and details of this process in paragraph 3.2.4. See Figure 3-7 for a diagram of scenario 5.

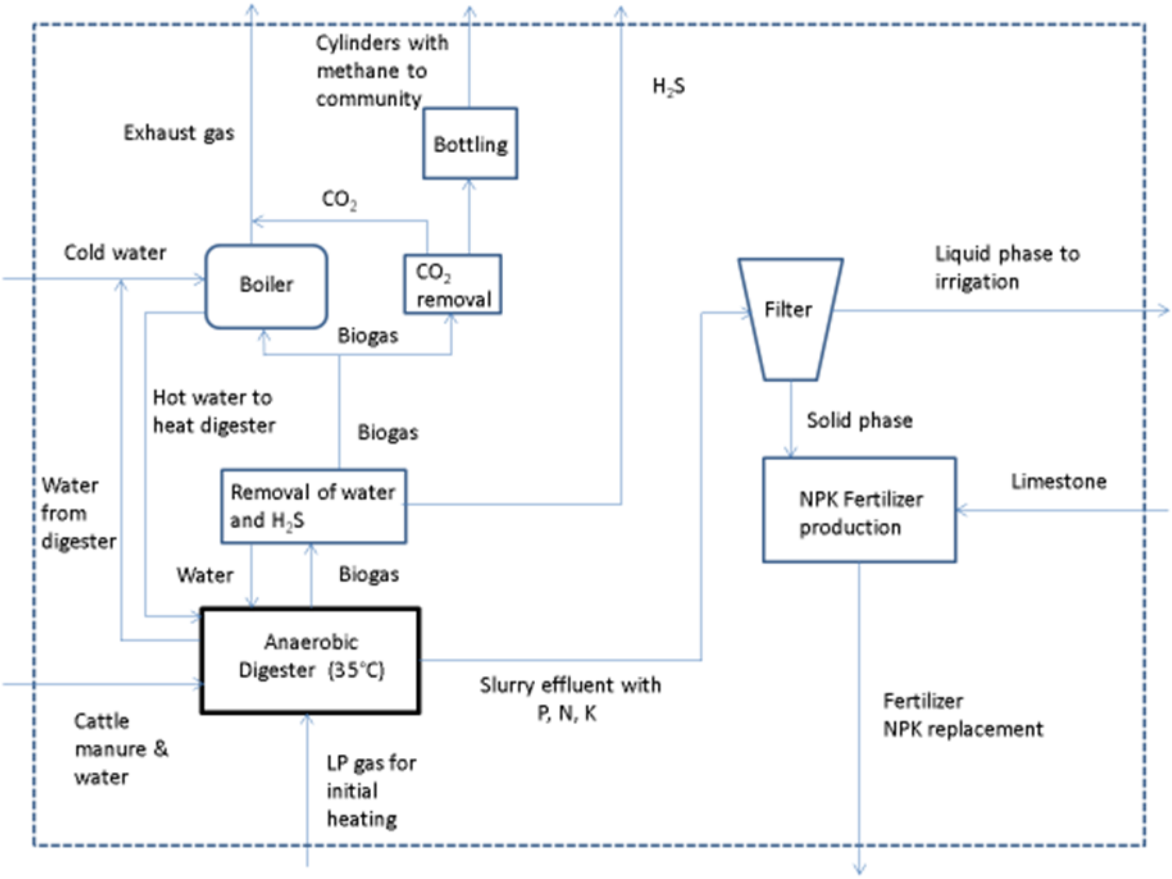

Figure 3-7 Flow diagram of Scenario 5

3.2.7 Scenario 6: Biodiesel from algae/bottling biogas

After heating the digester, the remaining biogas (105.4 kg/day) is water scrubbed to remove CO_2 and bottled as in scenarios 3 and 5. The bottled biogas is used by the local community as energy source replacing energy supply from the national supplier. The same process applies to this scenario as in scenarios 3 and 5.

The exhaust gas of the boiler as well as the liquid phase of the digestate is fed into an open pond photo-bioreactor (75m x 50m) for algae cultivation. The algae are cultivated for the production of biodiesel while glycerol is produced as by-product. The system boundaries for this scenario are defined up to the outlet of biodiesel, glycerol and hot water to storage facilities. The digestate from the digester is centrifuged/filtered. The solid fraction (354.5 kg/day) is used to fertilize nearby fields while the liquid fraction (2709 kg/day) is used as nutrients for the photo-bioreactor as it contains nitrogen in the form of nitrates and ammonia as well as phosphate. The algae oil is extracted with the use of hexane. The algae oil is then converted into biodiesel using methanol during a trans-esterification process with sodium hydroxide as catalyst. Glycerol is produced as a by-product (Halim et al. 2012). Bio-oil equal to 11.2 kg is produced daily, making production of 12.2 litre/day of biodiesel possible. The by-product, glycerol, is produced at 1.2 kg/day. Calculations are based on the ratios found in literature (Gnansounou & Jegannathan 2016) as seen in Table 3-6 below.

Table 3-6 Ratios of raw materials to final products in the production of biodiesel (Gnansounou & Jegannathan 2016)

For production of 1 kg of biodiesel, the following raw materials are required:	
Algae oil	1050g
Methanol	124.9g
NaOH	10.5g
Sulphuric acid	15.8g
Water	140g
Glycerol co-production	113.3g
1050g Algae oil requires:	
Protein	1940.4g
Algae biomass	1629.6g
To produce 1629.6g Algae biomass requires:	
Methanol	7.4g
Ethanol	139.6g
Dry algae	4620g
Hexane	2.95g

It is important to note that the environmental impacts determined for this scenario by means of life cycle assessment are only for the processes involved with the production of biodiesel and not the construction of any equipment required to produce biodiesel. See Figure 3-8 for a diagram of Scenario 6.

3.2.8 Base case (continue)

Electricity is generated from biogas produced by the anaerobic digester in scenario 4: Power generation/fertilizer pellets. This process is offset in the base case and the other 5 scenarios by an offset process generating power using hard coal as source of energy.

As the production of biodiesel using a photo bioreactor followed by the trans-esterification of bio-oil, is one of scenario 6: Biodiesel from algae/bottling biogas processes, an offset process needs to be included in the base case and the other 5 scenarios. This offset process produces the same volume of diesel from crude oil and its environmental impacts are determined. The impacts of the combustion of diesel in a freight vehicle are included as an offset process in the base case and scenarios 1 to 5. The impacts of the combustion of the same volume of biodiesel are included in scenario 6. See Appendix B for the detail of all the processes and offset processes included in each scenario.

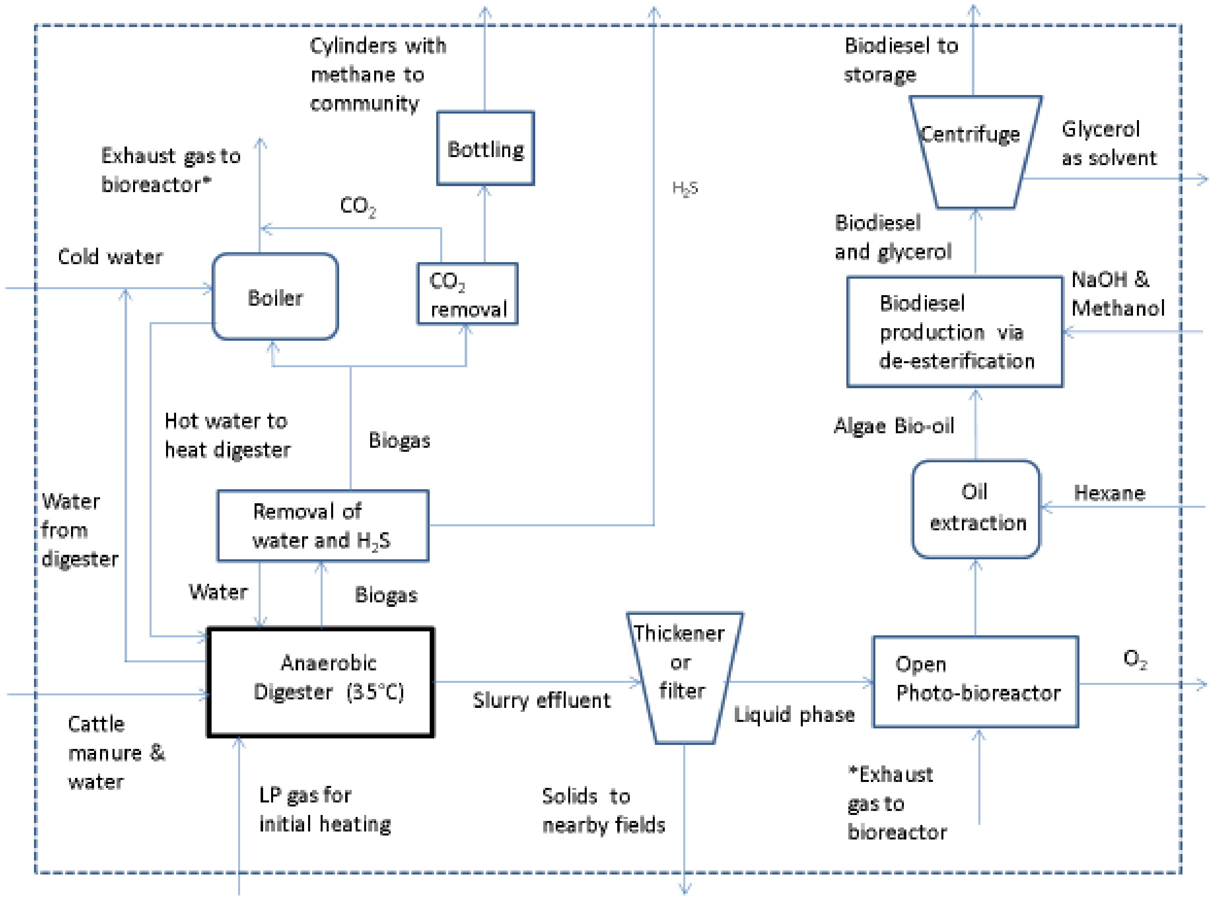

Figure 3-8 Flow diagram of Scenario 6

Note: The "milk cow stall operation without the impacts of manure" process is part of each scenario from 1 to 6. This process accounts for all the activities associated with a milk cow stall such as feeding, ventilation, milking, enteric processes and lighting. The activities and constituents associated with manure production in this process as well as handling and storage of the manure, were reduced by 80% as these processes are covered in the anaerobic digestion process. The greenhouse gas emissions from the stall were reduced to 55% as the enteric emissions from the cattle account for 45% of the GHG emissions from the cattle stall (Rotz 2017).

See Table 3-7 for a detail layout of the processes found in each scenario including the processes which were added to offset processes found in other scenarios.

Table 3-7 Layout of scenarios showing all processes and off-set processes

Process	Description	Product (unit)	Target amount						
			Base Case	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6
Operation housing milk cows	Milk production from cow/cow milk or amended milk stall operation	Milk (kg)	926.9	926.9	926.9	926.9	926.9	926.9	926.9
Anaerobic digestion of cattle manure to produce biogas	Anaerobic digestion of manure / biogas / cut- off	Biogas (Nm^3)	-	81.87	81.87	81.87	81.87	81.87	81.87
Heat offset from biogas using coal for all processes (no digester heating)	Heat and power co-generation, hard coal, heat, district or industrial	Energy (MJ)	1367	-	-	-	-	-	-
Heat generation from biogas for digester, dryer, pasteurisation, swimming pool as applicable	Heat production, biogas, at diffusion absorption heat pump 4 kW	Energy (MJ)	-	1801	1801	-	-	-	-
Heat generation from biogas for digester and dryer, before power generation	Heat production, biogas, at diffusion absorption heat pump 4 kW	Energy (MJ)	-	-	-	-	1567	-	-
Heat generation from biogas for digester and cooking from bottled gas	Heat production, biogas, at diffusion absorption heat pump 4 kW	Energy (MJ)	-	-	-	1801	-	1801	1801
Heating digester with propane	Heat production, propane, at industrial furnace > 100kW	Energy (MJ)	-	434	434	434	434	434	434

Process	**Description**	**Product (unit)**	**Target amount**						
			Base Case	**Scenario 1**	**Scenario 2**	**Scenario 3**	**Scenario 4**	**Scenario 5**	**Scenario 6**
Production of EDTA to use as catalyst for removal of H_2S from biogas	EDTA production/ ethylenediamine-tetra-acetic acid	EDTA (kg)	-	9.15	9.15	9.15	9.15	9.15	9.15
Production of iron(II)chloride for removal of H_2S from biogas	Iron(II)chloride production/iron(II)chloride	Iron (II)chlo-ride (kg)	-	9.7	9.7	9.7	9.7	9.7	9.7
Electricity offset from biogas using coal to generate electricity	Electricity production, hard coal, electricity, high voltage	Energy (kWh)	7	7	7	7	-	7	7
Generate electricity using cleaned up biogas	Electricity, natural gas, conventional power plant/electricity high voltage	Energy (kWh)	-	-	-	-	7	-	-
Solid manure application	Solid manure application, manure solid cattle	Manure (kg)	391.9	-	-	-	-	-	-
Irrigation with manure liquid	Irrigation using manure liquid	Liquid m^3	2.69	-	-	-	-	-	-
Digestate and condensate used as irrigation of agricultural fields	Nutrient supply from manure, liquid cattle, nitrogen fertilizer	Irrigation liquid (m^3)	-	-	-	3.064	-	-	
Production of NPK fertilizer from digestate and limestone	NPK fertilizer granules manufacturing	NPK fertilizer granules (kg)	-	-	-	-	-	119	-

Process	Description	Product (unit)	Target amount						
			Base Case	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6
Liquid digestate and condensate for irrigation	Irrigation of crops in field or greenhouse	Irrigation liquid (m^3)	-	2.935	-	-	2.935	2.711	-
Fertilizer supply from solid digestate	Nutrient supply from manure, solid cattle, nitrogen fertilizer	Nitrogen fertilizer (kg)	-	-	-	-	94	-	-
Nutrient supply from digestate solids	Using digestate solids to fertilize agricultural land	Digestate nutrients (kg)	-	124	124	-	-	-	124
Photo bioreactor for algae cultivation	Nutrients feed to photo bioreactor for algae cultivation	Photo bio-reactor nutrients (kg)	-	-	-	-	-	-	2709
Manufacture diesel from raw materials to offset biodiesel	Diesel production, low sulphur	Diesel (kg)	10.7	10.7	10.7	10.7	10.7	10.7	-
Esterification of bio-oil to produce biodiesel and glycerol	Esterification of palm-oil/vegetable oil methyl ester	Veg oil methyl ester (kg)	-	-	-	-	-	-	10.7
Methanol production for de-esterification/	Methanol production/methanol	Methanol (kg)	-	-	-	-	-	-	0.00016

Process	Description	Product (unit)	Target amount						
			Base Case	**Scenario 1**	**Scenario 2**	**Scenario 3**	**Scenario 4**	**Scenario 5**	**Scenario 6**
Production of sodium hydroxide production	Neutralising agent/neutralising agent to generic market	NaOH eq (kg)	-	-	-	-	-	-	0.112
Supply of hexane for oil extraction	Iso-hexane production	Iso-hexane (kg)	-	-	-	-	-	-	0.032
Clean-up biogas to produce methane for bottling	Methane production, 96% by volume from biogas, high pressure at user	Methane, 96% by volume for energy (MJ)	-	-	-	2197	-	2197	2197
Clean-up biogas to methane for turning turbine and difference in gas for bottling	Biogas purification to methane 96vol%	Methane, 96% by volume for energy (Nm^3)	-	-	-	-	7.8	-	-
Offset transport combusting diesel	Transport, freight lorry, all sizes, EURO3 to generic market for transport, freight, lorry, unspecified	Transport (t*km)	0.107	0.107	0.107	0.107	0.107	0.107	-
Transport combusting biodiesel instead of diesel	Transport, freight lorry, all sizes, EURO3 to generic market for transport, freight, lorry, unspecified	Transport (t*km)	-	-	-	-	-	-	0.107

3.3 LIFE CYCLE IMPACT ASSESSMENT CALCULATIONS FOR THE VARIOUS SCENARIOS

3.3.1 The Database used

OpenLCA 1.5.0, that is maintained by GreenDelta, Berlin since 2006 was chosen as the backbone software for the LCA assessment after investigating several databases for this application. The costs of databases such as SimaPro and USNREL were high while OpenLCA 1.5.0 (also widely recognised in the industry) could be downloaded free of charge as long as it is used for research purposes by an institution such as SU. One of the databases under scribed by OpenLCA 1.5.0 is Ecoinvent 3.3 (latest version of Ecoinvent software). It's LCA assessment methods could also be downloaded into the OpenLCA 1.5.0 backbone program. This software is widely used by industry and researchers while the online support is of a high standard. OpenLCA offers in total more than 100 000 different datasets.

There are 3 main system models in Ecoinvent 3.3, i.e. the "Cut-off model, the "APOS" model and the "Consequential model". The "cut-off" model is based on the cut-off approach whereby a producer has to treat all wastes and by-products and can't claim any credit for recycled components. When the calculations are done, the waste is treated as a negative input to the process. No credit goes to producers should the waste be re-used or changed into new products. The "APOS" (Allocation at the point of substitution) model moves all marketable by-products originating from treatment activities into activities that treat these products as waste. The "Consequential" model makes certain assumptions to determine what changes will have an effect on an existing system (Weidema et al. 2013)

The "Cutoff" model was picked for this study for the way wastes are allocated to the originators of the waste. This method simplifies all the waste handling while comparing the impacts of the processes handling the wastes with each other. The "Cutoff LCI" model that includes the system processes and not only units that are found in the simple "Cutoff" model was used for the assessment of all the processes in this study to ensure comprehensiveness.

There are a number of Impact Assessment methods available of which the CML impact assessment method was chosen for this study. CML was established in 2001 when the "Center of EnvironmentalScience of Leiden University" led a group of scientists in grouping a number of impact categories and characterisation methods for the 3rd step in the LCA methodology i.e. impact assessment (PRe 2018). The CML methodology covers the impact categories (Acero et al. 2017) which made up the scope of this thesis. The Ecoinvent database provides a number of calculation methods such as "quick analyses", "regionalised LCIA" and "Monte Carlo simulation". The "Quick analyses" method was used as calculation method because the purpose of the study is a comparison between different scenarios and a base case. This calculation method gives the results in a simple, quick way for comparison purposes and includes global impacts without the operator's interpretation of the maths.

Each scenario in the study was divided into single processes. The database was searched for processes as close as possible to these processes. The actual amounts and products from the mass balance were entered into the database and calculations done. Where no process could be found in the database to simulate the process in the study, a process was created using the actual inputs and outputs as defined in the mass balance of that process.

The results from each process were accumulated per scenario and presented in graph format. The results for each scenario were also compared to the impacts of the base case for normalization and presentation in graph format. The normalized impacts of the 6 scenarios are compared to each other to conclude which scenario is the most environmentally friendly and can be recommended to cattle farmers as energy and nutrient sources without having a major impact on the environmental categories investigated.

3.4 MODEL VALIDATION BY COMPARISON TO LITERATURE

3.4.1 General

Many LCA studies found in literature are not complete and focus only on certain impact categories such as carbon reduction or energy usage instead of presenting the full environmental impact review (Rehl & Müller 2011). The system boundaries are also often poorly defined or results are normalised without properly stating the boundaries or criteria of the study. The information in these studies cannot be compared to any other study such as this one (Mezzullo et al. 2013).

3.4.2 Database adjustments required by the various scenarios

Some modifications had to be made to the database outputs to present each scenario more accurately. Some of the processes need to follow on each other instead of taking place in isolation. All the biogas components released by the anaerobic digester were removed as outputs from "anaerobic digestion of cattle manure" to simulate the use of biogas in the next process where "heat is generated from biogas". The same was done for all the components of the digestate from the digester. They were removed from the anaerobic digestion outputs as these are used as inputs to the various processes where the solids and liquids of the digestate are used for irrigation or nutrient supply.

The milk stall process found in the database accounts for all the stall activities such as the reception and consumption of feed, all housing systems including bedding, milking equipment and drinking water. It also includes the emissions from the housing of the animals and enteric fermentation (GreenDelta 2016). The manure components such as potassium, nitrogen and phosphate were reduced to prevent double accounting of the environmental impacts from both this process and anaerobic digestion. The compounds such as CO_2, N_2O and methane causing GHG emissions by the stall were reduced to only include the effect of the housing of the animals and enteric fermentation in this process (Rotz 2017). The use of fossil fuels was reduced to compensate for the energy required by the manure handling equipment that is already accounted for in the anaerobic digestion process. Energy is still required for lighting, milking and cleaning. It was found that energy costs and consumptions by milk cow stalls vary from country to country as well as from one farm to the next (Upton et al. 2010).

It was decided to remove all cypermethrin outputs to soil from all the processes downstream of the cattle stall as the output figures for this insecticide were all less than 10^{-7} and there was no indication that this product is used at the actual milk cow stall.

Electricity required to keep this size digester running for 1 day is approximately 11 kWh (Whiting & Azapagic, 2014) as heat to the digester is either supplied by propane or biogas produced by anaerobic digestion. The assumption was made that this quantity of electricity is supplied by hard coal only. Every kg of hard coal can supply 8.14 kWh of energy (European Nuclear Society 2018).

The effect of chromium emission to air from “anaerobic digestion” was reduced by 90% as the source of chromium is mainly stainless-steel manufactured for use as digester equipment (Whiting & Azapagic 2014). The digester in the study is made of concrete and the pipes around the digester are made of plastic suitable for temperatures up to approximately 35°C.

The database also does not a contain a process for the combustion of biodiesel in a vehicle engine. From literature, the probable emissions during the combustion of biodiesel were used to create a process to evaluate these environmental impacts (Curto et al. 2015).

3.4.3 Database results compared to literature

The concentrations of heavy metals in manure vary considerably according to animal waste sources and farm locations. Nickel levels in cow manure are found to be approximately 0.13% and compares well with the figure produced by the database (Adesoye et al. 2014). The combined effect of “anaerobic digestion of cattle manure” and “heat generation from biogas” on freshwater ecotoxicity is 38.1 kg 1,4 dichlorobenzene (DCB) eq caused by this stall. The literature value for the combined processes is 2 kg DCB eq caused by nickel, beryllium, cobalt and copper. The flow contributions from these elements are higher in the database but the sources are not specified and one can therefore not make changes to the database outlet without proper motivation. The database value is accepted for this study.

The selenium concentrations in manure are 88 µg/litre for dairy Heifer and 70 µg/litre for cows. Using the average of these figures for the volume of manure produced by this stall, 173.6 mg/day of selenium is calculated (Frankenberger & Engberg 1998). The output for selenium by the database for the “operation of the cattle stall” is 480 mg/day and considered of the same order of magnitude as the literature value because the type of cows held by the stall in this study is not specified.

The figure for photochemical oxidation found for the combined processes “anaerobic digestion of cattle manure” and “heat generation from biogas” in literature is 74 g C_2H_4 eq/MWh (Whiting & Azapagic 2014). This figure compares fairly well with the figure from the database of 112 g C_2H_4 eq/MWh (“anaerobic digestion” at 50 g C_2H_4 eq/MWh and 62 g C_2H_4 eq/MWh for “heat generation from biogas”).

Figures on fertilizer production in the EU are compared to the results from the database for the processes of manufacturing different commercial fertilizers (phosphate, potassium and nitrogen) and the application of these products to agricultural fields. The impacts on climate change and depletion of fossil fuels are discussed (Ledgard et al. 2008). The results for potassium chloride for the database and literature compare very well. The results for nitrogen fertilizers don’t compare well due to different types of nitrogen fertilizers used in the comparison (urea vs ammonium nitrate). Literature also refers to triple single super phosphates while the database refers to single super phosphates resulting in different results. These results are summarized in Table 3-8 below.

Table 3-8 Comparison of fertilizers for base case with literature

	Nitrogen fertilizer production		**Phosphate fertilizer production**		**Potassium fertilizer production**	
	Fossil fuel (MJ)	**Climate change (kg CO_2)**	**Fossil fuel (MJ)**	**Climate change (kg CO_2)**	**Fossil fuel (MJ)**	**Climate change (kg CO_2)**
Database result	146	24	212.9	15.5	35.96	2.48
Literature result	278	9.02	22.8	1.4	45.6	3.2

A comparison was done on the results from the database on "Heat digester with propane" and the results for LPG combustion found in literature (Cashman et al. 2016). See Table 3-9 below.

Table 3-9 LPG combustion impacts from database compared to literature for 1 GJ of energy supplied for heating

	LCA for LPG in China	**LCA for LPG in India**	**Database results**
Energy demand (MJ)	2784 (all non-renewable)	2106 (all non-renewable)	1094 (fossil fuels only)
Eutrophication potential (kg PO_4^{3-})	0.008 (freshwater only)	0.0029 (freshwater only)	0.023 (total)
Ozone depletion potential (kg CFC-11 eq)	2.9×10^{-5}	2.0×10^{-6}	1.19×10^{-5}
Global warming potential (kg CO_2)	188	303	86.15
Acidification potential (kg SO_2 eq)	0.68	0.33	0.166

The database results are lower than the literature values except for eutrophication potential where the database results are higher, but they are of the same order of magnitude.

The environmental risk limits of EDTA (ethylenediamine tetra acetic acid) include the permissible levels of EDTA in water as well as the effect this compound can potentially have on aquatic organisms when released as part of waste waters by different industries. Although the eutrophication effect of EDTA is recognised, no quantitative value is given. The nitrogen content of EDTA can assist algae growth under certain conditions. Excess EDTA availability in water can lead to reduction of some elements and therefore influence the growth of algae negatively (Kalf et al. 2003).

The database does not present algae as source of bio-oil and a substitute had to be picked. Due to yields from palm oil being closest to that of algae, palm oil's information was used (Addison 2001). The results from the database for scenario 6 processes involving the production of biodiesel from algae were compared to information found in literature. According to literature, the energy needed from fossil fuels for the photo bioreactor's circulation, harvesting and extraction through esterification is 315 MJ/GJ of algal methyl ester produced (Collet et al. 2014). The figure from the database is 194.3MJ/GJ of algal methyl ester for the depletion of fossil fuels while producing biodiesel. The processes do differ in some aspects. The literature source produces fertilizer as nutrient supply to the photo bioreactor while scenario 6 uses the nutrients from the anaerobic digester and the CO_2 from the boiler outlet. It also runs at ambient temperature. The reuse of the CO_2 from the boiler exhaust has a positive impact on the climate change result for the database option with a nett effect of -97 kg CO_2 eq for the biodiesel related processes. The literature figure is 26 kg CO_2 for climate change of which more than 50% is due to the production of fertilizer and energy required for this process. The acidification potential result from the database for the photo bioreactor is higher than the figures obtained for the other scenarios on this impact category. This higher result agrees with literature commenting on the ammonia volatilization from the pond surface also leading to indirect N_2O emissions and higher acidification potential (Collet et al. 2014).

The figures for ozone depletion potential of the various scenarios were analysed and found to be all < 4.5 x 10^{-05} kg CFC-11 eq. These figures were compared to figures in an article about different management options of biogas (Beylot et al. 2013). One of the options mentioned is landfill emissions of biogas with combined heat and power generation during which halo-methane compounds such as chloro-fluoro-carbons are released and impacting on the ozone depletion potential. The average figure in literature for this process is 8.85 g CFC-11 eq for the same volume of biogas produced by this study (85 Nm^3/day). The combined processes of scenario 5 which has the highest total ozone depletion potential of all the scenarios at 4.39 x 10^{-05} kg CFC-11 eq or 0.0439 g CFC-11 eq (including offset processes) and is almost 1000 times smaller than the figure for the process in the article and therefore regarded as insignificant for this study's purposes.

The results for the "operation of the cattle stall" from the database were compared to a report on dairy farming in Georgia (Belflower 2009) as well as dairy production systems in Switzerland (Nemecek & Alig 2016). Both reports only cover the impact on climate change/global warming. The figures shown for nitrous oxide, methane and carbon dioxide released by the cattle and related activities are higher than what was calculated by the database. The report for Georgia's confined dairy activities calculates 615 kg CO_2 eq for the same size stall and number of cows as this stall, while the database number is 196 kg CO_2 eq. The main reason assumed for the difference is the intensity of farming in Georgia vs this study's stall. Many factors influence the CO_2 eq release such as the type and volume of feed the cows are given, whether the stall caters for the replacement animals as well as the breed per stall. On a dairy farm, there are many secondary sources impacting on climate change such as machinery and feed production. The study's stall is a much simpler setup that does not include all these farm activities and sources impacting on climate change.

Literature on the LCA of biogas clean-up methods did not present quantitative figures although all the CML environmental impacts were covered for a number of different CO_2 removal technologies. The specific technology evaluated by the database is not described but it is assumed to be the most common method used namely "high pressure water scrubbing" (HPWS). This method is compared to other established technologies as well as two newly developed methods namely "alkaline with regeneration" (AwR) and "bottom ash upgrading" (BABIU). The HPWS and BABIU have the lowest impacts of all the possible methods on most of the environmental categories. Electricity usage by HPWS has the biggest impact on the environment. The infrastructure required for this process has an impact on depletion of abiotic resources (elements) as steel needs to be manufactured for the equipment required. This process plays quite a significant role in the total impact on the environmental categories of scenario 3, 4, 5 and 6 (Starr et al. 2012).

3.4.4 Comparison between AD of cattle manure and extraction of natural gas

In a literature comparison (Han et al. 2011) of the benefits from "anaerobic digestion of cattle manure" vs "extraction of natural gas used for fossil fuel and its impacts", the following information was found:

- Methane gas together with nitrous oxide produced by cattle impacts greatly on global warming potential. Methane is 25 times and N_2O 298 times more powerful than CO_2 when its impact on climate change is considered. The manure can rather be pumped into an anaerobic digester to produce methane gas for transformation into liquid natural gas or compressed natural gas which can both be used as vehicle fuel. The environmental impact on the global warming potential from this process is much lower than the impact of the extraction of natural gas for fuel manufacturing purposes.
- When fossil fuels (coal, natural gas) are left in the ground, there are no methane released while methane will always be released from cattle stalls. The aim is to reduce the impact from the cattle manure on the global warming potential by transforming it into usable fuel.
- The digestate from the anaerobic digester can be applied to soil but small amounts of methane are emitted with CO_2 due to the unstable carbon in the sludge. Nitrogen is also emitted due to nitrification and denitrification or by the leaching of nitrate into water systems. To compare the impact on global warming potential from the digestate with the fossil fuel case, synthetic fertilizer impacts have to be considered with the fossil fuel's carbon and nitrogen emissions.
- The biogas from the anaerobic digester goes through purification steps to increase the methane concentration to a similar grade as natural gas. There is an impact on global warming from venting or leaking of methane during the anaerobic digestion and purification steps. The estimated CH_4 loss is up to 2% while natural gas upgrading processes can lose approximately 0.15%. There are also considerable losses of methane where manure needs to be transported to anaerobic digester facilities or when biogas needs to be stored.
- Renewable natural gas from anaerobic digestion normally requires more energy inputs than the processes involving fossil fuels. Energy required and greenhouse gas releases from liquid natural gas are much less than the requirements and releases from the compressed natural gas. If emissions from fuel usage by vehicles are omitted, the next highest emissions originate from the fossil fuel recovery process and that is due to leakage and venting of methane. Renewable natural gas from AD loses methane via

leaks and the low efficiency measured on the digester-reactors. CH_4 emissions from the AD-renewable natural gas process are much lower than the emission of methane from fossil fuel processes due to the digestibility of the carbon during anaerobic digestion as well as the credits received for the use of carbon as fuel where it would have been emitted otherwise. The methane emissions from AD is also much less than normal manure handling operations because of the use of carbon as fuel source. The difference in N_2O releases between AD-renewable natural gas and fossil fuel processes is not much but still lower for the afore-mentioned.

3.4.5 Summary of model validation

The results from the database for environmental impacts by the various processes were compared to literature values. Similar criteria and environmental categories could be compared for some of the processes evaluated in this LCA. Comparisons between the database results for the processes “anaerobic digestion” and “heat generation from biogas” and literature values were found to be of the same order of magnitude for photochemical oxidation and freshwater ecotoxicity. Comparisons for the impacts from different fertilizers on climate change varied between 20 and 150% for the different types of fertilizers checked. The same variety of values were found for the impacts from LPG on some of the environmental categories. The database values calculated were used for this study as the scope and boundaries of this LCA were known while the literature values were often difficult to define according to scope and input criteria. The excellent reputation of the Ecoinvent database with many references also contributed to the decision. The database figures were used in the normalisation and weighing steps of the assessment.

4 RESULTS AND DISCUSSION OF THE LCA CALCULATIONS

Notes:

- The base case consists of the operation of a conventional cattle stall of 60 cows combined with the application of raw manure to nearby agricultural fields. Some processes in the scenarios generate heat, electricity and biodiesel from the AD products. The offset processes for these ones are included in the base case as well as where required in certain scenarios. The impacts of the offset processes are not discussed in this section.
- The amended cattle stall process: “cattle stall without impacts from manure” process has higher impacts than the other processes on most of the environmental categories assessed in the 6 scenarios. The values of the impacts of this process contribute equally to the results of all the scenarios and are part of the total values used to compare the scenarios with the impacts of the base case during normalization. The nett effect of the “cattle stall without impacts from manure” process on climate change is negative. This is due to the manual reduction of the GHG impacts in the database to compensate for the impacts from the manure already accounted for in the anaerobic digestion process. The database includes CO_2 as resource input (reducing CO_2 by photosynthesis) as part of the production of feed to the milk cows in the stall.
- See Appendix C for tables showing the highest contributors to the impacts of the various processes in the six scenarios. The information was extracted from the “flow contributors” section in the database after the calculations were done.
- The results of this consequential LCA are presented as normalised figures only for comparison purposes and no absolute values are shown.

4.1 SCENARIO 1: HEATING POOL/SPLIT DIGESTATE APPLICATION

The environmental categories of the CML assessment method are mainly impacted by 4 of the processes in scenario 1. These processes are “anaerobic digestion”, “heat generation using biogas”, “heating digester using propane” and “nutrient supply from digestate solids”. “Nutrient supply from digestate solids” is the only process impacting on eutrophication. Phosphate and ammonium released to soil causes the highest impact on eutrophication but the chemical oxygen demand (COD) in water is reduced when the digestate solids are applied to fields nearby.

The process “heat generation using biogas” has the largest impact on several environmental categories such as acidification potential due to the release of ammonia and sulphur dioxide to the atmosphere. Due to the depletion of elements such as cadmium and lead, this process also has the largest impact on the depletion of abiotic resources (elements and ultimate reserves). The “heat generation using biogas” and “anaerobic digestion of cattle manure” processes have almost equal impacts on freshwater aquatic ecotoxicity because of the release of nickel and beryllium into groundwater. The process “heat generation using biogas” causes a higher impact on human toxicity due to the emission of chromium VI, selenium and arsenic to air.

The same process has the highest impact on marine aquatic ecotoxicity when beryllium and hydrogen fluoride is emitted to water and air respectively. The releases of methane and carbon monoxide from "heat generation using biogas" are responsible for the highest impacts on photochemical oxidation and on terrestrial ecotoxicity due to chromium emitted to air.

"Production of EDTA to use as catalyst for removal of H_2S from biogas" and "heating digester with propane" are the 2 processes with the highest impacts on ozone layer depletion. The impacts are due to the release of tetrachloro-methane and bromo-trifluoro methane to air. These two processes also have the largest impacts on the depletion of abiotic resources (fossil fuels) but the combined impact is only 18% of the base case impact.

The combination of scenario 1 processes has an impact of 31% of the base case impact on climate change (including the "positive" impact of the "cattle stall without impacts from manure"). The process "heat generation with biogas" contributes 68% of the scenario's impact on climate change. The base case processes mainly impacting on climate change are the "operation of the cattle stall" and "heat generation from coal to offset biogas". The release of carbon dioxide by the base case processes causes the impact on climate change.

Although the "solid digestate as nutrient supply" process has the highest impact on eutrophication, the impact is still only 10% of the base case's impact where raw manure from the cow stall is applied to the agricultural fields resulting in phosphate, ammonia, methane and COD impacting on soil and water.

The scenario 1 processes performed better than the base case on all of the impact categories but its impact on the depletion of abiotic resources (elements and ultimate reserves) is almost equal to that of the base case.

See Figure 4-1 for a comparison of the scenario 1 processes with each other and Figure 4-2 for a comparison of scenario 1 with the base case. The offset processes are only shown as additional impact in Figure 4-2.

4.2 SCENARIO 2: HEATING POOL/PASTEURISED WATER FOR DOMESTIC USE

Scenario 1 and 2 only differs in one aspect. Instead of releasing the liquid digestate as nutrient supply to nearby fields, the liquid phase is pasteurised to produce water for domestic use. The impact of the process "heat generation from biogas" on the various environmental categories is equal to the impacts it has in scenario 1 as it is only the distribution of the energy that differs and not the amount of heat generated.

The combined scenario 2 processes perform slightly better than the combined scenario 1 processes on all categories due to the absence of the liquid digestate's impacts. All the impacts are lower than the base case impacts.

See Figure 4-3 for comparison between the impacts of the scenario 2 processes on the environmental categories. See also Figure 4-4 for a comparison between the impacts of scenario 2 processes and the base case. The total of the offset processes' impacts are shown in Figure 4-4.

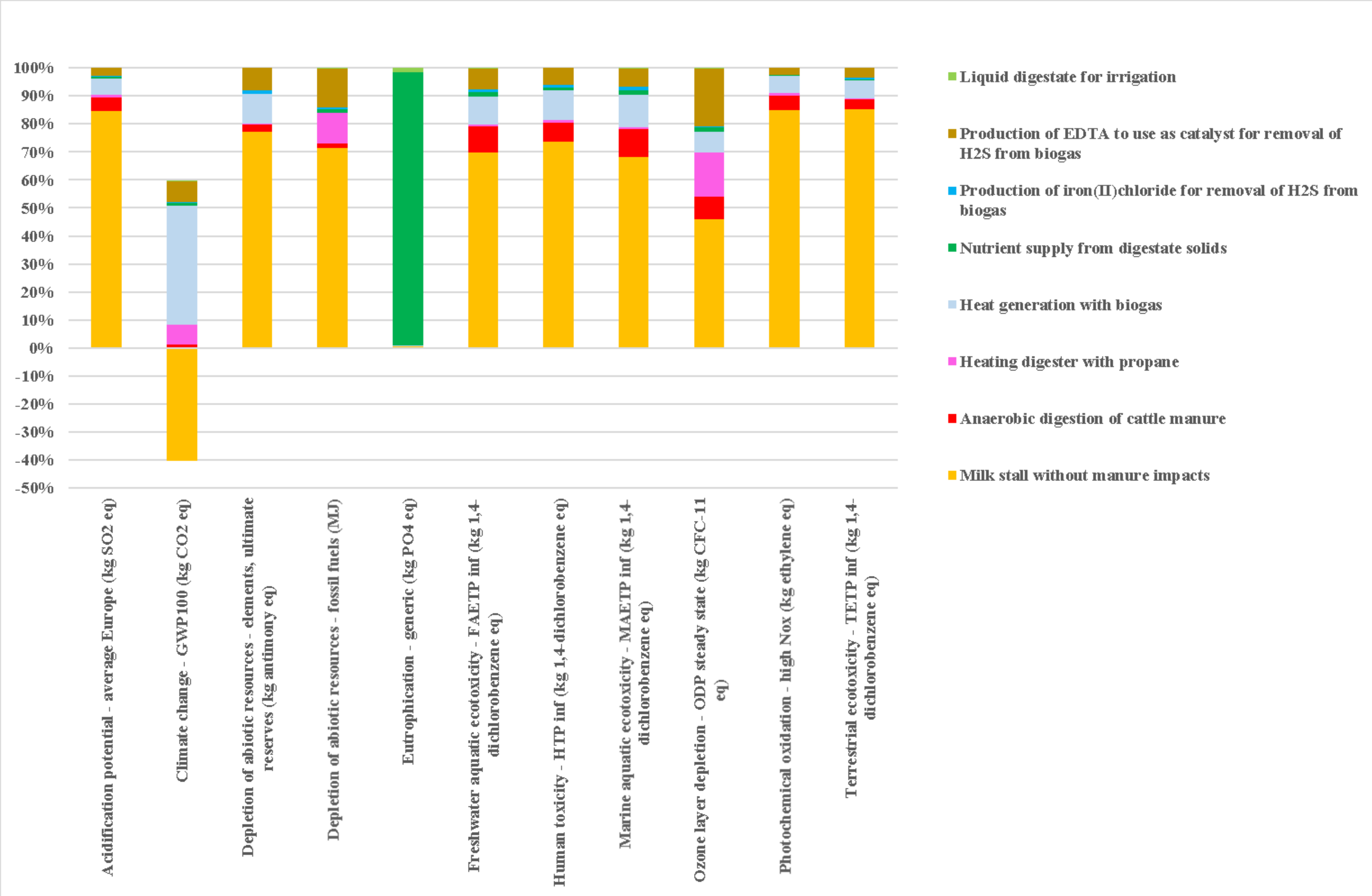

Figure 4-1 LCA Results: "Scenario 1: Heating pool/split digestate application" contribution analysis

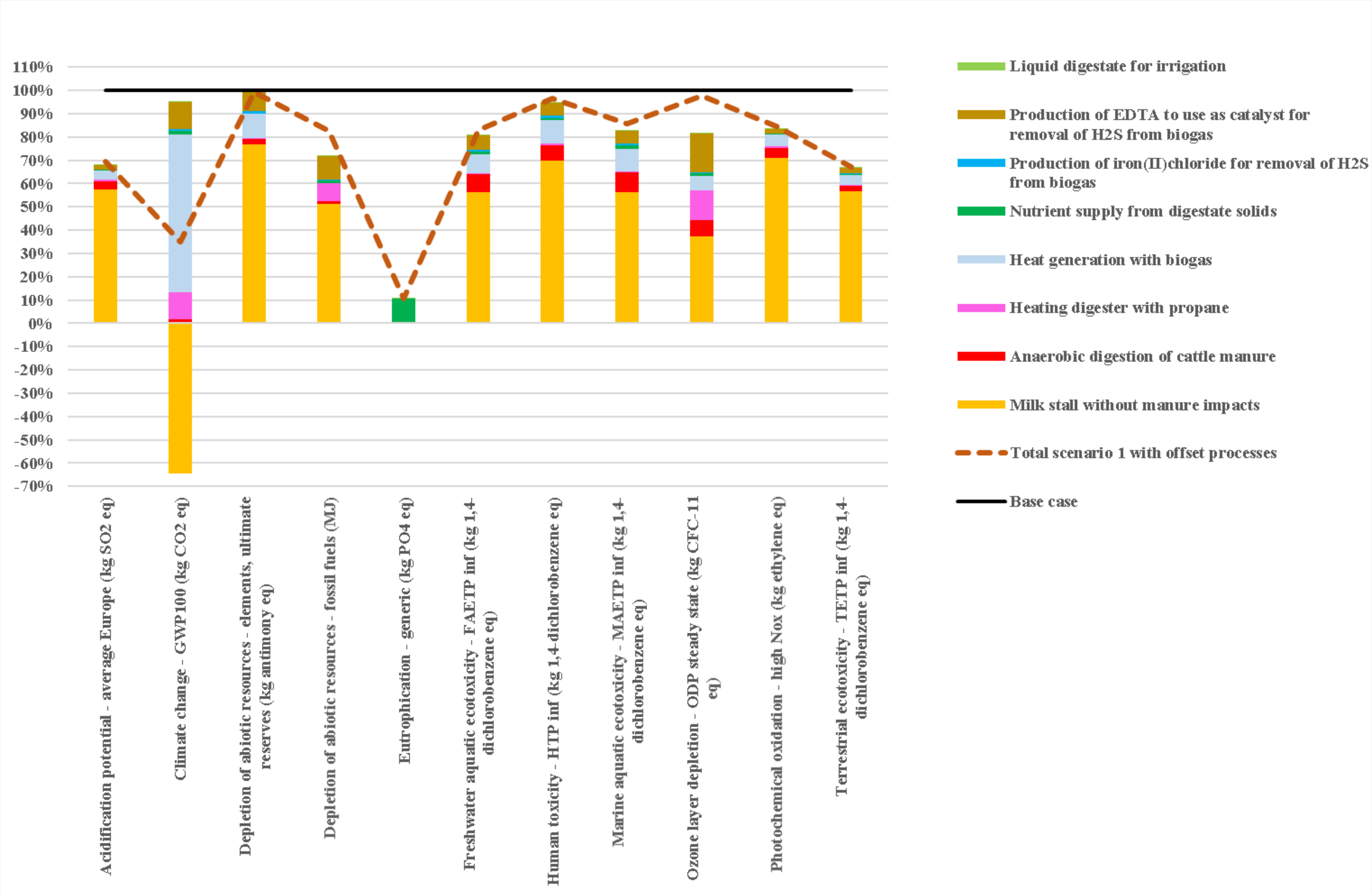

Figure 4-2 LCA Results: "Scenario 1: Heating pool/split digestate application" base case comparison

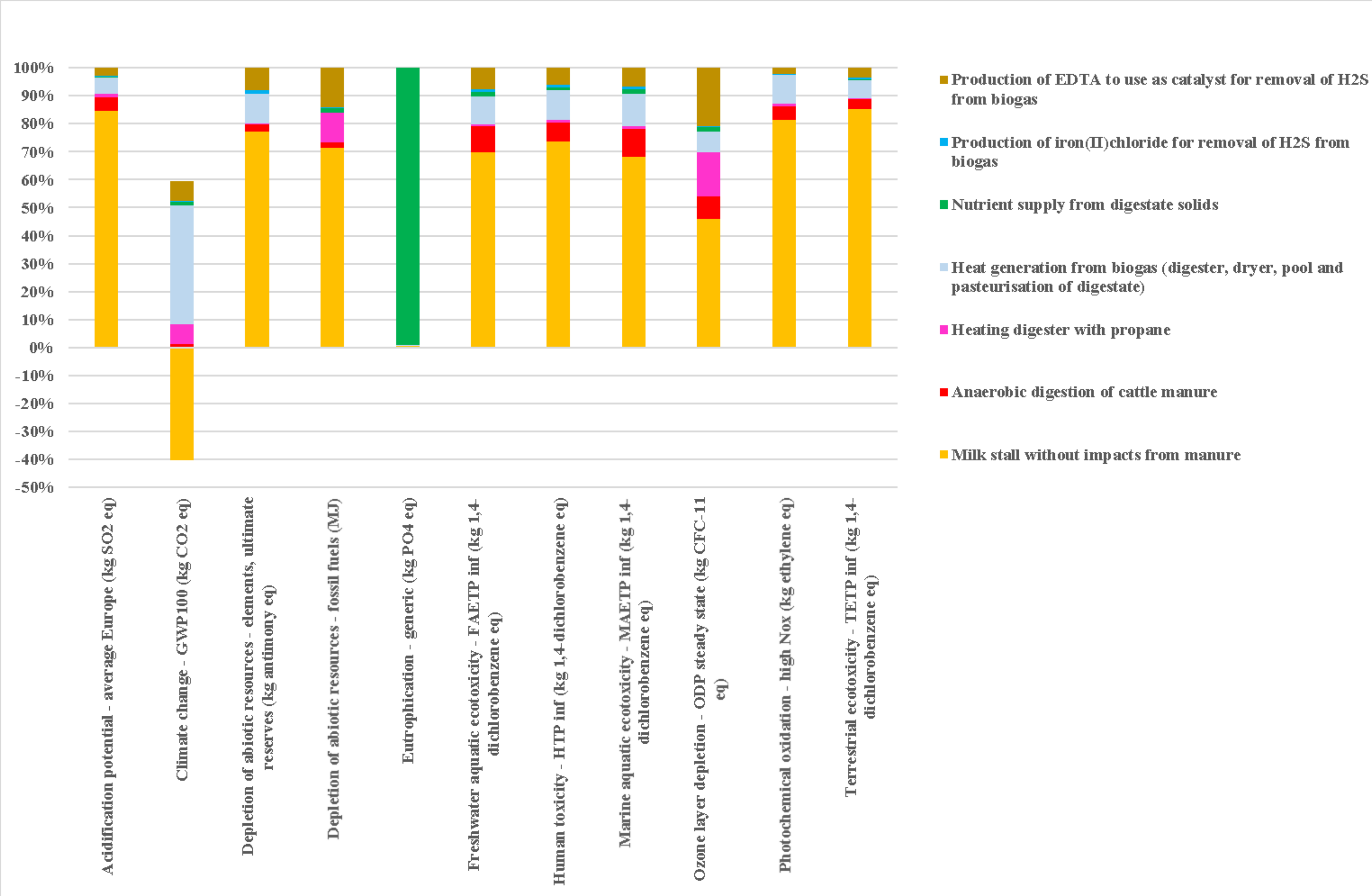

Figure 4-3 LCA Results: "Scenario 2: Heating pool/pasteurised water for domestic use" contribution analysis

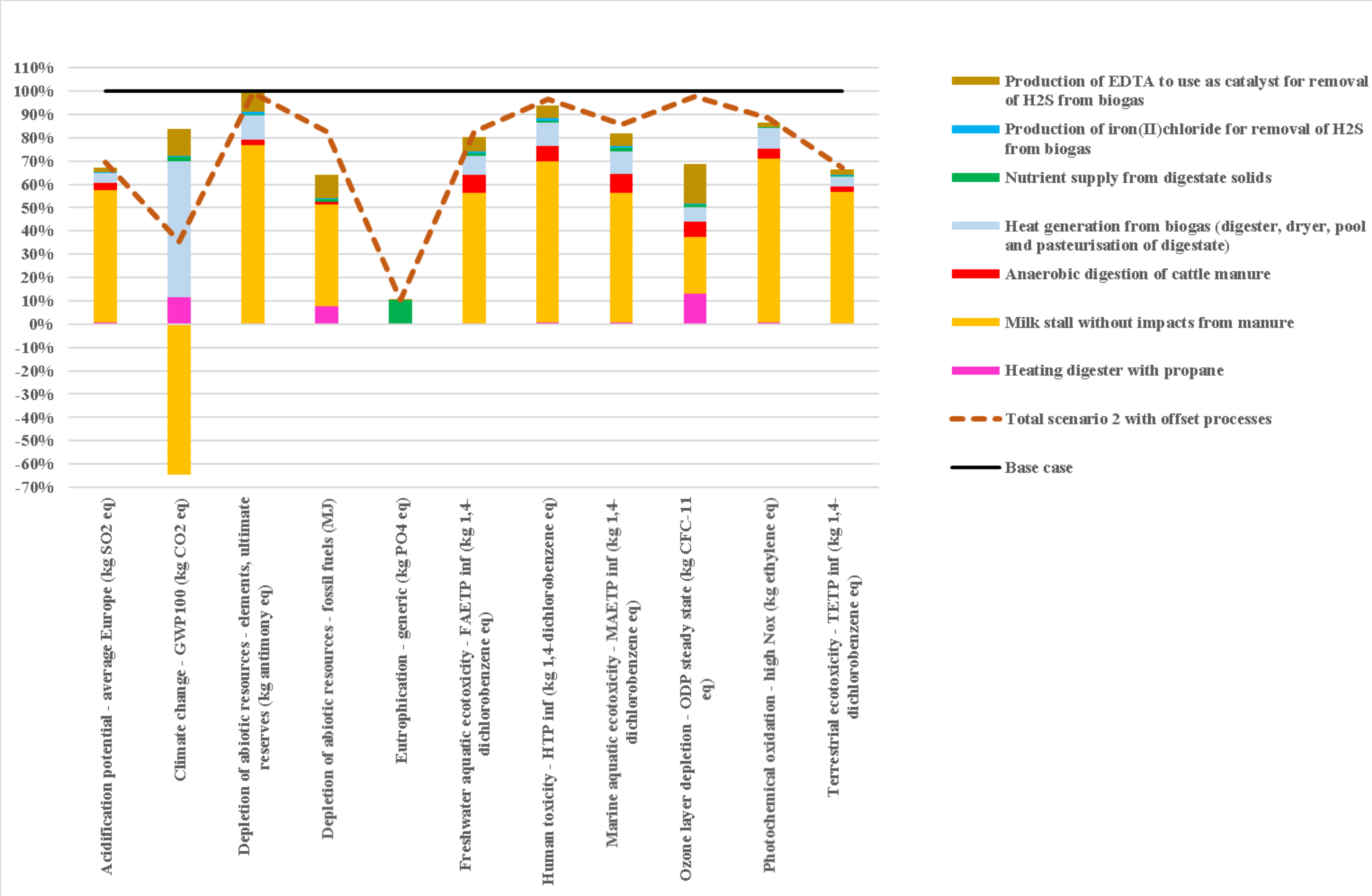

Figure 4-4 LCA Results: "Scenario 2: Heating pool/pasteurised water for domestic use" base case comparison

4.3 SCENARIO 3: BOTTLING BIOGAS/FULL DIGESTATE AS NUTRIENT SUPPLY

The process “cleanup of biogas to produce methane”has the largest impact on marine aquatic ecotoxicity due to the release of beryllium and hydrogen fluoride to water and air respectively. The scenario 3 impact on freshwater aquatic ecotoxicity is almost equal to that of marine aquatic ecotoxicity. Three processes have high impacts on freshwater aquatic ecotoxicity: “Anaerobic digestion”, “heat generation from biogas” and “clean-up of biogas to produce methane”. Nickel and beryllium releases to water are the main contaminants.

“Production of EDTA as catalyst for removal of H_2S from biogas” has the highest impact on ozone layer depletion due to tetra-chloro methane and bromo-trifluoro methane emitted to air..

“Clean up of biogas to produce methane for bottling” has the highest impact on photochemical oxidation due to carbon monoxide released to air. “Heat generation from biogas” and “anaerobic digestion of cattle manure” also impacts on this category. The base case releases the same component from the cattle stall operation. “Clean up of biogas to produce methane” and “heat generation from biogas”causes the highest impacts on terrestrial ecotoxicity due to chromium and chromium VI releases to air and soil respectively.

“Cleanup of biogas to produce methane” is the main contributor to the impact on acidification potential when releasing ammonia and sulphur dioxide to air. “Heating digester using biogas” and “clean-up of biogas to produce methane” are the main contributors to the climate change category as both processes release carbon dioxide to air in fairly large quantities.

“Heat generation from biogas” and “cleanup of biogas to produce methane” have the highest impacts on depletion of abiotic resources (elements, ultimate reserves) as small quantities of cadmium and lead are consumed in their upstream processes. “Production of EDTA as catalyst to remove H_2S from biogas”, “clean up of biogas to produce methane” and “heating digester with propane” have the largest impacts on the depletion of abiotic resources (fossil fuels). Natural gas and crude oil are consumed as energy sources during these processes.

“Anaerobic digestion” releases selenium and arsenic to water and air respectively, while “clean-up of biogas to produce methane” emits chromium VI to air. Chromium VI and arsenic are released to air by “heat generation from biogas”. These emissions impact on the human toxicity category.

“Fertilize fields with full digestate flow” is the only process impacting on eutrophication due to the phosphate and ammonia releases to soil. The impact is much lower at 8% than the impact from the base case where raw manure is applied to the agricultural fields.

The sum of scenario 3 impacts on ozone layer depletion is 90% of the impact of the base case that emits bromo-trifluoro methane to air. The total impact on terrestrial ecotoxicity is 72% of the base case impact. The total impact on acidification potential of scenario 3 processes is 0.74 times that of the base case impact. “Operation of cattle stall” and “heat offset from biogas using coal” are the 2 base case processes with the highest impacts on acidification potential as both processes emit sulphur dioxide.

The sum of the impacts from this scenario on climate change is 70% (taking into account the “positive” impact of the “cattle stall without impacts from manure” process) of the base case impact that releases carbon dioxide and methane to air from the “operation of cattle stall” process. The combined impact on depletion of abiotic resources (elements, ultimate reserves)

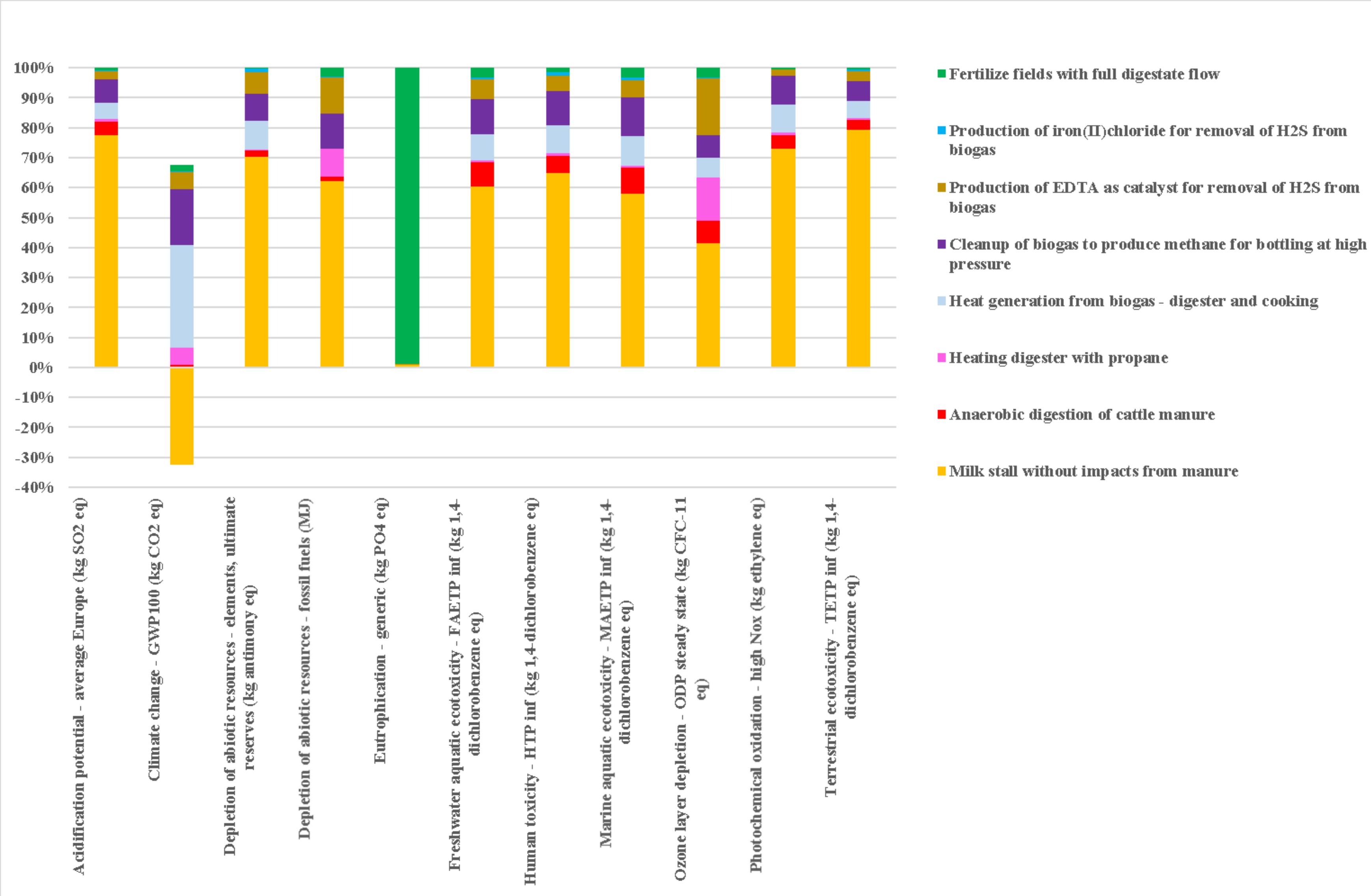

Figure 4-5 LCA Results: "Scenario 3: Bottling biogas/Full digestate as nutrient supply" contribution analysis

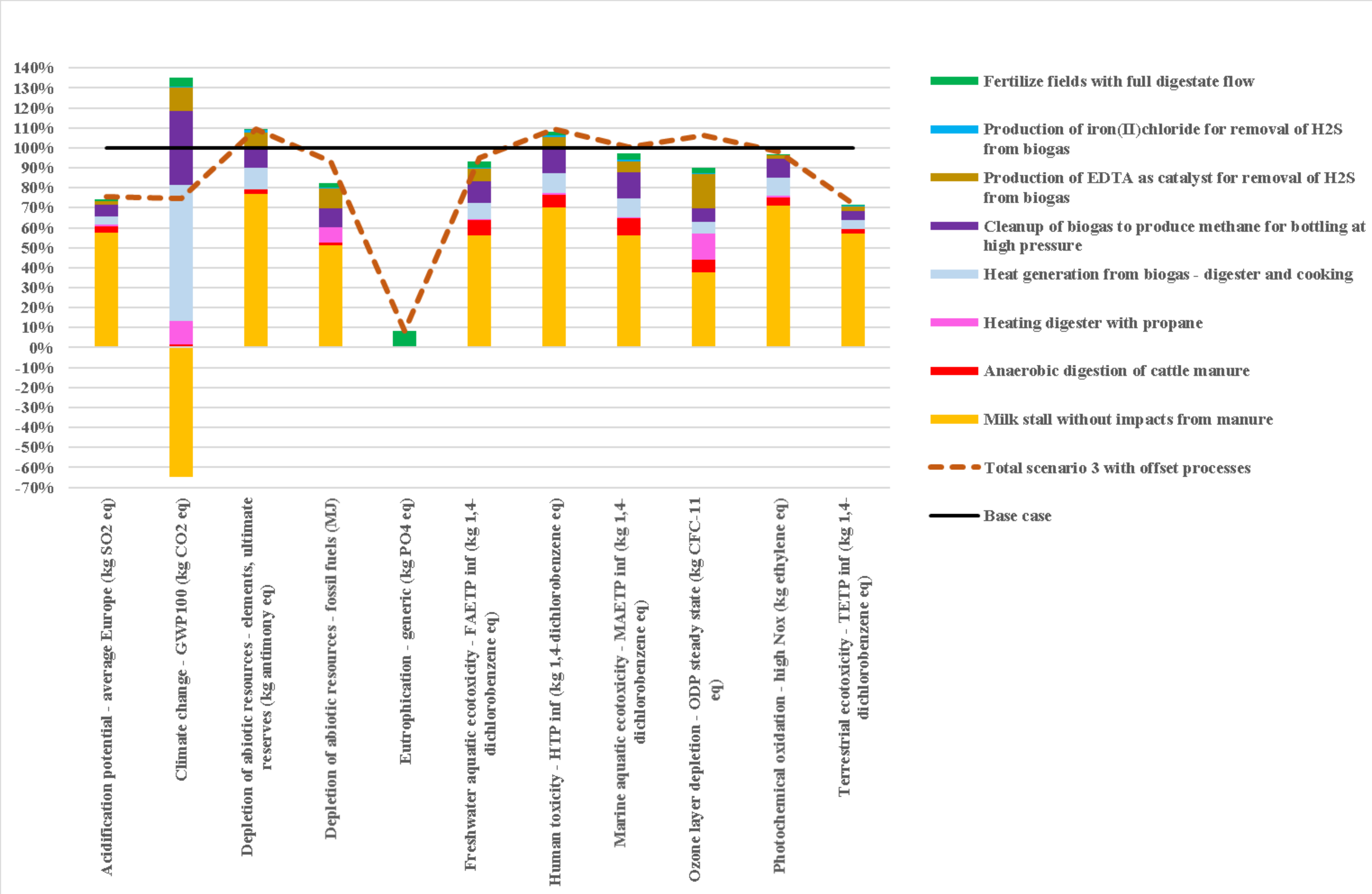

Figure 4-6 LCA Results: "Scenario 3: Bottling biogas/Full digestate as nutrient supply" base case comparison

by the scenario 3 processes is 109% of the base case impact where cadmium and borax are also consumed.

The combined impact for scenario 3 on marine aquatic ecotoxicity is 97% of base case impact that releases beryllium and hydrogen fluoride. The base case impact on freshwater aquatic ecotoxicity is due to the release of copper and nickel by “operation of cattle stall”. The total impact of this scenario is 1.08 times that of the base case impact on human toxicity.

The total impacts from scenario 3 are lower than the base case for all categories except human toxicity and depletion of abiotic resources (elements, ultimate reserves). The higher impacts by scenario 3 on these two categories are almost equal to the impacts of the “clean-up of biogas to produce methane” process.

See Figure 4-5 for the comparison of the impacts by the various scenario 3 processes and Figure 4-6 for the comparison between the base case impacts and the scenario 3 processes on the environmental categories. The total impact from the offset processes is included in Figure 4-6.

4.4 SCENARIO 4: POWER GENERATION/FERTILIZER PELLETS

“Heat generation from biogas” and “anaerobic digestion” processes show the highest impacts on acidification potential due to sulphur dioxide and ammonia released to air. The same two processes also have the largest impact on freshwater aquatic ecotoxicity as beryllium and nickel are emitted to water. “Heat generation from biogas” has a similar impact on marine aquatic ecotoxicity as “anaerobic digestion” due to hydrogen fluoride and beryllium releases to air and water respectively. The amount of carbon monoxide and methane released during “heat generation from biogas” causes the highest impact on photochemical oxidation. “Anaerobic digestion” also impacts on photochemical oxidation due to carbon monoxide and sulphur dioxide released to air.

“Heat generation from biogas” has the largest impact on terrestrial ecotoxicity due to the release of chromium to air and chromium VI to soil. The same process also emits chromium VI that is the main cause of the impact on human toxicity. This process also makes the largest contribution to the impact on climate change due to methane leaking from the process and carbon dioxide released to air. This process uses small quantities of cadmium and lead and therefore also impacts on the depletion of abiotic resources (elements and ultimate reserves).

“Production of EDTA to use as catalyst for removal of H_2S from biogas” has the largest impact on ozone layer depletion. The release of tetra-chloro-methane and bromo-trifluoro methane to air contributes to this impact. This process as well as “heat digester with propane” contributes to the impact on depletion of abiotic resources (fossil fuels) due to the use of hard coal, natural gas or oil as raw materials to generate electricity for the production of these products.

“Manufacturing digestate fertilizer pellets” is the only scenario 4 process that impacts on eutrophication due to phosphate released to soil and COD required in water for a total of 19% of the base case impact.

The total impact of this scenario on acidification potential and terrestrial ecotoxicity is 68% and 66.5% respectively of the base case impact. This scenario’s impact on depletion of abiotic resources (elements and ultimate reserves) is 99% of the base case impact. This scenario has an impact equal to 82% of the base case on ozone layer depletion.

The process "generate electricity using cleaned up biogas" is unique to this scenario but has a low impact on all of the CML environmental categories as only a small portion of the biogas is available for this application.

The combined impact of the scenario 4 processes is lower than the base case for all environmental categories. See Figure 4-7 for the comparison of the impacts by the various scenario 4 processes and Figure 4-8 for the comparison between the base case impacts and the scenario 4 processes on the environmental categories. The impact of the offset processes is indicated in Figure 4-8.

4.5 SCENARIO 5: BOTTLING BIOGAS/NPK FERTILIZER PELLETS

"Heat generation from biogas" has the highest impact on climate change due to the release of carbon dioxide and methane to air. The other processes in this scenario also contribute to the total impact on this category.

"Heat generation from biogas" and "clean-up of biogas to methane" have almost equal impacts on marine aquatic ecotoxicity due to beryllium released to groundwater. These two processes also have the largest impacts on the depletion of abiotic resources (elements and ultimate reserves) due to small quantities of cadmium and lead extracted from the ground. "Clean-up of biogas to methane" has the largest impact on human toxicity caused by chromium VI and selenium released to air. "Anaerobic digestion" and "heat generation with biogas" also contributes to the impact on human toxicity by releasing selenium into water and chromium VI to air, respectively.

"Clean-up of biogas to methane" has the largest impact on acidification potential due to sulphur dioxide and ammonia emitted to air but three other processes also contribute similarly to this impact. These processes are "anaerobic digestion", "heat generation from biogas" and "production of NPK fertilizer with limestone and digestate".

"Clean-up of biogas to methane" and "heat generation from biogas" have the largest impacts on freshwater aquatic ecotoxicity due to nickel and beryllium emitted to water. These 2 processes also show the largest impacts on terrestrial ecotoxicity caused by the release of chromium and chromium VI to air and soil respectively.

"Heat digester with propane" impacts on depletion of abiotic resources (fossil fuels) due to natural gas and crude oil used as energy sources for upstream processes. "Clean-up of biogas to methane" and "production of EDTA to use as catalyst for removal of H_2S from biogas" also contributes to the total impact of 86% of the base case impact on this category.

"Production of NPK fertilizer from digestate and limestone" is responsible for the main impact on eutrophication caused by ammonia and phosphate released to soil but the impact is reduced by the positive COD demand.

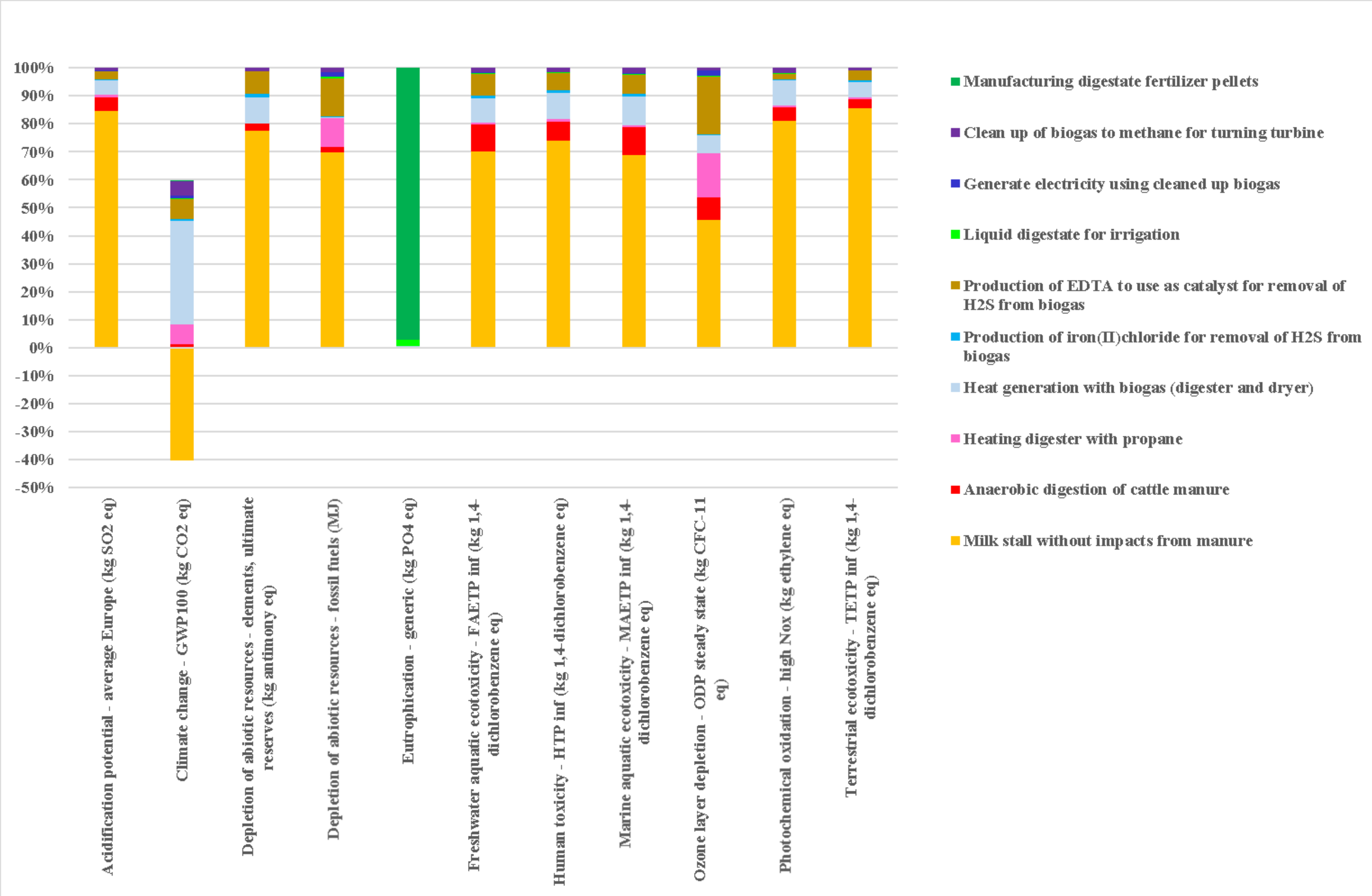

Figure 4-7 LCA Results: "Scenario 4: Power generation/Fertilizer pellets" contribution analysis

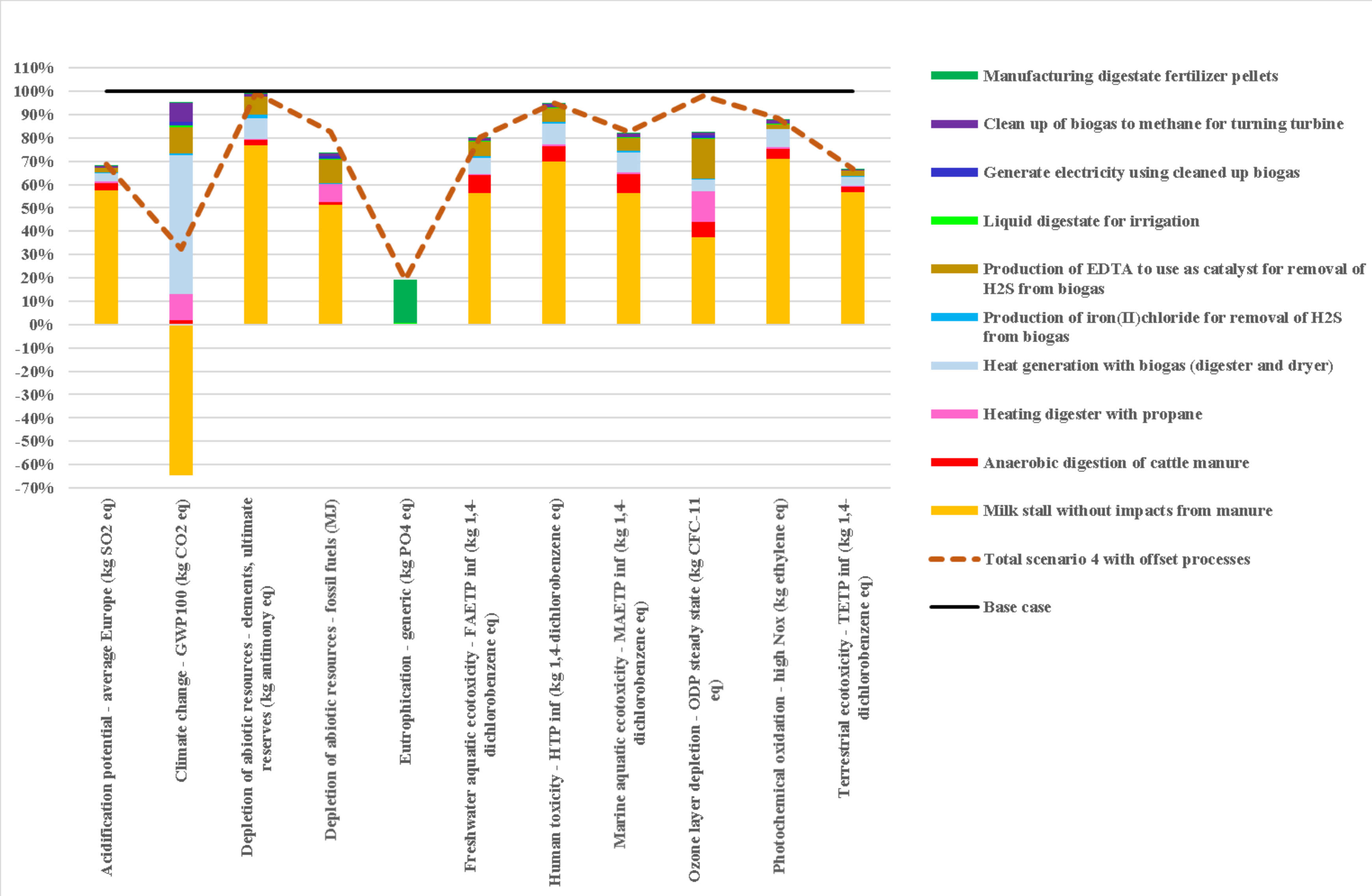

Figure 4-8 LCA Results: "Scenario 4: Power generation/Fertilizer pellets" base case comparison

This scenario has a total impact on climate change of 75% of the base case impact where the two processes “operation of cattle stall” and “heat offset from biogas using coal” release carbon dioxide and methane to air. Most of the scenario 5 processes impact on the ozone layer depletion category with a total impact of 95% of the base case impact.

The total impact of the scenario on marine aquatic ecotoxicity is 98.5% of the base case where beryllium and hydrogen fluoride are released from the “operation of cattle stall” and “heat offset from biogas using coal”. The impact from this scenario is 10% higher than the base case impact on depletion of abiotic resources (elements and ultimate reserves). The total impact on human toxicity is 9% higher than the base case impact.

Scenario 5’s total impact on acidification potential is 0.77 times that of the base case where “Operation of the cattle stall” releases ammonia and sulphur dioxide to air. “Heat offset from biogas using coal” releases sulphur dioxide and nitrogen oxide to air causing a higher impact on acidification potential by the base case. The combined impact on freshwater aquatic ecotoxicity of all the scenario 5 processes is 94% of the impact of the base case where copper and nickel are released to water during the “operation of cattle stall” process.

Scenario 3: Bottling biogas/full digestate as nutrient supply and scenario 5 both use the biogas produced by the anaerobic digester for heating the digester as well as “clean-up of biogas and bottling” for use by community for cooking, but scenario 3 applies the digestate as is to the agricultural fields while scenario 5 produces fertilizer. The impacts of scenario 3 are lower on most of the environmental categories than those of scenario 5. Scenario 5 shows the same trends as scenario 3 on human toxicity and depletion of abiotic resources (elements, ultimate resources). These two scenarios have higher impacts on these impact categories than the base case mainly due to the impacts of the process “clean-up of biogas to methane”.

See Figure 4-9 for the comparison of the impacts by the various scenario 5 processes and Figure 4-10 for the comparison between the base case impacts and the scenario 5 processes on the environmental categories. The total impacts from the offset processes are included in Figure 4-10.

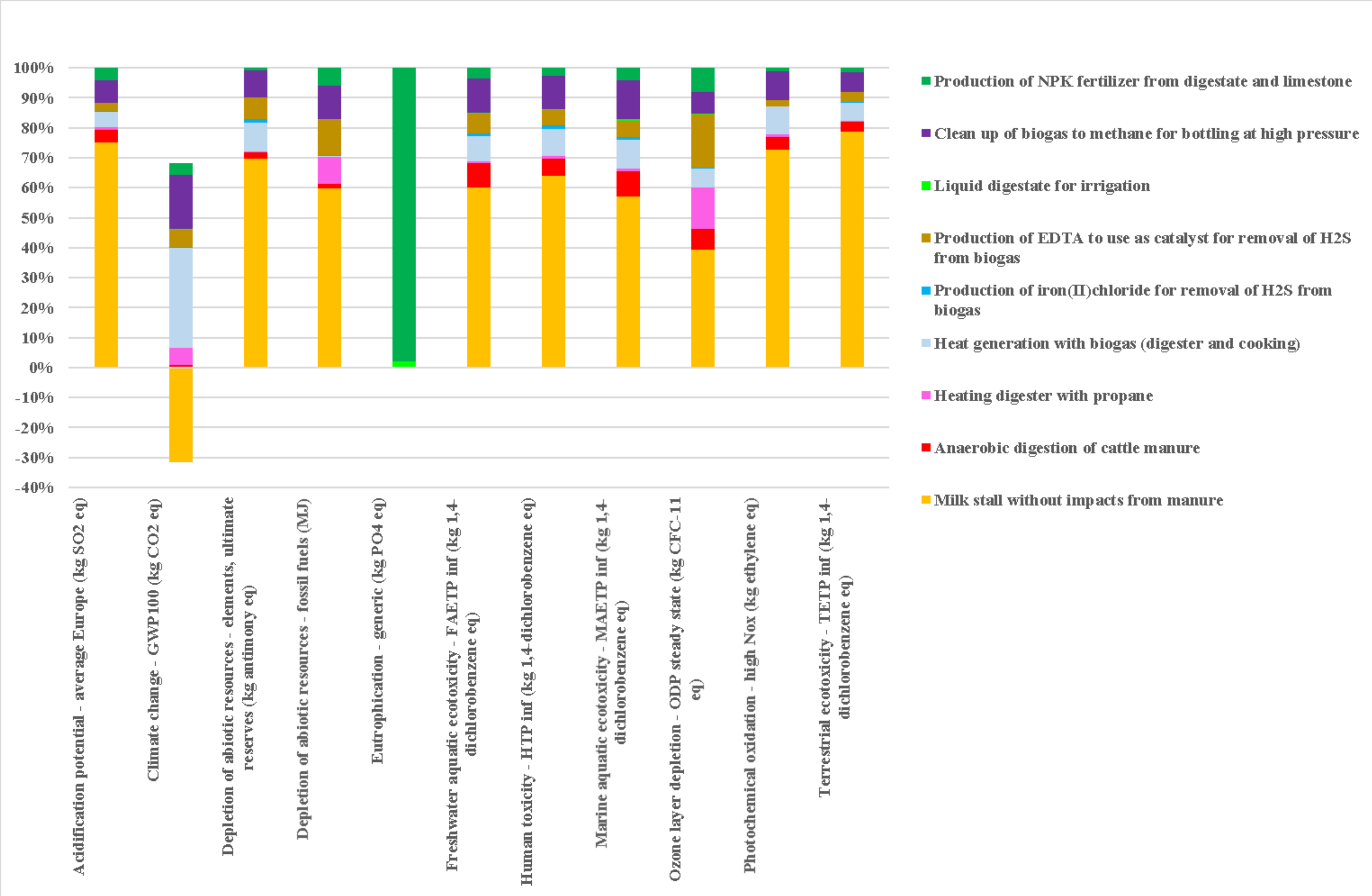

Figure 4-9 LCA Results: "Scenario 5: Bottling biogas/NPK fertilizer pellets" contribution analysis

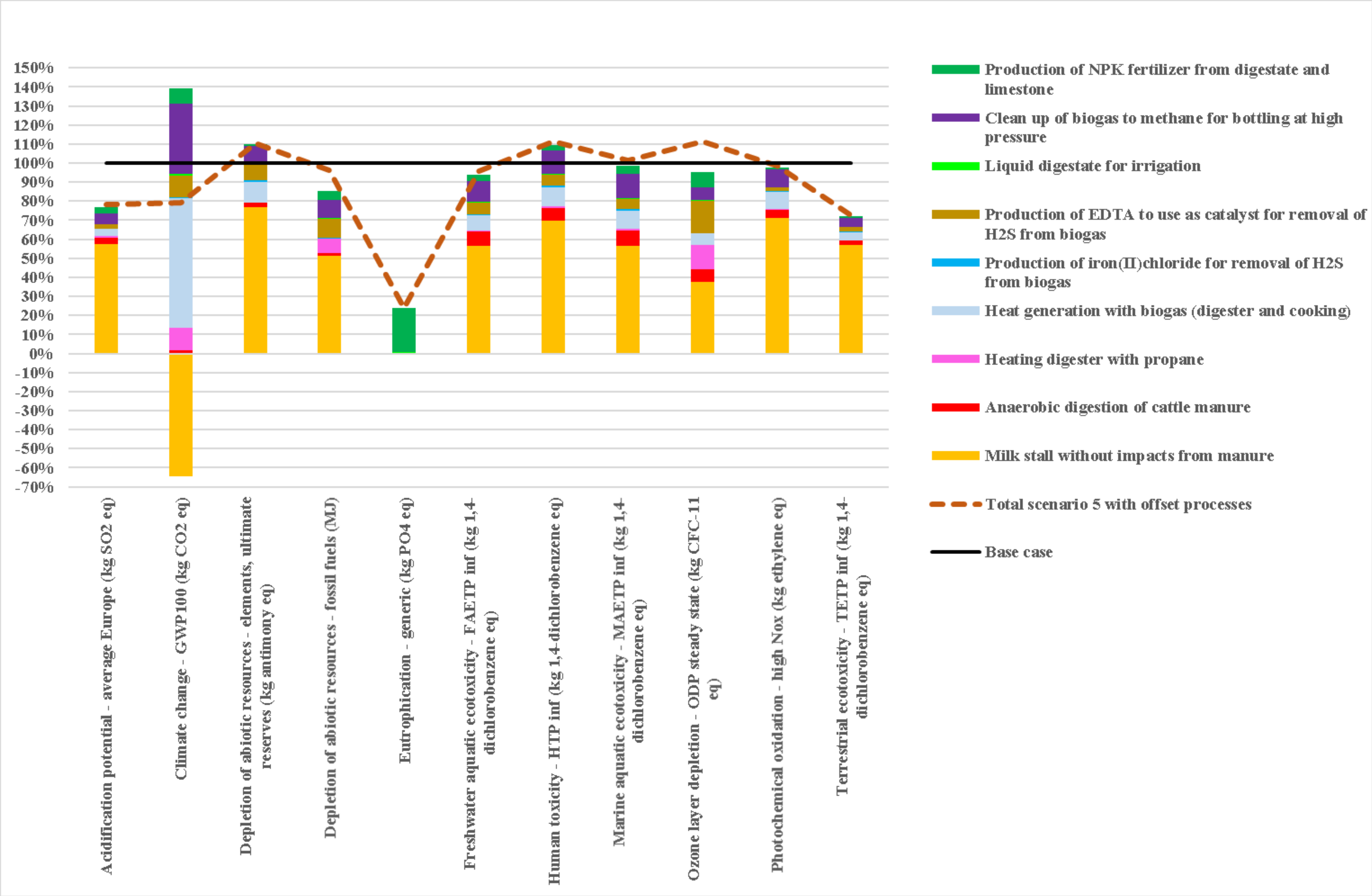

Figure 4-10 LCA Results: "Scenario 5: Bottling biogas/NPK fertilizer pellets" base case comparison

4.6 SCENARIO 6: BIODIESEL FROM ALGAE/BOTTLING BIOGAS

This scenario has more processes than any of the other scenarios as it includes all the products required for the biodiesel production process.

The release of ammonia to air by the "photo-bioreactor for algae cultivation" process has the largest impact on acidification potential.

"Heat generation from biogas" has the highest impact on many of the environmental categories. This process has the highest impact on climate change due to the emission of methane and carbon dioxide but the scenario's impact is reduced by the consumption of carbon dioxide by the "photo-bioreactor for algae cultivation" and the "milk stall without impacts from manure". "Clean-up of biogas to methane" and "heat generation from biogas" require small amounts of cadmium and lead from the ground, resulting in the main impacts on depletion of abiotic resources (elements and ultimate reserves). The release of beryllium and nickel to groundwater causes the main impact on freshwater aquatic ecotoxicity from "heat generation from biogas" process, but "clean-up of biogas to methane" has an even larger impact on this category.

"Clean-up of biogas to methane" and "heat generation from biogas" have the largest impacts on human toxicity due to the emission of chromium VI and selenium to air. The same two processes have the largest impact on marine aquatic ecotoxicity as beryllium and hydrogen fluoride are released to water and air respectively.

Carbon monoxide and sulphur dioxide emitted during "clean-up of biogas to methane" are combined with the impacts from "esterification of bio-oil", "anaerobic digestion" and "heat generation from biogas" to cause the total impact on photochemical oxidation.

Chromium and chromium VI releases by "clean-up of biogas to methane" result in the highest impact on terrestrial ecotoxicity.

"Clean-up of biogas to methane" and "production of EDTA to use as catalyst for removal of H_2S from biogas" have the highest impacts on depletion of abiotic resources (fossil fuels). The impact is caused by the consumption of fossil fuels during the production of the raw materials required by these process as well as electricity required.

"Nutrient supply from digestate solids" is the only process contributing to the impact on eutrophication. Phosphate and ammonium are released to soil but the effect is reduced by the lower COD requirement. This effect was also seen in scenario 3 but the extend is greater in that scenario as the full digestate flow is applied as nutrient source.

"Production of EDTA to use as catalyst for removal of H_2S from biogas" has the highest impact on ozone layer depletion due to tetrachloro methane and bromo-trifluoro methane releases to air. "Heat digester with propane" also contributes to this impact increasing the total impact to 90% of the base case impact.

The impact of the ammonia released by the photo-bioreactor combined with the impacts from "anaerobic digestion", "heat generation from biogas", "milk stall without impacts from manure" and "clean-up of biogas to methane" pushes the total impact on acidification potential up to 93% of the base case impact. The cattle stall operation causes the release of sulphur dioxide and ammonia. The total impact from this scenario on human toxicity is 108.5% while it has 101% of the base case impact on photochemical oxidation. The total impact on terrestrial ecotoxicity is 78% of the base case impact.

Scenario 6 processes have higher impacts than the base case on 3 of the environmental categories, i.e human toxicity, depletion of abiotic resources (elements, ultimate reserves) and photochemical oxidation. The sum of the impacts from the processes on climate change is reduced by the "positive" impact of the photo bioreactor consuming CO_2 gas.

The use of biogas in this scenario is similar to scenario 3: Bottling biogas/full digestate as nutrient supply and scenario 5: Bottling biogas/NPK fertilizer pellets. The different uses of the digestate in these scenarios cause different impacts on the various categories.

See Figure 4-11 for the comparison of the impacts by the various scenario 6 processes and Figure 4-12 for the comparison between the base case impacts and the scenario 6 processes on the environmental categories. The impacts from the offset processes are included in Figure 4-12.

4.7 COMPARISON OF LCA RESULTS FOR THE 6 DIFFERENT SCENARIOS

See Figures 4-13 and 4-14 for the comparison of the LCA results of the six scenarios investigated (excluding offset processes' impacts). The impact of the "milk stall without manure impacts" is equal in all the scenarios on all the environmental categories. All the total results for the scenarios are normalized by comparing them to the impacts of the base case.

The environmental category with the lowest relative impact from all the scenarios, is eutrophication due to the much higher impacts that the raw manure has when applied to nearby fields. Impacts from scenario 4 and 5 are higher where fertilizer is produced compared to the digestate application in scenarios 1, 2, 3 and 6, due to the conversion of nitrogen to ammonia by the digester for easier absorption by plants and less nutrients emitted to water sources impacting on eutrophication.

The "positive" impact in terms of negative credits on climate change from the "milk stall without manure impacts" process reduces this impact for all 6 scenarios. This is due to the photosynthesis of the plant material used as feed to the cows. The rest of the impact on climate change is resulting from methane as product of anaerobic digestion as well as the CO_2 releases from downstream processes in each specific scenario. The other components impacting on climate change are carbon monoxide and sulphur dioxide that are both products of the energy generation processes found in all the scenarios. The impacts from the combination of processes in the various scenarios add up to figures between 30 and 75% of the base case impact where GHG are emitted by the animals as well as the raw manure. Carbon dioxide released by the "heat generation from biogas" is the main pollutant impacting on climate change especially when combined with "clean-up of biogas to methane for bottling at high pressure" in scenarios 3: Bottling biogas/full digestate as nutrient supply and 5: Bottling biogas//NPK fertilizer pellets. Scenario 6: Biodiesel from algae/bottling biogas has a smaller impact as CO_2 is consumed by the photo bioreactor cultivating algae.

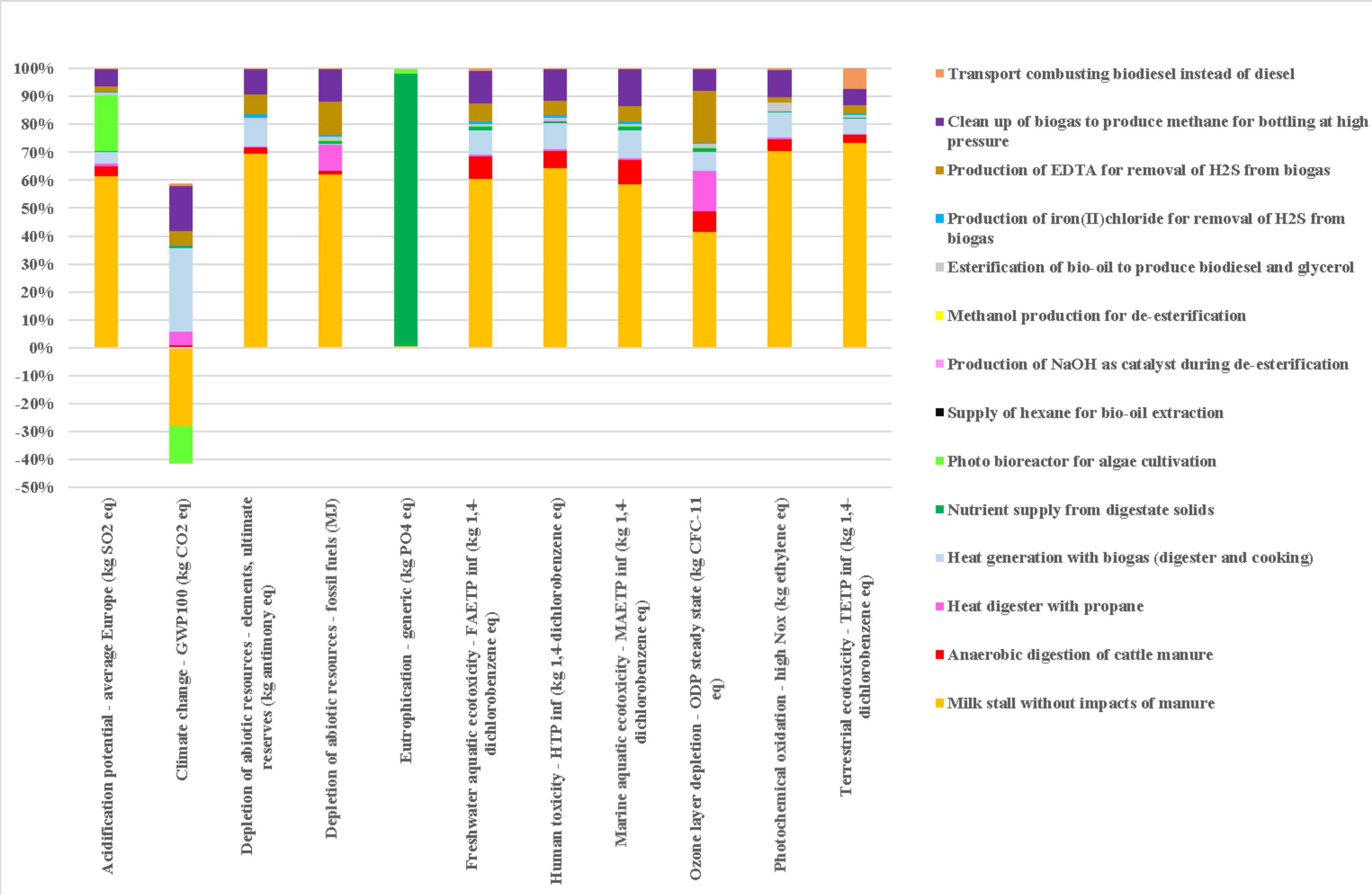

Figure 4-11 LCA Results: "Scenario 6: Biodiesel from algae/Bottling biogas" contribution analysis

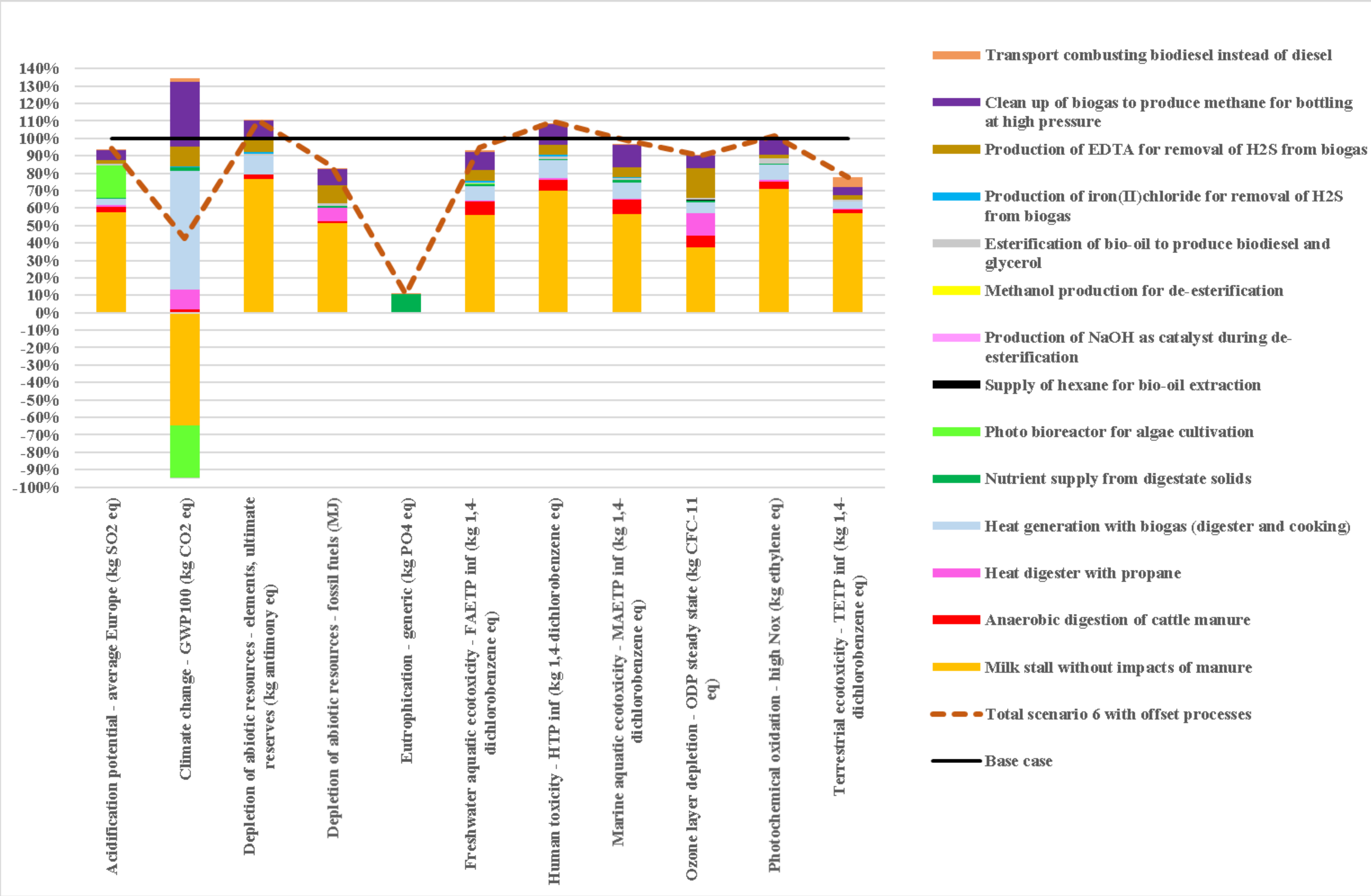

Figure 4-12 LCA Results: "Scenario 6: Biodiesel from algae/Bottling biogas" base case comparison

The impact on ozone depletion by all the scenarios are between 80 and 95% of the base case impact. The actual numbers for this category presented by the database for all the processes including the base case due to halo-methane emissions, are very small compared to that of landfill emissions and releases from CHP generation. The impact on this category by the process "production of EDTA to use as catalyst for removal of H_2S in biogas" is between 20 and 25% of the scenarios' impacts but the database indicates that there is uncertainty about some of the components of this production process (GreenDelta 2016). The impact of this process on ozone layer depletion is therefore doubtful and the actual figures very small. This environmental category is therefore not discussed any further.

There is one other individual impact worth mentioning: The acidification potential impact by scenario 6: Biodiesel from algae/bottling biogas is higher than that of the other scenarios. The ammonia released by the "photo-bioreactor for algae cultivation" plays the main role in this result causing an impact that is 20% higher than those of the other scenarios.

Secondly, the impact on eutrophication by scenario 3: Bottling biogas/full digestate as nutrient supply" is lower than that of scenario 1: Heating pool/split digestate application, 2: Heating pool/pasteurised water for domestic use and 6: Biodiesel from algae/bottling biogas. This is due to the more diluted digestate applied in scenario 3 where no separation of digestate phases is attempted. The anaerobic digestion process does not have a large impact on the nitrogen and phosphate contents of the digestate, but the impact on eutrophication obtained from the database is lower for the application of digestate to fields than it is for the application of manure as expected (US Department of Agriculture 2007). The impacts on eutrophication by the manufactured fertilizers in scenario 4: Power generation/fertilizer pellets and 5: Bottling biogas//NPK fertilizer pellets are higher than that of the "unmodified" digestate solids applied to the nearby fields in scenarios 1: Heating pool/split digestate application, 2: Heating pool/pasteurised water for domestic use and 6: Biodiesel from algae/bottling biogas as expected according to literature (Withers et al. 2001). Digestate sludge contains nitrogen as ammonia and is easier for plants to absorb than the nitrogen component in manufactured fertilizers. Thus, less nitrogen is released to water sources that can impact on eutrophication.

Scenario 4: Power generation/fertilizer pellets has the lowest impact on 7 out of 11 of the environmental categories. The results for scenario 4 are very close to that of scenario 1: Heating pool/split digestate application and 2: Heating pool/pasteurised water for domestic use. It is thus the preferred combination of processes according to the results of this study. Scenario 4 uses the biogas to heat the digester and the dryer of the digestate solids before generating electricity with the remaining energy available. The dried digestate solids is transformed into fertilizer pellets containing nitrogen, phosphate and potassium. The energy and nutrients are utilized in a manner that optimises its benefits to the user while having lower impacts on the environment. If the digestate in this scenario is applied to the nearby fields as is, instead of converting it to fertilizer pellets, this scenario will have the same impact on eutrophication as scenario 3: Bottling biogas/full digestate as nutrient supply.

It was attempted to create an optimum scenario by mixing the processes from the scenarios showing the lowest environmental impacts. For instance, the biogas applications of scenario 4: Power generation/fertilizer pellets were combined with the digestate application of scenario 1: Heating pool/split digestate application or 3: Bottling biogas/full digestate as nutrient supply as well as various other options. The environmental impacts of these combinations were compared with the chosen 6 scenarios' impacts but scenario 4 still outperformed all these mixed options on overall environmental impact.

Scenario 5: Bottling biogas/NPK fertilizer pellets has the highest impact on 7 of the 11 environmental categories and is therefore the least preferred combination of processes. Scenario 6: Biodiesel from algae/bottling biogas has higher impacts than scenario 5 on acidification potential, photochemical oxidation, terrestrial ecotoxicity and depletion of abiotic resources (elements, ultimate reserves). It is observed that the process "clean-up of biogas to produce methane for bottling at high pressure" has a significant impact on many of the environmental categories. To reduce the impact of scenario 5: Bottling biogas/NPK fertilizer pellets on the environmental categories, the effect of utilizing the biogas as is rather than upgrading biogas to bio-methane was investigated. The impacts are similar to the effects in scenario 1: Heating pool/split digestate application and 2: Heating pool/pasteurised water for domestic use because no additional energy and chemicals are required that have higher environmental impacts. When eliminating the process "clean-up of biogas to produce methane for bottling at high pressure" in scenario 5: Bottling biogas/NPK fertilizer pellets, the scenario becomes a more acceptable option with regards to environmental impacts.

The comparison between the impacts of the scenarios shows that the option of using digestate as nutrient source without separation of phases, has the lowest impact on eutrophication. Application of digestate with or without phase separation had lower impacts than the conversion of the digestate into fertilizer.

According to this LCA, the use of biogas for generating heat and electricity is more favourable to the environment than heating, scrubbing and bottling of the biogas when the same volume of biogas is available. The combination of fertilizer pellets with heat and power generation resulted in much lower environmental impacts than the combination of NPK fertilizer and bottling of biogas.

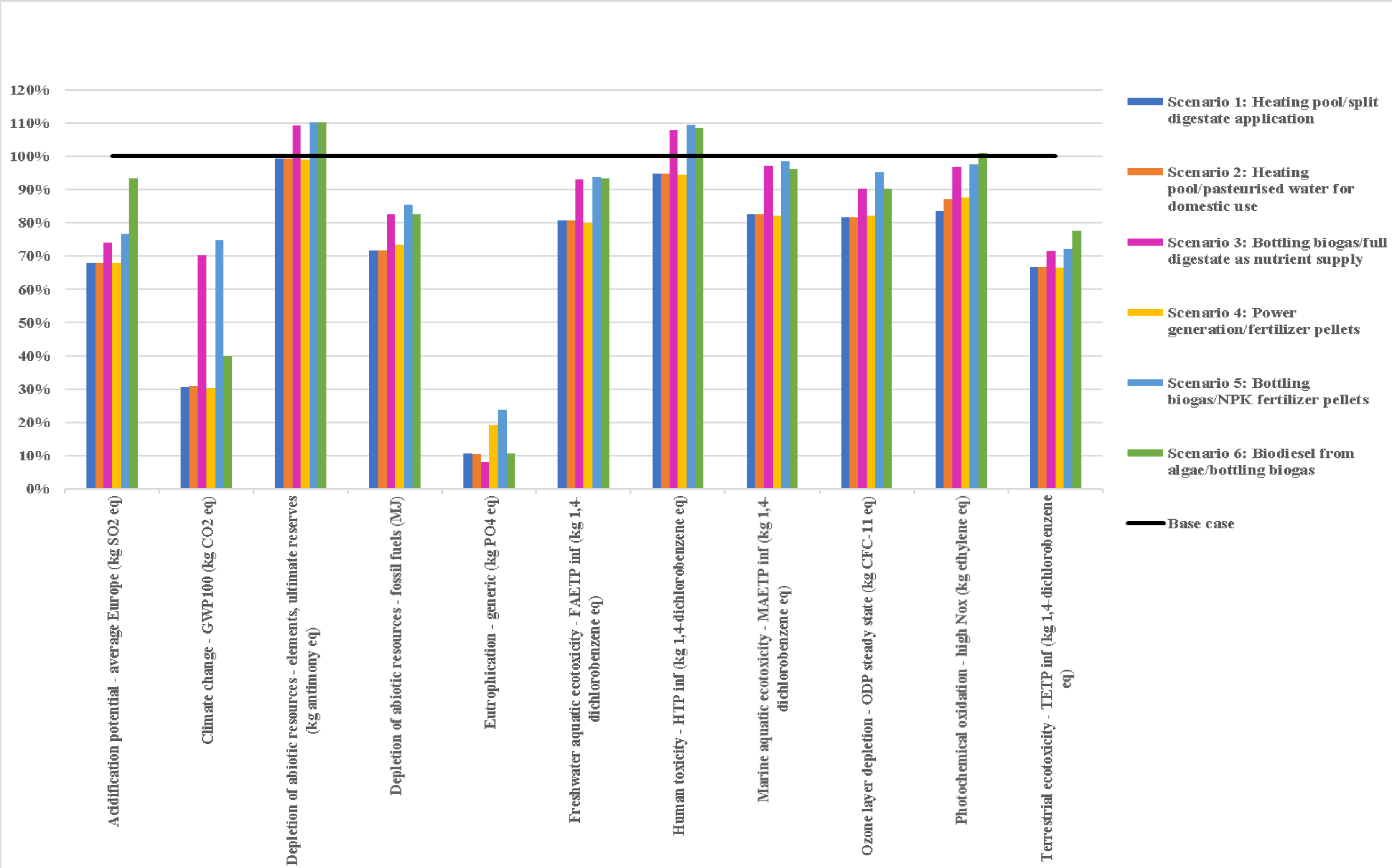

Figure 4-13 Comparison of scenarios vs base case for CML impact categories (without offset processes)

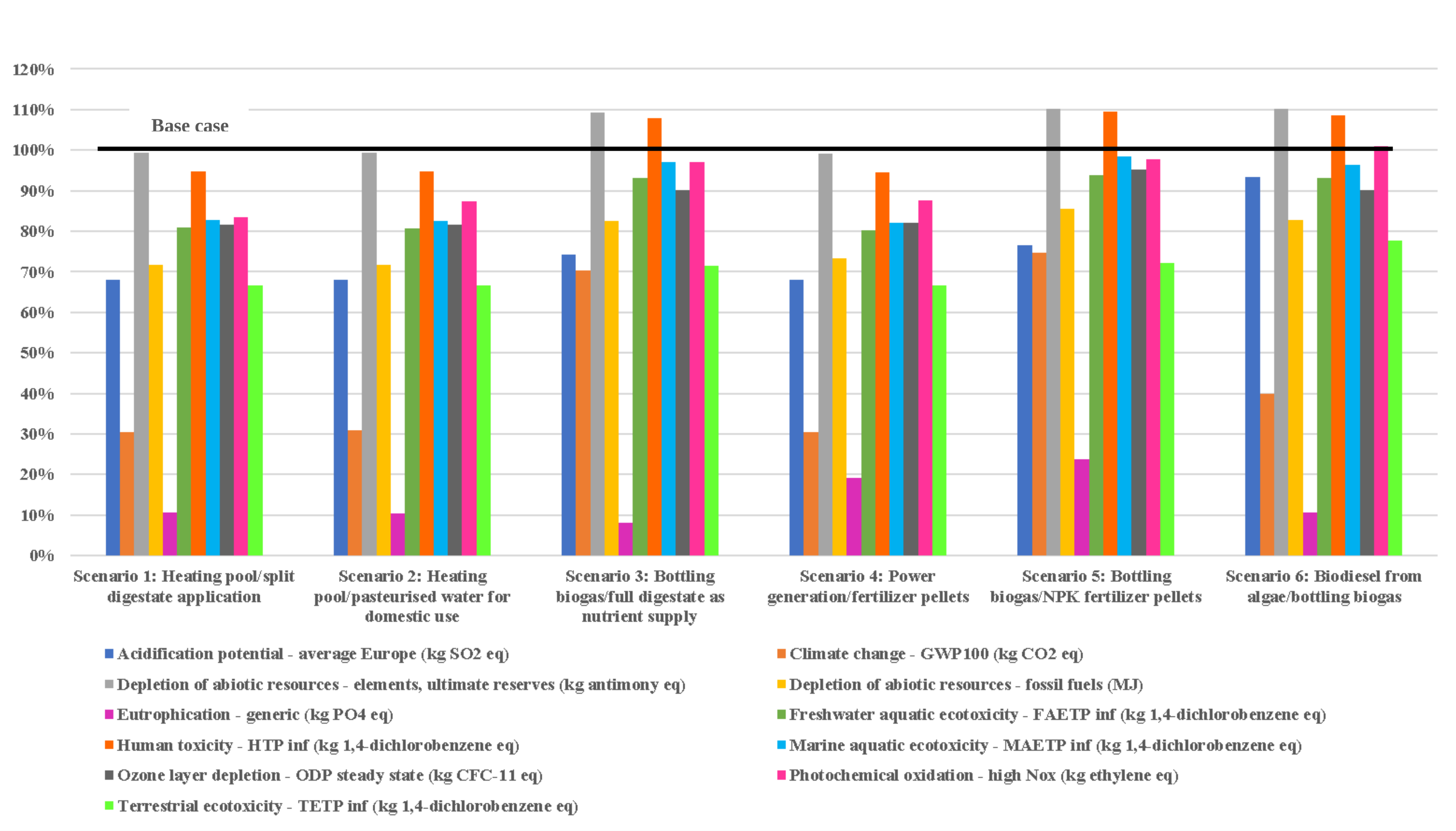

Figure 4-14 Comparison of scenarios vs base case for CML impact categories (inverse) without offset processes

See Figure 4-15 showing the small impacts that the offset processes have on each scenario's results especially in scenario 6.

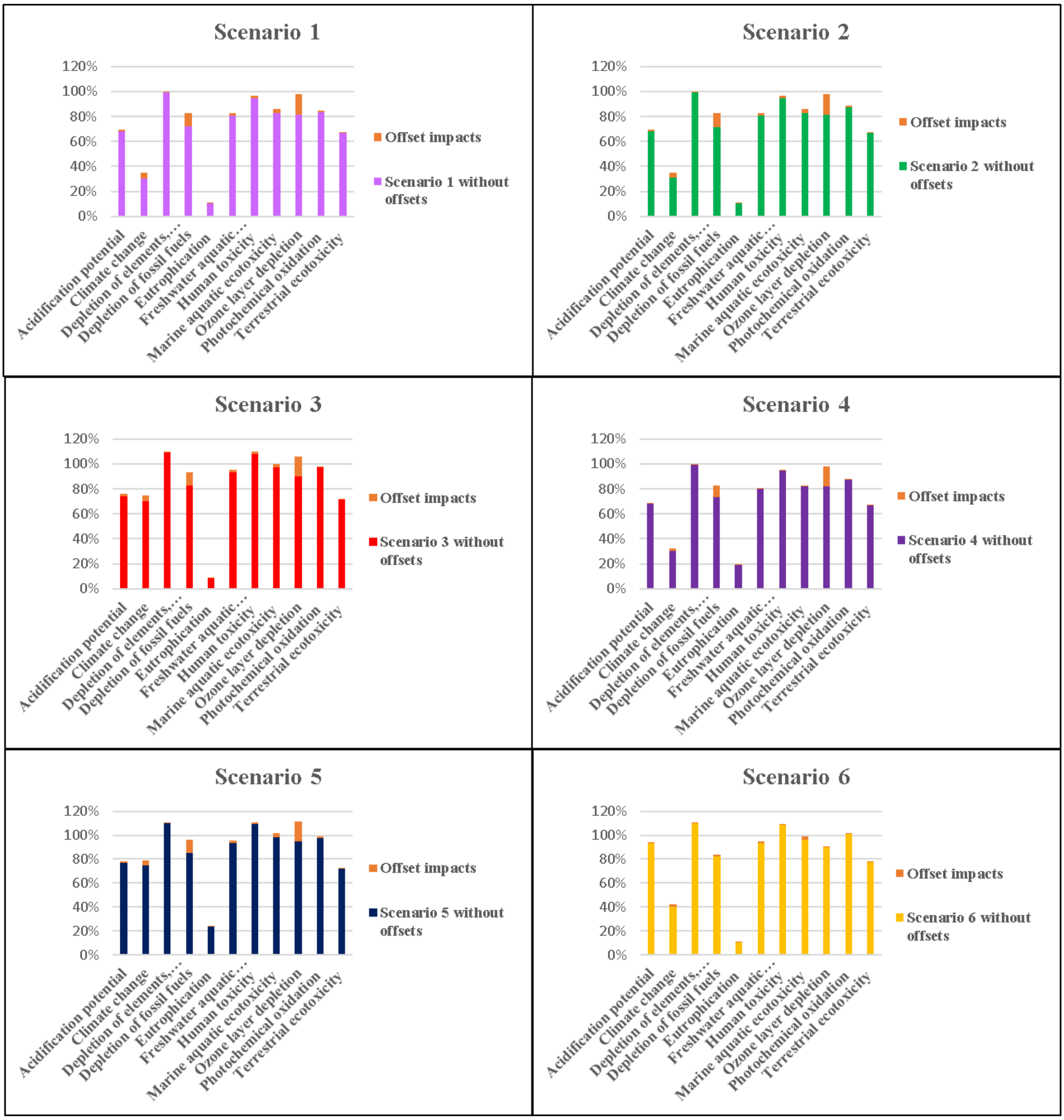

Figure 4-15 Impacts of scenarios with the impacts of the offset processes

4.8 INTERPRETATION AND POSSIBLE APPLICATION OF RESULTS FROM THIS LCA

As suggested earlier, the benefits of anaerobic digestion lie in the reduction of waste such as cattle manure that otherwise needs to be discarded of in a way that leads to various forms of pollution. While reducing wastes, AD produces a source of energy that can be applied for heating, electricity generation and fuel. Anaerobic digestion also reduces odours and supplies higher quality fertilizer options (Holm-Nielsen et al. 2009).

The current environmental impacts of cattle operation and its associated processes, are severe if South Africa's cattle population of 13.7 million in 2014/2015 is taken into consideration (Directorate Statistics and Economic Analysis 2016). This fact is even worse if it is combined with the small number of anaerobic digestion applications currently existing in South Africa. BiogasSA only commissioned their first 0.4 MW plant in 2016 (BiogasSA 2017). When comparing the local facts with the vast number of implemented systems found in Europe where a total installed capacity of 10000 MW was reported by 2016 (European Biogas Association 2017), it is clear that South Africa's cattle population is still causing too much impact on the CML environmental categories. According to the European Biogas Association's latest report of 2017, Europe operated more than 17000 biogas plants by 2016 that gain the benefits from AD already explained (European Biogas Association 2017).

This study indicated that when processes are added to AD to utilise biogas as source of energy, the ratio of the biogas used for heating vs the portion cleaned to generate electricity, becomes quite important. It seems as if the ratio used in scenario 4 "Power generation/fertilizer pellets" is optimum for the impact categories. Various different ratios for the use of the available biogas were investigated, but no better results could be managed than what is used in scenario 4. The ratio used is approximately 8:1 for heating to electricity generation. As more biogas is allocated to electricity generation, the larger the impact from the biogas cleaning process becomes. Generating electricity on cattle farms using equipment not requiring CO_2 scrubbed biogas, is critical to eliminate the impacts from the cleaning process.

The higher impact on acidification potential by the photo bioreactor cultivating algae in scenario 6: Biodiesel from algae/bottling biogas can be reduced by transforming the ammonia emission into a useful fertilizing product. The storage of carbon dioxide emitted during the heat generation process in all 6 scenarios can be a sensible way of reducing this impact on climate change. The stored CO_2 can be used for algae cultivation, as a raw material for liquid fuel production and in the manufacturing of fizzy cold drinks (Global CCS Institute 2017). Although the farmer will need to invest some initial capital for the equipment required for these processes, there will be a payback from the products potentially sellable.

If this study is simplified to comparing only the impacts of "anaerobic digestion of cattle manure" (including all biogas and digestate impacts) plus the "milk stall without impacts from manure" to the impacts of the "operation of cattle stall", it is clear that anaerobic digestion plays an important role in reducing environmental impacts of a cattle stall operation. The highlight of the study is the reduction in the impact on climate change by implementing anaerobic digestion. See Figure 4-16 for this simplified comparison of the environmental impacts of "anaerobic digestion of cattle manure" plus "milk stall without impacts from manure" to that of "operation of cattle stall".

Before farmers can benefit financially by implementing anaerobic digesters, it is important that they are educated on the proper operation of the system and do not fall in the trap that some American farmers did in the 1980's but rather know how to properly manage the system on a 24/7 basis to optimise its benefits. European governments often support farmers economically to promote the technology associated with anaerobic digestion and the need for cleaner energy. This is one of the reasons for the amazing growth of this application in Europe (Klinkner 2014).

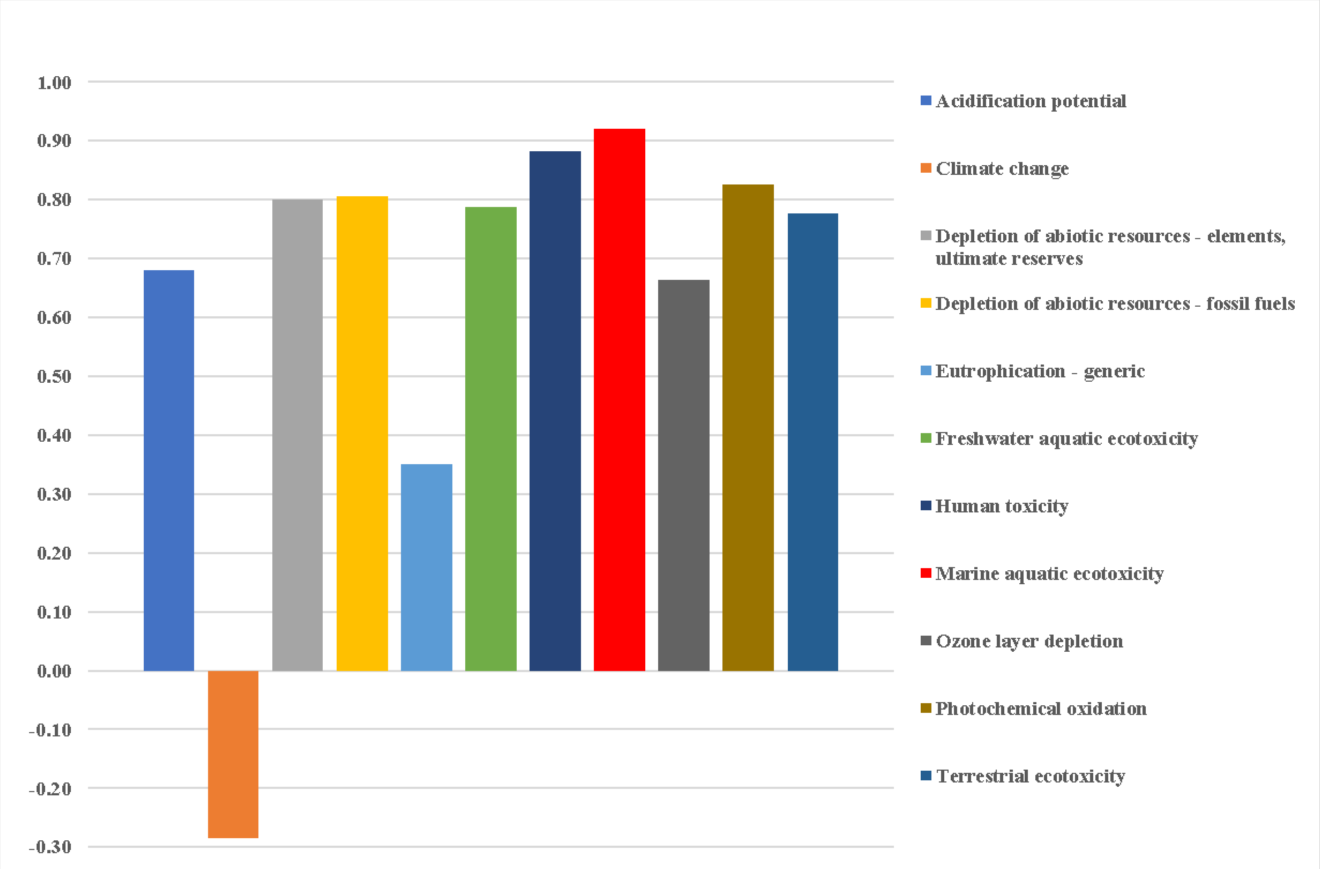

Figure 4-16 Simplified comparison of the impacts of "amended stall" plus AD with "operation of cattle stall" (Impacts for "Operation of cattle stall" equals 1)

Surely, the once off capital expenditure of an anaerobic digestion system combined with a gas turbine for generation of electricity or a gas boiler may put off many South African small farmers, but through proper education about the long-term savings and environmental benefits from being self-sufficient in energy and fertilizers supply, the number of installations in South Africa should grow considerably.

It is also critical that a feed-in-tariff strategy (supplying energy to the national grid from household/farm power generation) is finalised in South Africa to act as an additional motivator for the implementation of biogas generating processes. More anaerobic digestion systems combined with the already increasing use of solar and wind energy systems in South Africa will reduce this country's environmental impacts as they replace the current energy generation processes using coal, crude oil and natural gas.

A perfect example of a self-sufficient farm was found in Finland. All required fuel, heat, electricity and fertilizer requirements are met by an anaerobic digester operating under mesophilic conditions fed by the manure of 40 cows and 60 calves together with the household's organic waste. The farmer even produces extra energy to sell to the Finnish national supplier (Lampinen 2004). This example indicates that any farmer who is serious about energy self-sufficiency and the reduction of environmental impacts from his/her cattle operation, can be successful.

5 CONCLUSION AND RECOMMENDATIONS

Firstly, the method "life cycle assessment" was found an effective comparison tool for the environmental impacts of different scenarios. It is also concluded that the scope and definition, functional unit definition and the boundaries of a system are of utmost importance and have to be in sync with the purpose of the study. The comprehensiveness of the database chosen for the assessment determines how representative the results of the study will be. In this case >90% of the processes chosen for the study could be matched with processes already defined in the database used. The same database could be used throughout the study to compare the results for the various scenarios. When processes could not be found in the database, the input and output elements/flows used to define each process were found in the database and used to ensure the results obtained could be compared with each other. The LCA methodology is easier to trust in a comparative study like this one, than perhaps in case of a descriptive study where figures have to be calculated and presented as exact numbers.

Secondly, certain conclusions were made from the results of the life cycle assessment performed on the six different combinations of processes following anaerobic digestion. These scenarios are based on possible uses for the products from the anaerobic digestion of the cattle manure of a stall containing 60 cows at the Welgevallen experimental farm (Stellenbosch University, SU). The environmental impacts of the scenarios were compared to a base case. The base case is defined as the cattle stall with 60 cows operated without the anaerobic digester and its outflows. It is further defined by the processes that off-set those processes associated with the anaerobic digestion's products in the various scenarios.

It was found that the base case has a larger impact than the six scenarios on most of the CML environmental categories. Scenario 3: Bottling biogas/full digestate as nutrient supply, scenario 5: Bottling biogas//NPK fertilizer pellets and scenario 6: Biodiesel from algae/bottling biogas exceed the impact of the base case on depletion of abiotic resources (elements, ultimate reserves) and human toxicity by 7-10% mainly due to the resources required for the scrubbing and bottling of biogas and emissions from this process. The combination of the processes for esterification of bio-oil, anaerobic digestion and cleaning of biogas results in scenario 6: Biodiesel from algae/bottling biogas exceeding the base case impact on photochemical oxidation by 1%.

Due to the uncertainty of the database info on the production of EDTA (for removal of H_2S in biogas) (GreenDelta 2016) and the large percentage impact it has on ozone layer depletion, the results of this environmental category are ignored.

The combination of scenario 4: Power generation/fertilizer pellets processes had the best result for the life cycle assessment calculated using the "Ecoinvent" database. The lowest values were recorded in 7 of the 11 environmental categories. The results for scenario 4 are only slightly better than those of scenario 1: Heating pool/split digestate application and scenario 2: Heating pool/pasteurised water for domestic use. If the digestate in scenario 4 is applied to the agricultural fields as is, instead of converting it into NPK fertilizer, the impact on eutrophication will be reduced by 50%. By changing this application, scenario 4 will also have the lowest impact (equal to scenario 3: Bottling biogas/full digestate as nutrient supply) on eutrophication.

Scenario 5: Bottling biogas//NPK fertilizer pellets combination of processes proved to be the worst combination in terms of environmental impacts. It shows the highest impacts in 7 of the 11 categories assessed. It is mainly the combined impacts from the heat generation from biogas, biogas clean-up and fertilizer manufacturing processes that caused these high impacts. Fortunately, all these impacts can be reduced should this combination of processes seem feasible to the farmer by making use of processes such as (CCS) “capturing of carbon and storing” (Global CCS Institute 2017) before converting CO_2 into other useful applications or products.

Application of digestate to agricultural fields without phase separation has a lower impact on eutrophication than the digestate solids converted into some form of fertilizer. The combination of heat and power generation from biogas has a lower impact on most of the environmental categories than combining biogas for heat generation with cooking after scrubbing and botting of biogas. Utilizing biogas and digestate in their raw states proved to be more environmentally friendly than upgrading or transforming these anaerobic digestion products.

There are various size turbines available for the generation of electricity using biogas. Modern technology equipment such as a micro-CHP engine similar to what is used in “Valtra” tractors allows the small farmer to generate electricity without even scrubbing CO_2 from the biogas. This is illustrated by a small Finnish farm using a micro-CHP engine to generate 40 MWh of electricity annually (110 kWh per day) from the biogas produced by an anaerobic digester fed with the manure of 60 cows and 40 calves combined with the kitchen and farm biowaste (Lampinen 2004). The stall of 60 cows used in this study is approximately half the size of the Finnish farm in terms of biowaste supply. It certainly has the potential to generate adequate electricity after heating the digester, to sustain the operation of the digester (11 kWhe/day) (Whiting & Azapagic 2014) and generate additional power of at least 45 kWhe/day for use at the stall or to sell into the National grid.

Without applying the products from the anaerobic digester, the sole benefit of the process will be lower environmental impacts from the conventional cattle stall. If the farmer chooses to produce biogas for heat or power generation and apply the digestate as nutrient and irrigation source, he/she will also benefit financially over the long-term. The biogas industry in South Africa is still small and developing. Much can be learnt from the Europeans who apply this technology in many sectors of farming and industry to supply large volumes of biogas and biofuel with much lower environmental impacts than the conventional methods of energy generation still used in South Africa.

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7 APPENDIX A

Table 7-1 Mass balance of common processes for scenarios 1 – 6

Manure		**References**		
No of cows	60			
Manure/cow/day	36 kg	ASAE 2005		
Manure total/day	2160 kg	Fisheries 2015	Total solids/day	250.8 kg
Water at 88%	1900.8 kg		Volatile solids/day	213.6 kg
Bulk density of manure	993.24 kg/m^3	Lorimor et al. 2008		
Water added	1000 litre			
Total digester feed/day	3.17 m^3			
Density of Digester feed	992 kg/m^3			
Digester feed composition/day:			Solid fraction	Liquid fraction
Nitrogen	12.36 kg	Fisheries 2015	6.18 kg	6.18 kg
Phosphate	4.08 kg		3.26 kg	0.816 kg
Potassium	8.94 kg		1.79 kg	7.15 kg
Water	2900.8 kg		290.08 kg	2610.72 kg
Carbon	148.32 kg		89 kg	59.32 kg
Sulphur	3.24 kg		1.62 kg	1.62 kg
Total	3077.74 kg		391.93 kg	2685.81 kg
Biogas				
Volatile solids conversion % to biogas	40%	Dennis & Burke 2001		
Biogas produced/day	85.44 kg			
Biogas volume/day at 20°C and 1 atm	85.1 Nm^3			
Composition of biogas		de Mes et al. 2003		
CH_4	65%			
CO_2	28%			
N_2	1%			
H_2	1%			
H_2S	1%			
O_2	0.5%			
H_2O	0.35%			
Energy value of biogas	22 MJ/Nm^3	de Mes et al. 2003		

Total energy in biogas per day after 80% of water is removed	1801.05 MJ			
Energy required to keep digester at 35°C				
Average Cp of cattle manure	3.606 kJ/kg°C	Nayyeri et al. 2009		
Temperature in digester	35°C			
Ave temperature for Stellenbosch	20.59°C	NASA 2016		
Heat required daily for manure fed to digester	163.65 MJ			
Heat loss daily through concrete walls of digester	270.15 MJ	Fulton et al. 2001		
Total daily energy required to keep digester at 35°C	433.8 MJ			
Digestate				
Digestate leaving the digester daily (Feed flow– biogas flow)	3063.86 kg			
	Before filtration	After filtration	Solid phase	Liquid phase
		Moore 2008	354.53 kg	2709.33 kg
Solids at 75% of solid phase			124.09 kg	41.36 kg
Phosphate	4.1 kg or 0.13%		3.06 kg	1.02 kg
Nitrogen	11.4 kg or 0.37%		2.84 kg	8.53 kg
Potassium	8.9 kg or 0.29%		1.34 kg	7.6 kg
Carbon	108.8 kg or 3.55%		81.63 kg	27.21 kg
Water	2899 kg or 94.6%		230.45 kg	2668.12 kg
Sulphur	2.1 kg or 0.07%		1.58 kg	0.53 kg
Other nutrients	30 kg or 0.98%		23.97 kg	5.99 g

8 APPENDIX B

8.1 Description of the processes created in the database to establish the life cycle assessment of each scenario (all values are based on 1 day)

See Table 8.1 to 8.7 for descriptions of the processes involved with each scenario. (Processes in italics were created in the database from the mass balance).

Table 8-1 Description of Scenario 1 Processes

Scenario 1	Title	Ecoinvent/created process	Product	Target amount
Process 1	Operation housing milk cows	Milk production from cow/cow milk with FPCM correction (amended)	Milk kg	926.9
Process 2	Anaerobic digestion of cattle manure to produce biogas	Anaerobic digestion of manure/biogas/cut-off	Biogas Nm^3	81.87
Process 3	Heat generation from biogas for digester, dryer and swimming pool	Heat production, biogas, at diffusion absorption heat pump 4 kW	Energy MJ	1801
Process 4	Heat digester with propane	Heat production, propane, at industrial furnace > 100kW	Energy MJ	434
Process 5	Liquid digestate and condensate for irrigation	*Irrigation of crops in field or greenhouse*	Irrigation liquid m^3	2.935
Process 6	Production of EDTA to use as catalyst for removal of H_2S from biogas	EDTA production/ ethylenediamine-tetra-acetic acid	EDTA kg	9.15
Process 7	Production of iron(II)chloride for removal of H_2S from biogas	Iron(II)chloride production/iron(II)chloride	Iron (II)chlo-ride kg	9.7
Process 8	Nutrient supply from digestate solids.	*Using digestate solids to fertilize agricultural land*	Digestate nutrients kg	124
Process 9	Transport combusting diesel instead of biodiesel	Transport, freight lorry, all sizes, EURO3 to generic market for transport, freight, lorry, unspecified	Transport t*km	0.107
Process 10	Electricity offset from biogas using coal to generate electricity	Electricity production, hard coal, electricity, high voltage	Electricity kWh	7.0
Process 11	Offset manufacture diesel from raw material	Diesel production, low sulphur	Diesel kg	10.7

Table 8-2 Description of Scenario 2 Processes

Scenario 2	Title	Ecoinvent/created process	Product	Target amount
Process 1	Operation housing milk cows	Milk production from cow/cow milk with FPCM correction (amended)	Milk kg	926.9
Process 2	Anaerobic digestion of cattle manure to produce biogas	Anaerobic digestion of manure/biogas/cut-off	Biogas Nm^3	81.87
Process 3	Heat generation with biogas for digester, dryer, swimming pool and pasteurisation of liquid digestate fraction	Heat production, biogas, at diffusion absorption heat pump 4 kW	Energy MJ	1801
Process 4	Heat digester with propane	Heat production, propane, at industrial furnace > 100kW	Energy MJ	434
Process 5	Production of EDTA to use as catalyst for removal of H_2S from biogas	EDTA production/ ethylenediamine-tetra-acetic acid	EDTA kg	9.15
Process 6	Production of iron(II)chloride for removal of H_2S from biogas	Iron(II)chloride production/iron(II)chloride	Iron (II)chlo-ride kg	9.7
Process 7	Nutrient supply from digestate solids	*Using digestate solids to fertilize agricultural land*	Digestate nutrients kg	124
Process 8	Transport combusting diesel instead of biodiesel	Transport, freight lorry, all sizes, EURO3 to generic market for transport, freight, lorry, unspecified	Transport t*km	0.107
Process 9	Electricity offset from biogas using coal to generate electricity	Electricity production, hard coal, electricity, high voltage	Electricity kWh	7.0
Process 10	Offset manufacture diesel from raw material	Diesel production, low sulphur	Diesel kg	10.7

Table 8-3 Description of Scenario 3 processes

Scenario 3	Title	Ecoinvent/created process	Product	Target amount
Process 1	Operation housing milk cows	Milk production from cow/cow milk with FPCM correction (amended)	Milk kg	926.9
Process 2	Anaerobic digestion of cattle manure to produce biogas	Anaerobic digestion of manure/biogas/cut-off	Biogas Nm^3	81.87
Process 3	Heat generation from biogas for digester and cooking from bottled gas	Heat production, biogas, at diffusion absorption heat pump 4 kW	Energy MJ	1801
Process 4	Heat digester with propane	Heat production, propane, at industrial furnace > 100kW	Energy MJ	434
Process 5	Digestate and condensate used as irrigation of agricultural fields	Nutrient supply from manure, liquid cattle, nitrogen fertilizer	Irrigation liquid m^3	3.064
Process 6	Production of EDTA to use as catalyst for removal of H_2S from biogas	EDTA production/ ethylenediamine-tetra-acetic acid	EDTA kg	9.15
Process 7	Production of iron(II)chloride for removal of H_2S from biogas	Iron(II)chloride production/iron(II)chloride	Iron (II)chlo-ride kg	9.7
Process 8	Clean-up of biogas to produce methane for bottling	Methane production, 96% by volume from biogas, high pressure at user	Methane, 96% by volume for energy MJ	2197
Process 9	Transport combusting diesel instead of biodiesel	Transport, freight lorry, all sizes, EURO3 to generic market for transport, freight, lorry, unspecified	Transport t*km	0.107
Process 10	Electricity offset from biogas using coal to generate electricity	Electricity production, hard coal, electricity, high voltage	Electricity kWh	7.0
Process 11	Offset manufacture diesel from raw material	Diesel production, low sulphur	Diesel kg	10.7

Table 8-4 Description of Scenario 4 processes

Scenario 4	Title	Ecoinvent/created process	Product	Target amount
Process 1	Operation housing milk cows	Milk production from cow/cow milk with FPCM correction (amended)	Milk kg	926.9
Process 2	Anaerobic digestion of cattle manure to produce biogas	Anaerobic digestion of manure/biogas/cut-off	Biogas Nm^3	81.87
Process 3	Heat generation from biogas for digester and dryer	Heat production, biogas, at diffusion absorption heat pump 4 kW	Energy MJ	1567
Process 4	Heat digester with propane	Heat production, propane, at industrial furnace > 100kW	Energy MJ	434
Process 5	Liquid digestate and condensate for irrigation	*Irrigation of crops in field or greenhouse*	Irrigation liquid m^3	2.935
Process 6	Production of EDTA to use as catalyst for removal of H_2S from biogas	EDTA production/ ethylenediamine-tetra-acetic acid	EDTA kg	9.15
Process 7	Production of iron(II)chloride for removal of H_2S from biogas	Iron(II)chloride production/iron(II)chloride	Iron (II)chlo-ride kg	9.7
Process 8	Clean-up of biogas to methane for turning turbine	Biogas purification to methane 96vol%	Methane Nm^3	7.8
Process 9	Generate electricity using cleaned up biogas	Electricity, natural gas, conventional power plant/electricity high voltage	Energy kWh	7.0
Process 10	Fertilizer supply from solid digestate	Nutrient supply from manure, solid cattle, nitrogen fertilizer	Nitrogen fertilizer kg	94
Process 11	Transport combusting diesel instead of biodiesel	Transport, freight lorry, all sizes, EURO3 to generic market for transport, freight, lorry, unspecified	Transport t*km	0.107
Process 12	Offset manufacture diesel from raw material	Diesel production, low sulphur	Diesel kg	10.7

Table 8-5 Description of Scenario 5 processes

Scenario 5	Title	Ecoinvent/created process	Product	Target amount
Process 1	Operation housing milk cows	Milk production from cow/cow milk with FPCM correction (amended)	Milk kg	926.9
Process 2	Anaerobic digestion of cattle manure to produce biogas	Anaerobic digestion of manure/biogas/cut-off	Biogas Nm^3	81.87
Process 3	Heat generation from biogas for digester and cooking from bottled gas	Heat production, biogas, at diffusion absorption heat pump 4 kW	Energy MJ	1801
Process 4	Heat digester with propane	Heat production, propane, at industrial furnace > 100kW	Energy MJ	434
Process 5	Liquid digestate and condensate for irrigation	*Irrigation of crops in field or greenhouse*	Irrigation liquid m^3	2.711
Process 6	Production of EDTA to use as catalyst for removal of H_2S from biogas	EDTA production/ ethylenediamine-tetra-acetic acid	EDTA kg	9.15
Process 7	Production of iron(II)chloride for removal of H_2S from biogas	Iron(II)chloride production/iron(II)chloride	Iron (II)chlo-ride kg	9.7
Process 8	Production of NPK fertilizer from digestate and limestone	*NPK fertilizer granules manufacturing*	NPK fertilizer granules kg	119
Process 9	Clean-up of biogas to produce methane for bottling	Methane production, 96% by volume from biogas, high pressure at user	Methane, 96% by volume for energy MJ	2197
Process 10	Transport combusting diesel instead of biodiesel	Transport, freight lorry, all sizes, EURO3 to generic market for transport, freight, lorry, unspecified	Transport t*km	0.107
Process 11	Electricity offset from biogas using coal to generate electricity	Electricity production, hard coal, electricity, high voltage	Electricity kWh	7.0
Process 12	Offset manufacture diesel from raw material	Diesel production, low sulphur	Diesel kg	10.7

Table 8-6 Description of Scenario 6 processes

Scenario 6	Title	Ecoinvent/created process	Product	Target amount
Process 1	Operation housing milk cows	Milk production from cow/cow milk with FPCM correction (amended)	Milk kg	926.9
Process 2	Anaerobic digestion of cattle manure to produce biogas	Anaerobic digestion of manure/biogas/cut-off	Biogas Nm^3	81.87
Process 3	Heat generation from biogas for digester and cooking from bottled gas	Heat production, biogas, at diffusion absorption heat pump 4 kW	Energy MJ	1801
Process 4	Heat digester with propane	Heat production, propane, at industrial furnace > 100kW	Energy MJ	434
Process 5	Photo bioreactor for algae cultivation	*Nutrients feed to photo bioreactor for algae cultivation*	Photo bioreactor effluent kg	2709
Process 6	Esterification of bio-oil to produce biodiesel and glycerol	Esterification of palm-oil/vegetable oil methyl ester	Vegetable oil methyl ester kg	10.7
Process 7	Methanol production for de-esterification	Methanol production/methanol	Methanol kg	0.00016
Process 8	Production of EDTA to use as catalyst for removal of H_2S from biogas	EDTA production/ ethylenediamine-tetra-acetic acid	EDTA kg	9.15
Process 9	Production of iron(II)chloride for removal of H_2S from biogas	Iron(II)chloride production/iron(II)chloride	Iron (II)chlo-ride kg	9.7
Process 10	Production of sodium hydroxide to act as catalyst during de-esterification	Sodium hydroxide to generic market for neutralising agent/neutralising agent	Sodium hydroxide equivalent kg	0.112
Process 11	Supply of hexane for oil extraction	Iso-hexane production	Iso-hexane kg	0.032
Process 12	Clean-up of biogas to produce methane for bottling	Methane production, 96% by volume from biogas, high pressure at user	Methane, 96% by volume MJ	2197
Process 13	Nutrient supply from digestate solids	*Using digestate solids to fertilize agricultural land*	Digestate nutrients kg	124
Process 14	Transport combustion biodiesel	*Transport, freight, lorry, all sizes, | transport,*	Transport t*km	0.107

		freight, lorry with biodiesel		
Process 15	Electricity offset from biogas using coal to generate electricity	Electricity production, hard coal, electricity, high voltage	Electricity kWh	7.0

Table 8-7 Description of Base case processes

Base case	**Title**	**Ecoinvent process/created process**	**Product**	**Target amount**
Process 1	Operation housing milk cows	Milk production from cow/cow milk with FPCM correction	Milk kg	926.9
Process 2	Solid manure application	*Solid manure application, manure solid cattle*	Solid manure kg	391.9
Process 3	Irrigation with manure liquid	*Irrigation using manure liquid*	Liquid manure m^3	2.69
Process 4	Heat offset from biogas using coal for all processes	Heat and power co-generation, hard coal, heat, district or industrial	Energy MJ	1367
Process 5	Transport combusting diesel instead of biodiesel	Transport, freight lorry, all sizes, EURO3 to generic market for transport, freight, lorry, unspecified	Transport t*km	0.107
Process 6	Electricity offset from biogas using coal to generate electricity	Electricity production, hard coal, electricity, high voltage	Electricity kWh	7.0
Process 7	Off set manufacture diesel from raw materials	Diesel production, low sulphur	Diesel kg	10.7

9 APPENDIX C

9.1 TABLES WITH HIGHEST CONTRIBUTORS TO THE ENVIRONMENTAL IMPACT CATEGORIES FOR EACH PROCESS

Table 9-1 Highest impacts from base case processes on CML environmental categories

	Milk stall operation	**Solid manure application**	**Heat offset using coal for all processes**	**Offset manufacture diesel from raw materials**
Base case Acidification potential	Ammonia released from manure, SO_2 released during power generation for processes			
Base case Climate change	CO_2, nitrogen oxides, methane released during enteric and energy generation processes		CO_2 and methane released during combustion of coal	
Base case Depletion of abiotic resources (elements, reserves)	Aluminium, calcium, magnesium and others used as resources for equipment and processes			
Base case Depletion of abiotic resources (fossil fuels)	Coal, oil and natural gas for power generation for processes (lighting, milking, cleaning, feeding, manure handling)		Coal used as resource for heat generation	Crude Oil or coal as resource
Base case Freshwater aquatic ecotoxicity	Nickel, iron, manganese from upstream stainless-steel manufacturing of appliances used		Nickel ion used for stainless-steel manufacturing of equipment	

	Milk stall operation	**Solid manure application**	**Heat offset using coal for all processes**	**Offset manufacture diesel from raw materials**
Base case Human toxicity	Benzene released during energy production.		Selenium found in manure when feed for cattle is supplemented	
Base case Marine aquatic ecotoxicity	Hydrogen fluoride used in manufacturing of light bulbs etc used in stall		Beryllium used in electrical parts of the equipment. Hydrogen fluoride used in manufacturing of equipment used	
Base case Ozone depletion	Bromo trifluoro-methane used in electrical equipment used in stall			
Base case Photochemical oxidation	CO and methane from processes in stall and for power generation		SO_2 released during combustion of coal	
Base case Terrestrial ecotoxicity	Chromium to soil from upstream manufacturing of stainless-steel apparatus, calcium, sulphate and sodium emissions to soil			
Base case Eutrophication		Phosphate, ammonia released from manure		

Table 9-2 Highest impacts on CML environmental categories from processes common to scenarios investigated

	Amended milk stall operation	**Anaerobic Digestion**	**Heating with propane**	**Production of EDTA**	**Heat processes using biogas**
Scenario 1 – 6 Acidification potential	Ammonia to air from stall operation				SO_2 and ammonia released during combustion of biogas
Scenario 1 – 6 Climate change			CO_2 release during combustion	CO_2 released during energy production	CO_2 and methane released
Scenario 1 – 6 Depletion of Abiotic resources (elements, reserves)	Borax for cleaning, cadmium for plastic appliances				
Scenario 1 - 6 Depletion of abiotic resources (fossil fuels)	Crude oil, natural gas and coal for energy		Oil used as resource for LPG	Natural gas used as energy source	
Scenario 1 - 6 Freshwater aquatic toxicity	Nickel ion, copper ion for upstream manufacturing processes			Formaldehyde as input material for EDTA production	Nickel ion from upstream manufacturing processes
Scenario 1 – 6 Human toxicity	Selenium as component in feed to animals, benzene released during energy production.	Selenium as part of manure input to digester, arsenic if insecticides are present in manure		Chromium VI released during manufacturing of upstream equipment	Chromium VI released during manufacturing of upstream equipment
Scenario 1 – 6 Marine aquatic toxicity	Hydrogen fluoride used in manufacturing of	Beryllium used in electrical parts of the digester		Beryllium used in electrical parts of the equipment needed for EDTA production	Beryllium used in electrical parts of equipment used.

	Amended milk stall operation	**Anaerobic Digestion**	**Heating with propane**	**Production of EDTA**	**Heat processes using biogas**
	light bulbs etc used in stall				Hydrogen fluoride used in manufacturing of equipment
Scenario 1 – 6 Ozone depletion potential	Bromo trifluoro-methane used in electrical equipment		Bromo trifluoro-methane used in electrical equipment in upstream process	Tetra chloro-methane used as cleaning/degreasing agent in production process	
Scenario 1 – 6 Photochemical oxidation	CO and methane to air from operations	SO_2 released by process			CO from incomplete combustion
Scenario 1 – 6 Terrestrial ecotoxicity	Chromium to soil from upstream manufacturing of stainless-steel apparatus	Small quantities of chromium from stainless steel manufacturing parts			Chromium from stainless steel manufacturing parts

Table 9-3 Highest impacts on CML environmental categories from various processes included in scenarios investigated

	Nutrient supply from digestate solids	**Clean-up of biogas to methane and bottling at high pressure**	**Fertilize with full digestate**	**Clean-up of biogas for use in turbine**	**Production of NPK fertilizer**	**Liquid digestate for irrigation**	**Photo bioreactor for algae cultivation**
Scenario 1, 2, 6 Eutrophication	Phosphate, ammonium to soil from digestate						
Scenario 1, 4, 5 Eutrophication						Ammonia, phosphate released to soil	
Scenario 3, 5, 6 Acidification potential		SO_2 to air during electricity generation for processes					
Scenario 3, 5, 6 Climate change		CO_2 released during clean-up					
Scenario 3, 5, 6 Depletion of abiotic resources (elements, reserves)		Cadmium used in plastic components for process					
Scenario 3, 5, 6 Depletion of abiotic resources (fossil fuels)		Coal for power generation for processes					

	Nutrient supply from digestate solids	Clean-up of biogas to methane and bottling at high pressure	Fertilize with full digestate	Clean-up of biogas for use in turbine	Production of NPK fertilizer	Liquid digestate for irrigation	Photo bioreactor for algae cultivation
Scenario 3, 5, 6 Freshwater aquatic ecotoxicity		Nickel ion to water from stainless-steel manufacturing					
Scenario 3, 5, 6 Human toxicity		Chromium VI released during manufacturing of upstream equipment					
Scenario 3, 5, 6 Marine aquatic ecotoxicity		Beryllium used in electrical parts for the equipment used					
Scenario 3, 5, 6 Ozone depletion		Bromo trifluoro-methane used in electrical equipment					
Scenario 3, 5, 6 Photochemical oxidation		CO released during power generation for use in process					
Scenario 3, 5,6 Terrestrial ecotoxicity		Chromium from stainless steel					

	Nutrient supply from digestate solids	**Clean-up of biogas to methane and bottling at high pressure**	**Fertilize with full digestate**	**Clean-up of biogas for use in turbine**	**Production of NPK fertilizer**	**Liquid digestate for irrigation**	**Photo bioreactor for algae cultivation**
		manufacturing parts					
Scenario 3 Eutrophication			Phosphate, ammonia to soil from digestate				
Scenario 3 Climate change			CO_2 released				
Scenario 4 Climate change				CO_2 and methane released			
Scenario 4 Depletion of abiotic resources (elements, reserves)				Cadmium used in manufacturing of plastic equipment used			
Scenario 4 Human Toxicity				Chromium VI released during manufacturing of equipment used			
Scenario 4 Marine aquatic ecotoxicity				Beryllium used in electrical parts for the equipment used			

	Nutrient supply from digestate solids	Clean-up of biogas to methane and bottling at high pressure	Fertilize with full digestate	Clean-up of biogas for use in turbine	Production of NPK fertilizer	Liquid digestate for irrigation	Photo bioreactor for algae cultivation
Scenario 5 Acidification potential					Nitrogen oxides released		
Scenario 5 Eutrophication					Phosphate, ammonia released to soil		
Scenario 5 Climate change					CO_2 released during power generation for processes		
Scenario 5 Depletion of abiotic resources (fossil fuels)					Oil/coal as resource for electricity generation for processes		
Scenario 5 Freshwater aquatic ecotoxicity					Nickel ion to water from stainless-steel production		
Scenario 5 Ozone depletion					Bromo trifluoro-methane used in electrical equipment		
Scenario 6 Acidification potential							Ammonia released

	Nutrient supply from digestate solids	Clean-up of biogas to methane and bottling at high pressure	Fertilize with full digestate	Clean-up of biogas for use in turbine	Production of NPK fertilizer	Liquid digestate for irrigation	Photo bioreactor for algae cultivation
Scenario 6 Depletion of abiotic resources (fossil fuels)							Natural gas used for energy supply to process