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The Life Cycle Assessment of Methane Production with anaerobic digestion integrated with pyrolysis techniques for Sludge waste minimization

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Summary:

Anaerobic digestion (AD) is an effective method widely used for treating organic waste and converting treated waste into biogas, a renewable energy source. Recently, there has been a focus on combining anaerobic digestion with pyrolysis because of its possibility to increase biogas yield and better utilization of wastes. The main purpose of this research was to compare two potential biogas production systems fed with municipal sludge in terms of the effects they had on the environment. The anaerobic digestion of municipal waste sludge is depicted in the two following scenarios: Scenario 1 is focused on a simple anaerobic digestion process whereas Scenario 2 involves a combination of anaerobic digestion with pyrolysis. The objective of the study was to understand and evaluate the following scenarios that would lead to the least environmental impacts throughout the production lifecycle. An LCIA method can be used in order to systematically compare the environmental profile of both scenarios within a cradle-to-gate concept. When comparing the two scenarios, the analysis proved that Scenario 2, which introduced pyrolysis, had higher immediate environmental impacts which resulted from a more complicated process and energy needs. This analysis demonstrates that the selection of process efficiency and sustainability objectives is crucial and that additional progress in energy efficiency or emissions reduction may enable Scenario 2 to be an energy-efficient and environmentally superior method of biogas generation. The potential long-term benefits of integrating pyrolysis, such as reduced waste and valuable byproducts, suggest that Scenario 2 could become a more sustainable approach to biogas production with improvements in energy efficiency and emissions control.

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Preface

This thesis is the final result of extensive research on the environmental impacts of high-rate anaerobic digestion processes, which includes the combined process of production to reduce the digested sludge volumes. The research and findings herein aim to improve sustainable methane production practices.

The successful completion of this work could not have been possible without the support and guidance of some people and institutions. I sincerely thank Thea Lucia Sauro Indrebø who was the guide and mentor throughout the research process. Her advice and support have had a profound impact on the orientation and outcomes of this research.

I am equally thankful to Gamunu Arachchige for his unfailing support and helpful criticism. His thorough knowledge of biogas production techniques and environmental life cycle assessments has been a main factor in improving the focus and depth of this thesis.

In addition, I would like to thank the Lindum Biogas Plant in Drammen for its support by providing the resources and facilities needed for this research. The knowledge gained from the operations at Lindum has added a practical aspect to the findings and conclusions of this thesis.

I am deeply grateful to the University of Sri Jayewardenepura and the University of South-Eastern Norway for offering me the academic environment and resources that have enabled me to conduct this research. The academic exchange and intellectual stimulation in these institutions have been critical to the successful completion of this thesis.

I would like to thank the Norpart Project for their wonderful funding and support that has made this international collaboration possible. Last, I would like to express my deepest gratitude to my family and friends for their unconditional love and motivation during this time. My belief in my abilities has been greatly helped by their belief in me.

Porsgrunn, 19.05.2024

Samarasinghe R.G.S.B

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Nomenclature

LCA	Life Cycle Assessment
RE	Renewable Energy
NRE	Non-Renewable Energy
CHP	combined heat and power
EBA	European Biogas Association
HS	Hydrolyzed sludge
HRT	Hydraulic retention time
PL	Pyrolysis Liquid
COD	Chemical Oxygen Demand
sCOD	Soluble Chemical Oxygen Demand
tCOD	Total chemical oxygen demand
GHG	Green House Gas
AD	Anaerobic digestion
HPWS	High-pressure Water scrubber
GWP	Global warming potential
PAH	Polycyclic aromatic hydrocarbons
TS	Total solids
CH4	Methane
CO_2	Carbon Dioxide

1 Introduction

1.1 Background

As an environmentally beneficial renewable option, biogas is a promising prospect in the search for sustainable energy sources. It is critical to learn about a complete life cycle assessment (LCA) of biogas production as societies around the world struggle with an urgent requirement to decrease emissions and minimize their reliance on fossil fuel. This introduction explores all aspects of biogas generation while performing a comprehensive life cycle assessment to capture its environmental impact. Considering the current world energy context, the world is moving into renewable energy to Reduce impacts of the non-renewable energy.

Due to rapid urbanization, population growth and social expansion caused to consume more energy than in previous years (Kumar et al., 2017). In addition, Population growth caused an increase in the waste amount released to the environment. Increasing energy consumption and waste generation directly affected world energy sustainability. Currently, People use waste to create energy sustainably. Biogas is one of the energy products from waste. Biogas is a mix of carbon dioxide, methane and a small number of other gases that are produced by anaerobic digestion. Renewable natural gas should be pure to use energy demand. Biomethane is also type of Bio-natural gas. It consists of pure methane by upgrading biogas. To produce Biogas, organic matter is digested in an oxygen-free environment. The composition of biogas depends on the type of organic matter and production types(Gerardi et al., n.d.).

A typical biogas production process produces 40–85% of methane (CH4) and 15–60% carbon dioxide (CO2) with some other gasses(N. Aryal & Kvist, 2018). In addition to that, it consists of a large portion of CH4 and CO2 and other gasses like hydrogen sulfide(H2S), Nitrogen (N2) oxygen (O2), ammonia (NH3), and siloxanes, depending on the organic materials (Angelidaki et al., 2018). Currently, three main biogas production technologies are available

Biodigester method- this method is commonly used for biogas production. It is an airtight system, with anaerobic conditions that degrade organic waste by micro-organisms. In this breakdown process, biogas are produced in the reactor.

Landfill biogas Recovery method - the municipal solid waste (MSW) landfill site produced a biogas capturing technique used in this method using extraction wells and pipelines.

Wastewater treatment plant biogas production- water treatment removes sewage sludge from the treatment process.This sludge have capability to produce biogas by AD process.

These methods contains organic matter with nutrients, and with some preprocessing, this sludge is used as feedstock to produce biogas. Currently, traditional biogas production creates a huge amount of sludge waste. These sludge waste impacts and waste management are significant issues in methane production.

Biogas is used for several energy-related purposes, including energy for vehicles, combined heat and power(CHP) generation, energy cells or microturbines for electricity production, and direct combustion for creating heat(Bauer et al., 2013a). Apart from methane, all other substances in biogas are considered as pollutants. According to the European Biogas Association (EBA), Bio-Methane is an almost 100% methane form of biogas and it is considered a natural gas. Converting biogas to biomethane is called biogas upgrading. Several types of biogas Upgrading methods are used to remove unwanted gases from biogas. Five chemical & physical upgrading methods are used to transform and separate methane and carbon dioxide commercially. Membrane separation, absorption, Chemical hydrogenation, and Cryogenic process are involved in this upgrading process and these technologies are still developing to reach optimized upgrade (Angelidaki et al., 2018b).

This study focuses on the biogas production process using combined process scenarios of thermal hydrolysis, dewatering, and pyrolysis with anaerobic digestion to minimize waste sludge impact on the environment and identify the impacts from the whole product life cycle

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1.2 Objectives

The objective of this aster's thesis study is to identify the environmental impact that affects the global environment with different biogas production processes. Moreover, it is specifically to analyze and compare an available biogas production system of municipal sludge with an alternative integrated biogas production system. To achieve this, the following research objectives are designed:

- Inventory Analysis of Methane Production in a traditional biogas plant and integrated biogas production system.
- Development of LCA for the process scenarios.
- Comparison of two production scenarios' environmental impacts to quantify the environmental impacts of these two production pathways, with a particular focus on methane production and the management of digested sludge.
    - THP→ AD
    - THP→ DW→AD
      └→PY→ AD

1.3 Scope of study

The following areas were also covered in the process, to meet the study's objective:

- A Literature Analysis Relevant to the Study
- studying different scenarios and variants of biogas production methods
- Data collection for life cycle analysis
- LCA modeling in OpenLCA with Ecoinvent database
- The lifecycle environmental impacts calculations with sensitivity impact analysis
- Some selected findings are presented and compared with results in the two process scenarios

1.4 Report Outline

This thesis is a research-based thesis that incorporates Analysing background data and elements of classical LCA reports. It is developed as the PhD work subproject. The chapters below are included in this report:

Chapter 1: **Introduction**
  Provide background Knowledge about Biogas production and LCA
Chapter 2: **Theory and Literature Review**
  Illustrate the theory behind the biodegradation/ Pyrolysis process/THP and biogas upgrading process with it is various technological configurations and current background scenarios
Chapter 3: **Methodology**
  This comprises the LCA methodological framework and project definition, model description, calculations, scenarios setup, major data, and assumptions.
Chapter 4: **Results**
  Includes the results of LCA modelling with uncertainty and sensitivity analysis
Chapter 6: **Discussion**
  Elaborate on the main result findings related to Biogas production Impact categories, methodology robustness considerations and comparison with both scenarios.
Chapter 7: **Conclusion**
  summarization of work results, Agreements and conclusive remarks
Chapter 8: **Future Works**

2 Theory & Literature study

This chapter discusses the theoretical background of biogas production and processes of biodegradation in Areobic and anaerobic conditions. Process-wise theoretical summarization is discussed in this 2.1 theory section.

2.1 Theory

2.1.1 Biodegradation

Biodegradation refers to a single or sequence of reactions that occurs conversion of organic matter to simple molecules(Shackelford, 2003). Organic substances are a mixture of materials containing carbon derived from dead lives. These substances are called organic waste. Biodegradation can take place in natural environments or specialized facilities. There are two types of biorefining processes; anaerobic digestion (AD) and aerobic oxidation (composting).

Aerobic Biodegradation

Aerobic Biodegradation means organic substrates degrade in the oxygen presence environment. Normally this effect is called composting. Composting is a simple process that is done by microbial oxidation of carbon in an aerobic environment. The process produces carbon dioxide, water, minerals and organic compounds and energy release as heat (Danielsson, 2015)

Process Overview

Natural decomposition of organic matter is involved in this process and it is used in many waste treatment and environmental remediation processes. Oxygen Supply:Aerobic biodegradation is dependent on the presence of oxygen. This is usually done through natural aeration or mechanical aeration systems. Oxygen is used by aerobic microorganisms in the process of oxidizing organic compounds. Microbial Activity:Primary Microorganisms: The microorganisms that participate in aerobic biodegradation are bacteria, fungi, and actinomycetes. These microorganisms release extracellular enzymes that degrade complex organic molecules into simple compounds that can be metabolized. Degradation Pathways:Primary Degradation: The initial breakdown of the organic molecule into simpler compounds.Ultimate Biodegradation: The complete mineralization of the organic compounds to inorganic molecules (CO_2, H_2O, and mineral salts).

Anarobic Digestion(AD)

AD starts, when the microorganism speciescapable of anaerobic metabolism with the inherent energy sources and other substrates of feedstock to facilitate their function and Populate in them under absence of oxygen (O2)conditions.(Danielsson,2015). Bio-residual and biogas are the two final products and biogas contains carbon dioxide (CO2) and methane (CH4) in addition to the most significant energy is CH4 (Danielsson, 2015).

Steps of Anaerobic Digestion

1. Hydrolysis step: Hydrolysis is the first stage of anaerobic digestion and involves the breakdown of complex organic compounds like carbohydrates, proteins, and lipids to soluble molecules by hydrolytic bacteria. These enzymes hydrolyze chemical bonds and release soluble sugars, amino acids, and fatty acids in the medium. Hydrolysis is regarded as the rate-limiting step in anaerobic digestion because it governs the amount of substrate available for the subsequent microbial processes.
2. Acidogenesis step: During the acidogenesis stage, the hydrolysis products are further metabolized by acidogenic bacteria to produce VFAs, alcohols, H2 and CO2. Acidogenesis is an anaerobic process that involves fermentative metabolism that produces organic acids and other intermediate compounds as a result of partial oxidation of the substrates. This process leads to the production of VFAs such as acetic acid, propionic acid and butyric acid as well as low concentrations of alcohols and gases such as hydrogen, and carbon dioxide.
3. Acetogenesis step: Acetogenesis produce acetic acid, hydrogen, and carbon dioxide from the VFAs and alcohols by acetogenic bacteria. These acetogens are anaerobic bacteria that utilize organic acids and hydrogen as electron donors to reduce carbon dioxide to acetic acid. Acetogenesis is a key process in the anaerobic environment to maintain the redox balance and facilitate the subsequent methanogenesis.
4. Methanogenesis step: The last phase of anaerobic digestion is methanogenesis; methanogenic archaea convert acetic acid, hydrogen, and carbon dioxide into CH4 and CO2. Methanogens are specialized microorganisms that have evolved distinctive metabolic pathways to generate methane as a product of metabolism. There are two primary pathways of methanogenesis: acetoclastic methanogenesis, which is the direct conversion of acetate to methane and carbon dioxide, and hydrogenotrophic methanogenesis, where methane is produced from the combination of hydrogen and carbon dioxide. Hydrogen and carbon dioxide are transformed into methane and water by the methanogenic Process.

2.1.2 Biogas Upgrading

Biogas commonly contains a mixture of methane and carbon dioxide 50-75% and 25-50% respectively. AD process is used to treat a wide variety of organic waste because its products are rich in energy gas and good biofertilizers. Biogas should be purified into methane for use. This methane purification is called biogas upgrading in the biogas production process(Plugge, 2017) Biogas can be used in combustion engines by various purification methods. The current biogas upgrading process upgrades biogas into 95%-99%-pure methane and mainly removes CO_2 to upgrade biogas into valuable fuel. Currently, there are several different biogas upgrading techniques, but the most often applied biogas up-gradation methods are the ones that are used to remove CO2 from the biogas mainly either to satisfy vehicle fuel requirements or to achieve the natural gas qualities to be injected into the natural gas system(Bauer et al., 2013). Three major biogas upgrading technologies are mentioned below.

High-Pressure Water Scrubbing Technology

Scrubbers based on high-pressure water scrubbers (HPWS) are substance scrubbers that consider that CO2 is far more soluble in water than methane. Scrubbing is the most widely used method and it mainly includes cleaning with water. Through HPWS, an important process featuring the role of both CO2 and H2S absorption takes place which yields bio-methane with a relatively high degree of purity. CO2 and H2S are more soluble in the gas phase than CH4, N2, and O2, hence this pair of compounds is essential to this process. CO2 captured from the raw gas by high pressure to form CO2 gas dissolved in the scrubber water, which provides a high degree of purity and low cost(A. Aryal, 2022).

Pressure Swing Adsorption Technology (PSA)

Process operation is adopted adsorption under high pressure, feed or product are fed into, pressure equalization, blowdown, or purging. The technology of PSA consumes minimal energy standards and has so far been used for biogas, landfill gas and natural gas production facilities at small and intermediate scales to make very pure methane. The efficiency of this process is essentially impacted by key parameters such as surface area and pore size of the adsorbent materials, the partial pressure of the adsorbates, system temperature, and intermolecular forces originating from the adsorbents and adsorbates. Additionally, the material's capacity to re-use at certain conditions and point of generation of the sorbent material also affects the efficiency of the whole process(A. Aryal, 2022).

Microbial electrosynthesis (MES) Technology

The primary application of MES is as a microbial catalyst to transfer biodegradable enzymes into chemical energy over the biomass of wastewater by applying a voltage. Past studies have already shown that only a limited amount of energy is needed to fulfil the chemical process of microorganisms permitting both releases of hydrogen according to the electrochemical potential and the intermediate from currying energy barriers, with a much lower energy input compared to traditional electrolysis methods that consumes a much more amount of energy. An artificial way of photosynthesis referred to as microbial electrosynthesis has many advantages over the bioenergy methods that are realized using fossil fuels if the energy required externally for microbial electrosynthesis is derived from renewable sources such as solar, wind or biogas. (A. Aryal, 2022)

2.1.3 Thermal Hydrolysis Process

The thermal hydrolysis process (THP) is an advanced pre-treatment method applied in biogas production for enhanced degradation of organic material, particularly in municipal waste sludge. This procedure includes the application of high temperature and pressure to the sludge, which then goes to anaerobic digestion. Thermal hydrolysis carries out the physical degradation of sewage sludge or other wet organics at elevated pressure and temperature. Due to heat and pressure, fed raw sludge is broken down into simple parts.

Heating: The sludge is heated to a high temperature (approximately 100-120°C) under elevated pressure (usually 6-8 bar) for a short period of time (20-30 minutes).Depressurization: The sludge is then quickly depressurized. This immediate release of pressure induces the cells in the sludge to burst, greatly increasing the amount of organic matter that is available for microbial digestion. Anaerobic Digestion: The treated sludge is next fed into anaerobic digesters where methane is produced in higher yields. Figure 2.1 shows general THP process steps(Cambi, n.d.)

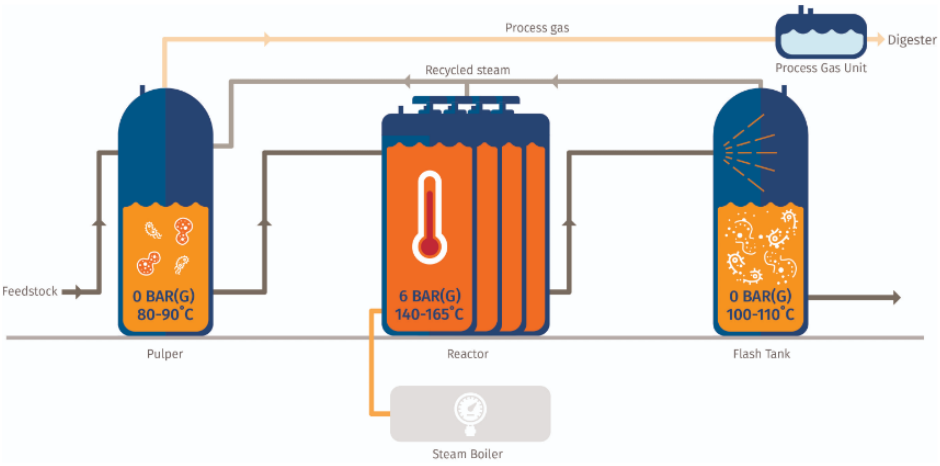


Figure 2.1 Thermal Hydrolysis Process

2.1.4 Pyrolysis Process

Pyrolysis is a thermal treatment of of organic matter, which is wood, coal, plastics, etc (materials carrying carbon). The process of pyrolysis occurs when biomass is heated without oxygen at temperatures of 400-1000 °C and yields cyclic compounds pyrolysis oils, char and non-condensable gases are also produced.

In the process of decomposition of complex molecules, the material is exposed to a high temperature with no oxygen presence. The decomposition occurs at the limit to the rates of thermal stability of chemical bonds of the materials, which make them melt and disintegrate by supplying heat. Thermal disintegration results in molecules getting new molecules from Components. The unaltered elements can receive a stronger, often much better character than the original sediment.

Biochar

Biochar is a C-enriched, stable material resulting from the pyrolysis of biomass under a controlled environment of limited oxygen(Rajapaksha et al., 2016). The utilization of biochar is aimed at a number of applications, including features which do not involve the burning of biochar, for instance, its use as a soil conditioner, a sorbent in water treatment or construction material. International Biochar Initiative (2013) defines biochar as:

“Biochar is a solid material obtained from the thermochemical conversion of biomass in an oxygen-limited environment. Biochar can be used as a product itself or as an ingredient within a blended product, with a range of applications as an agent for soil improvement, improved resource use efficiency, remediation and/or protection against particular environmental pollution, and as an avenue for greenhouse gas mitigation.”

2.1.5 Life Cycle Assessment

LCA (Life Cycle Assessment) indicates the whole environmental impact that a product or activity can make through the varied phases of its existence based on a given function. It identifies trends as well as places to improve the environment and also assists in the design of new products. The LCA implementation is a unique one as it can be used for the comparison of products, processes and systems as well as for the numerous stages of a product.

As per the definitions defined by the Society of Environmental Toxicology and Chemistry (SETAC) and the International Organization for Standardization (ISO), LCA contains **Four Key Phases**, purpose specification and boundaries, the inventory of properties, the effect assessment and the result reading. These phases must be addressed step by step way and outcomes should be considered to measure and reflect how the environment gets exaggerated by the product or service(Jason Pierce & Seeley, 2014)

1. **Goal and scope definition phase**
2. **Inventory analysis phase**
3. **Impact assessment phase**
4. **Interpretation stage**

Goal and Scope Definition Phase

The objectives and problem generation of the study are distinct in the goal and scope definition phase during which the problem is glazed and the restrictions labelled. In this stage, an inventory of important factors like the function of the system, the functional unit for performing the calculation of emissions and resource use, and the definition of system limits is made.

When defining a goal of an LCA, it's essential to clearly define, the intended purpose, the motivations behind conducting the analysis, target spectators for the study results and Whether the findings are meant for virtual statements intended for public disclosure.

After establishing the goal, the scope of an LCA should consider and explicitly outline the following components(Jason Pierce & Seeley, 2014):

- The functional unit (FU) used for analysis
- The limits of the system being studied.
- Methodologies for allocation
- Methods and categories of impacts measured in the life cycle impact assessment
- Procedures for interpretation
- Data requirements, including assumptions and any elective elements.
- Recognize the limitations of the study.
- Necessities for data quality.
- If available, specifications for serious review.
- Content and format specifications for the study report

In addition, It is important that the research field be sufficiently defined to ensure that the scope, measure, and degree of detail align with the goals and purposes of the study. Since the Life

Cycle Assessment (LCA) is an iterative process, it is feasible to refine the scope of the study as additional data is obtained.

Scope Definition

The necessary inputs for the system are produced by the environment; resources (land and energy) are the most prevalent kind of inputs. The system receives emissions from human activity as inputs, even as the system itself generates emissions into the air, water, and soil (Jason Pierce & Seeley, 2014).

The system that is to be assessed through modelling passes through specific process modules. These procedures use the product's mechanism and parts to determine how the product works and performs. As a result, it will either exist as a single process or as a sequence of smaller processes called unit processes. Every unit process is assessed with the proper input and output. Auxiliary flows known as intermediate funds combine all system runs to represent the amount of each step so that steps after it can be used(Jason Pierce & Seeley, 2014).

Principles of System Boundaries

The Boundary line aids in identifying the precise combination of parts and techniques utilized in the system modelling exercise. In a perfect world, they would cover every step from conception to death as well as any that a particular system needs to run. However, the practical implementations of these boundaries will make their application in real life more difficult to implement with caution. Establishing the parameters for the processes of selecting and deselecting is essential, and industrial activities must adhere to the ISO 14000 standard for decision-making.

Rules to Define System Boundaries(Jason Pierce & Seeley, 2014)

- **Rule 1-** System boundaries should cover the same functional unit in all scenarios
- **Rule 2 -**Cut-off criteria for the inclusion of processes in the system boundary should be clearly described
- **Rule 3-** Processes that are identical in the different scenarios can only be excluded if the reference and intermediary flows affected by these processes are directly equal.

Inventory Analysis Phase

During this stage, the inventory analysis procedures show the air, water, and soil pollutants, along with raw materials drawn out from renewable and non-renewable. This latter phase also expels the resource consumption which is the requirement for the system to work. LCA, an inventory produces a qualitative description of the process that crosses borders in terms of the flow of materials, energy, and contaminants. This includes the release of pollutants into the environment as well as the process of extracting resources from the life cycle of the product or service under investigation(Jason Pierce & Seeley, 2014). By multiplying the reference flow per functional unit (FU) by the intermediary flow per FU by the direct emission or extraction factors for each unit process, the inventory is created for the process approach. These variables, which include the amount of pollutants released for each step as well as the month and year of effective extraction, are taken from databases. Life Cycle Assessment (LCA) utilizes high-quality databases that are used to supply the required data for the assessment of the environmental impacts of products, processes and services throughout their life cycle. These databases provide detailed information about various materials, energy resources, transport technologies, and waste management. Currently, available databases are as follows (Martínez-Rocamora et al., 2016):

European Databases- Ecoinvent
ELCD database 3.1
GaBi Database
PlasticsEurope Eco-Profiles
American Databases- Athena database
U.S. Life Cycle Inventory Database
National databases - Base Carbone
BEDEC database
CPM LCA database
ProBas

Life Cycle Impact Assessment

Life Cycle Impact Assessment (LCIA), the next step in the life cycle assessment process, comes after data collection on the materials extracted and compounds produced during a product's lifetime. The analysis of the inventory data, which establishes connections between various environmental burdens and environmental consequences, is the focus of this step. It involves multiple steps: damage (ultimate) characterization, characterization of the (midpoint) impacts, and classification of emissions into (midpoint) impact kinds. Impact assessment tools are easy to use, yet developing some of them might be difficult.

The theory behind LCIA Methods

Life cycle assessment (LCA) is a technique that measures the total environmental impact of products. The life cycle is associated with a very large number of resource extractions and emissions which can be significantly different in terms of their environmental impact. LCIA is used to assist in the interpretation of LCA studies by converting these emissions and resource extractions into a limited number of environmental impact scores (Rosenbaum, 2015). This is achieved through the use of characterization factors. Characterization factors represent the environmental impact per unit stressor. (it means per unit of resource consumed or emission generated). There are two mainstream pathways for solving characterization factors: at the midpoint or endpoint. Midpoint characterization factors are located at some point along the impact pathway generally after the point at which the environmental mechanism is the same for all the environmental flows that are assigned to that impact category. These two approaches are easy to understand since the characterization factor at the midpoint is closely related to the environmental flows and has a comparatively lower variability than that at the endpoint of characterization, which offers more precise information on the environment related to the environmental flows in question and at the same time is characterized by higher variability in the characterization factors(Rosenbaum, 2015).

LCA Tools

Common European LCA software packages for Life Cycle assessments are as follows(Rice et al., 1997):

- EcoPro 1.3
- GaBi 2.0 KCL-ECO (with ECODATA database)
- LMS Eco-Inventory Tool
- PEMS 3.0
- PIA 11
- SimaPro 3.1
- SimaTool
- OpenLCA

GaBi, SimaPro and Open LCA are the most commonly used LCA software. These LCA software can use different LCIA methods to calculate impact according to the preference. Currently, several LCIA methods are available for the various impact calculations. Currently available LCIA methods:

- ReCiPe (2016) Midpoint and Endpoint
- CML-IA (Baseline)
- TRACI (Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts)
- Eco-Indicator 99
- ILCD (International Reference Life Cycle Data System)
- IPCC 2013 GWP 100a
- AWARE
- BEES+

Interpretation Phase

The last step of the LCA tool is the analysis of results. This phase involves the identification of critical factors in the previous phases, completeness, sensitivity, consistency, conclusions, limitations, and recommendations (Lucia Indrebø, 2022). The connection between the interpretation phase and the other phases in the LCA method is shown in Figure 2.2.

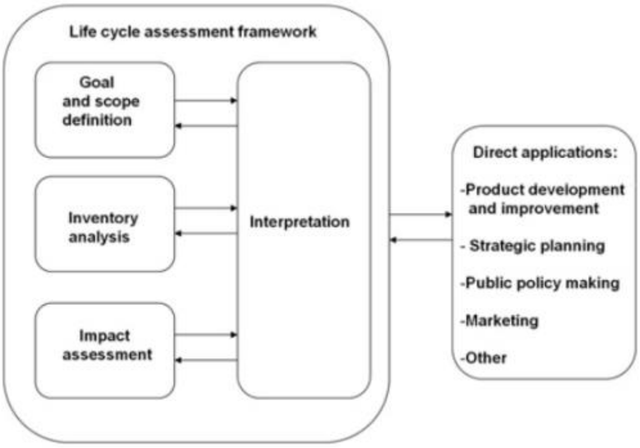


Figure 2.2 Connection between the interpretation phase and the other phases in the LCA method

2.2 Literature Review

This chapter comprises findings from the scientific literature. Most studies are limited to a particular context, with few other European and international studies. Sections are divided by focusing on the current status of world biogas production, Biogas potential in Norway and studies of LCA on biogas. Other studies relevant to the scope of this research project are also presented.

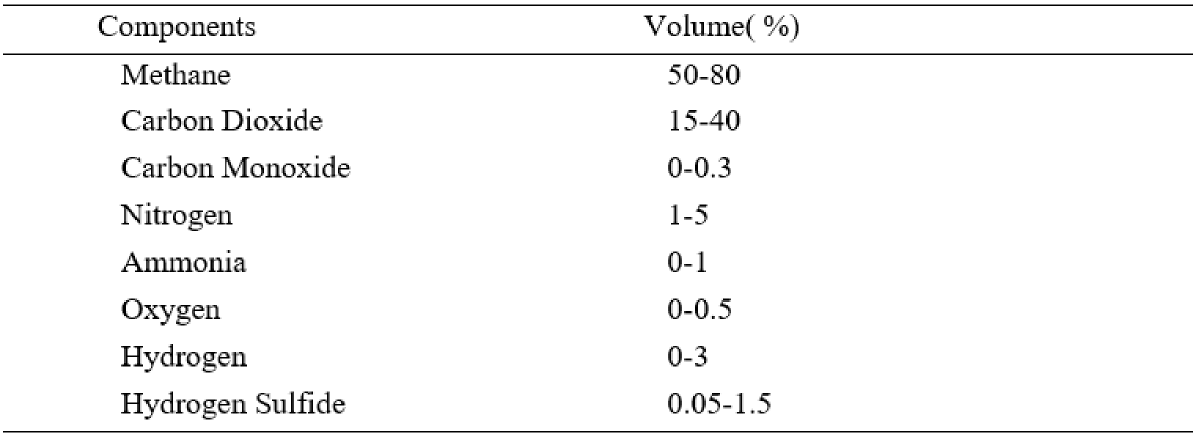
2.2.1 Biogas

Biogas is a combination of methane Carbon dioxide and small amounts of other gases. Generally 40- 85% of methane (CH_4) and 15–60%Carbon dioxide mixture are available (N. Aryal & Kvist, 2018). Table 2.2 shows the typical composition of reactor biogas respectively.

The Institute of Gas Technology Chicago registered this biogas word as a trade name.(Ni, 2024). Biogas is produced through an anaerobic digestion process which includes microbial and bio-chemical processes, breaking down this organic matter in an oxygen-free environment with appropriate temperature(Gerardi et al., n.d.). Due to this higher amount of Methane content, several technologies developed to harness this fuel.

The Biogas production process includes controlled anaerobic digesters or biogas digesters. A Biogas Digester is an airtight, solid, simple to complex structured container used for household waste slurry digestion for household biogas production. Beyond that, In an Industrial scenario, a Biogas digester plant includes several types of infrastructures and equipment for biogas production such as feedstock reception tanks, effluent storage, gas processing units, gas storage, generators, Boilers, THP Units and many more. Produced biogas used for several functions such as heat and electricity production, use as an energy carrier, use as vehicle fuel etc.

Table 2.1 Typical composition of Reactor Biogas(Gerardi et al., n.d.)



Components	Volume(%)
Methane	50-80
Carbon Dioxide	15-40
Carbon Monoxide	0-0.3
Nitrogen	1-5
Ammonia	0-1
Oxygen	0-0.5
Hydrogen	0-3
Hydrogen Sulfide	0.05-1.5

2.2.2 Renewable and non-renewable energy context in the world

Fossil fuels such as petroleum and coal, as the main sources of energy supply, have been of great deficiency since the Industrial Revolution. Recently, world energy consumption has grown rapidly due to high energy demand. To fulfil this world energy requirement, people currently use renewable and non-renewable energy(NRE) sources. According to the 2023 Statistical Review of World Energy of the Energy Institute (EI) states that by 2023 fossil fuels will remain 82% of the total share of primary energy consumption in the world. Figure 2.3 shows the world's primary energy consumption in 2022 (Institute, 2023).

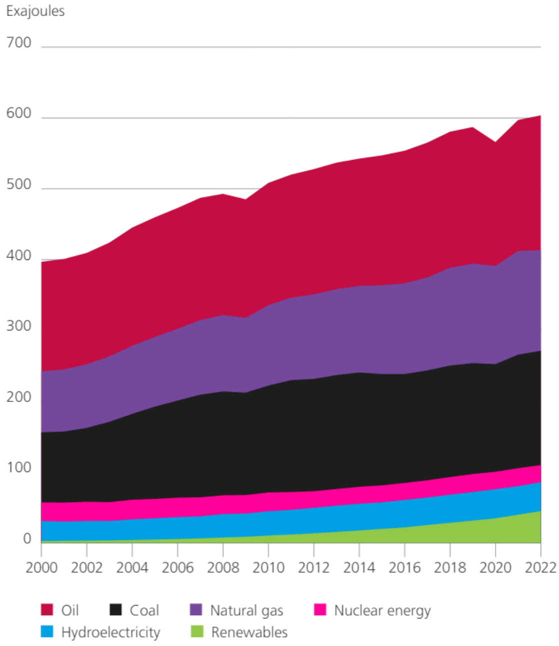


Figure 2.3 world energy consumption

In addition to that, British Petroleum statistics data shows that primary energy consumption increased by 1.3% in 2019(Petroleum: BP Statistical Review of World Energy. - Google Scholar, 2020). According to the Most Non-renewable energy sources are depleting over time people are now researching alternative energy resources in both renewable and non-renewable. Nowadays, finding the most sustainable and renewable energy option is the most significant topic in the world. Among the energy sources, non-renewable energies are the most considerable consuming primary energy in the world and renewable energy(RE) is grouped in the largest increase in consuming energy, followed by natural gas.(Hashemizadeh et al., 2022).

For the past two decades, fossil oil has remained the leading fuel in the world, and it is the most important NRE source. International Energy Agency (IEA) said that “fossil fuels will still account for over 70% of supply (down from ~82% in 2022).”(Wright, 2023). And also basic consumption of oil will remain at 100 million barrels per day until 2050 (Forbs, n.d.). Human Development and population expansion caused an increase in energy consumption in the world. Most common scenarios such as food demand, transportation, Manufacturing, Security, and Quality of life also developed with Human development. As a result of this cause, competition was created by people to people/company to company /county to county. However, all of these things depend on each person or country's economic status. When looking into the Economic branch, the primary input of the economy is considered Energy. Each economic activity depends on energy(Bui et al., 2021). At that time, to secure economic stability, the easiest energy resource is the non-renewable energy source. Therefore, most nations moved to consume non-renewable energy as their primary energy source.

Economic development is directly linked to global energy consumption and in coming years it is projected to increase more than before(Hashemizadeh et al., 2022). To satisfy basic human needs, energy contributes more than 80% to provide them. The shortage of energy services will cause several human well-being. Due to that consistent energy supply is essential to delivering a sustainable future. By 2030 energy demand will increase 50% than now.(Hashemizadeh et al., 2022). These forecasts and current non-renewable energy usage directly and indirectly affect the creation of world Economic/Environmental/ social defects. Mainly these non-renewable energies consist of fossil fuels such as petroleum, Coal, Natural gas and nuclear. These resources burn to convert into useful human needs such as transportation/ electricity/ Heating etc. Burning these fuels emits various kinds of air into the atmosphere such as CO_2/ CO / SOx /NOx and many more. By increasing this burning, it will emit more air into the atmosphere. Due to that natural ecosystem fails to balance air concentrations in the atmosphere. This unbalancing ecosystem will cause several health & and environmental problems such as global warming, Acid rain, deforestation, Air pollution etc. As a result of these things, the world energy consumption trend currently shifting to renewable energies.

Several definitions are available for renewable energy. Energy that comes from natural energy sources or processes that are replenished consistently(Srensen, 1979). According to(Srensen, 1979) defines it as, that is energy comes from a natural source and it replenishes faster than they consumed. These natural resources include sun, wind, tidal, Hydro, Biogas etc. Biogas is one of the major Renewable energy sources in the world.

2.2.3 Bio-methane Production Potential in Norway

The Norwegian Department of Agriculture and Food 2009 by Norwegian Government, introduced Biogas production through a white paper to contribute minimization of Greenhouse gas (GHG) in the agricultural sector in Norway. That focused on utilizing 30% of livestock manure of farms for biogas production by 2020(K. A. Lyng et al., 2015). In 2008, theoretically, 42% of biogas production potential was revealed by the Raadal(Raadal et al., 2008) biogas potential study. Currently, Norwegian biogas plants commonly use sewage sludge and organic waste as their feedstock. Norwegian organic fertilizer ordinance currently limit this sewage sludge usage by implementing several rules regarding Effluent digestate quality(Regulation 2003).

Biogas production in Norway differs from all other EU- (European Union) countries due to several conditions such as cold climate, relatively low electricity cost and high fuel prices, small farming industry and government rules regarding Environmental impact(K. A. Lyng et al., 2015).

Theroitical biogas potential value is estimated by each raw material generation for a specific time period multiplied by the methane yield of each raw material. As the literature these calculations did not count technical, or economic limitations or any other conditions. In Norway, the theoretical biogas production potential is 5.5TWh based on current raw materials and current technology.(K. Lyng & Charlotte, 2023) For this calculation, based raw materials are manure and straw from agriculture, fish sludge and food waste from households and industries. Based on current technology, the potential of biogas production potential in future raw materials is estimated to be 11.3TWh. It was calculated by looking at the goals and developing trends in industries and reducing food waste amount by 50% due to future goals of food security. Upgrading biogas into methane, theoretical CO2 capturing potential is estimated to be approximately 298000 tonnes currently and 611000 tonnes for the future possible raw material base.

Biogas Potential Based on Food Waste From Household and Industry

For this calculation, food waste is defined as waste that is suitable for human consumption and excludes any waste produced before it is converted into food. in addition to that, it does not include side streams of the food process. (Danielsen et al., 2021).The potential of biogas production depends on the composition of the food waste. It was different from the sorting rate of food waste in several industries. Table 2.3 shows biogas potential based on food waste with a value chain. When calculating biogas potential it is necessary to make simplification and assumptions for all stages of food waste that have the same yield of biogas.

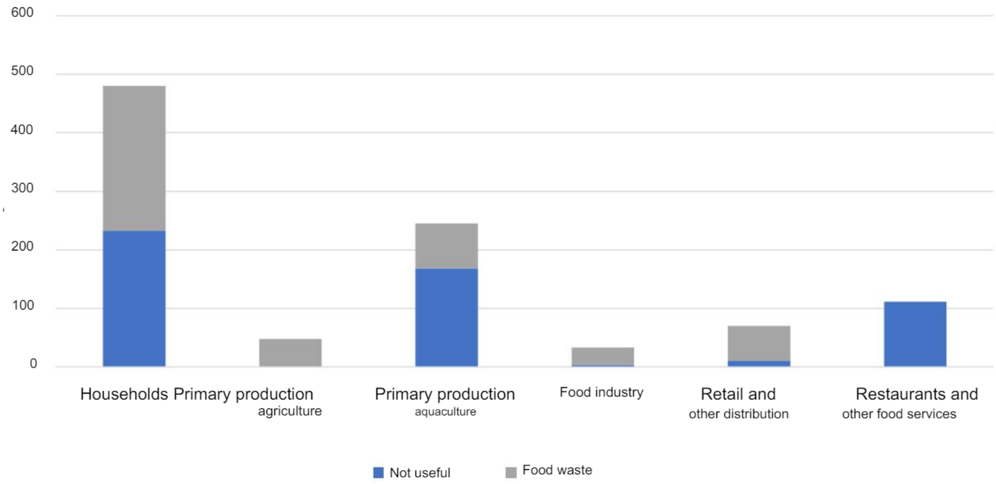


Figure 2.4 Biogas potential based on food waste(Isakova et al., 2019).

Biogas potential based on Sewage sludge

For the biogas calculations based on Sewage sludge, this data is taken from Norsk Vann values that are estimated until 2050 for sewage sludge availability in Norway. These calculations estimate a 0.2 m^3/ ton methane yield for dry matter. figure 2.4 shows the theoretical potential of biogas production from sewage sludge per region. As the literature shows, In 2020 the total production of biogas was estimated to be 345GWh and In 2050 It was estimated to 388GWh. Expected Population growth will cause this higher increase from 2020 to 2050(Isakova et al., 2019).

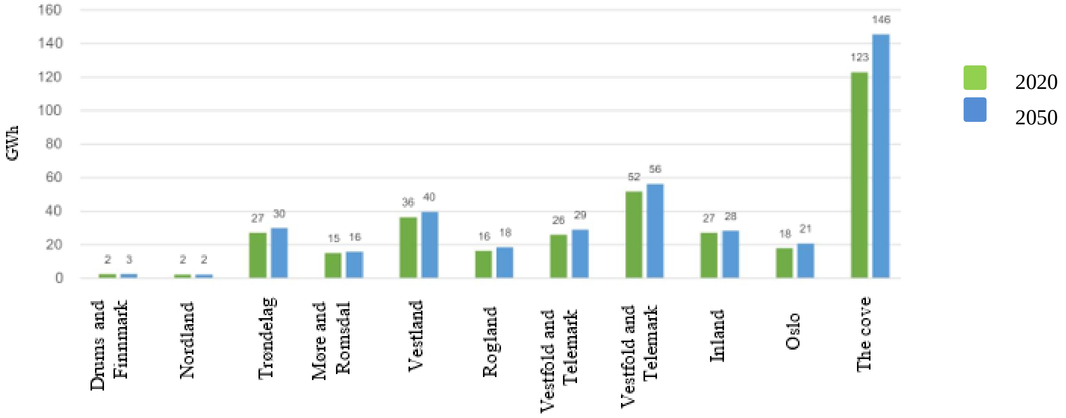


Figure 2.5 theoretical potential of biogas production from sewage sludge per region (Isakova et al., 2019).

Biogas Potential from Fish Sludge

Fish sludge includes faeces and waste feeds(Sediment).In Norway, Aquaculture facilities are going on land and sea. In land-based industries, fish sludge must be treated before removing to the environment. However large quantities of fish sludge caused environmental impacts. In 2020, 12000 tonnes of phosphorus and 67000 tonnes of nitrogen from aquaculture(Danielsen et al., 2021). In lab experiments, data shows only fish sludge provides 60.5 Nm^3 /tonne.of methane. According to Cabell's report in 2019, the calculated biogas potential from fish sludge is 1303GWh.According to that report, If the fish industry increases its production fivefold, the annual biogas potential from fish sludge will be 6.5TWh(Cabell, 2019). Kristiansen and Hetland report that the biogas potential of fish sludge was estimated 26 to 246 GWh in 2030 and 30 to 1952 GWh in 2050. (Kristiansen.,2021)

2.2.4 Biogas Potential Based on Technology

Production of f biogas is noted in the scientific literature as a way to combine residual organic source materials with other technologies to improve their future usability. This is referred in several names, including biogas generation as part of industrial symbiosis, cascading organic resource treatment, anaerobic digestion as part of a biorefinery, and connecting or integrating technologies(Pecchi & Baratieri, 2019).

The technologies that can be coupled with anaerobic digestion to enhance methane generation in the future are outlined below. The data was collected from a review of the existing literatures. It is need to remember that the technologies listed here are mostly at the research and pilot stage and that this is not meant to be an exhaustive list of all available technologies. Due to that, a significant amount of research and development effort may be necessary before they can be used in industrial facilities.

Traditional Biogas Production (THP-AD)

In the 10th century B.C., Biogas was used to heat water for bathing and other purposes in Assyria(ancient Mesopotamian civilization), and in Ancient China, it was used as an anaerobic digestion technique for solid waste(He, 2010). In addition to that documented proofs of biogas harness from anaerobic digestion were found in the middle of 1800 in in India and New Zealand. In addition, a sewage sludge digester was constructed in Exeter, England, to fulfill the energy needs for street lamps (Bond & Templeton, 2011).Traditional biogas production was done by anerobic digestion as shown in figure 2.2.

Figure 2.6Traditional Biogas Production

In the initial stage, most countries started to produce biogas domestically. Developing countries used low-rate digesters, and it was 3 major types; Chinese fixed dome digesters, Indian Floating drum digesters, and balloon (tube) digesters, as shown in Figure 2.3 Source based on(Gunnerson CG, 1986) (Plöchl and Heiermann, 2006)

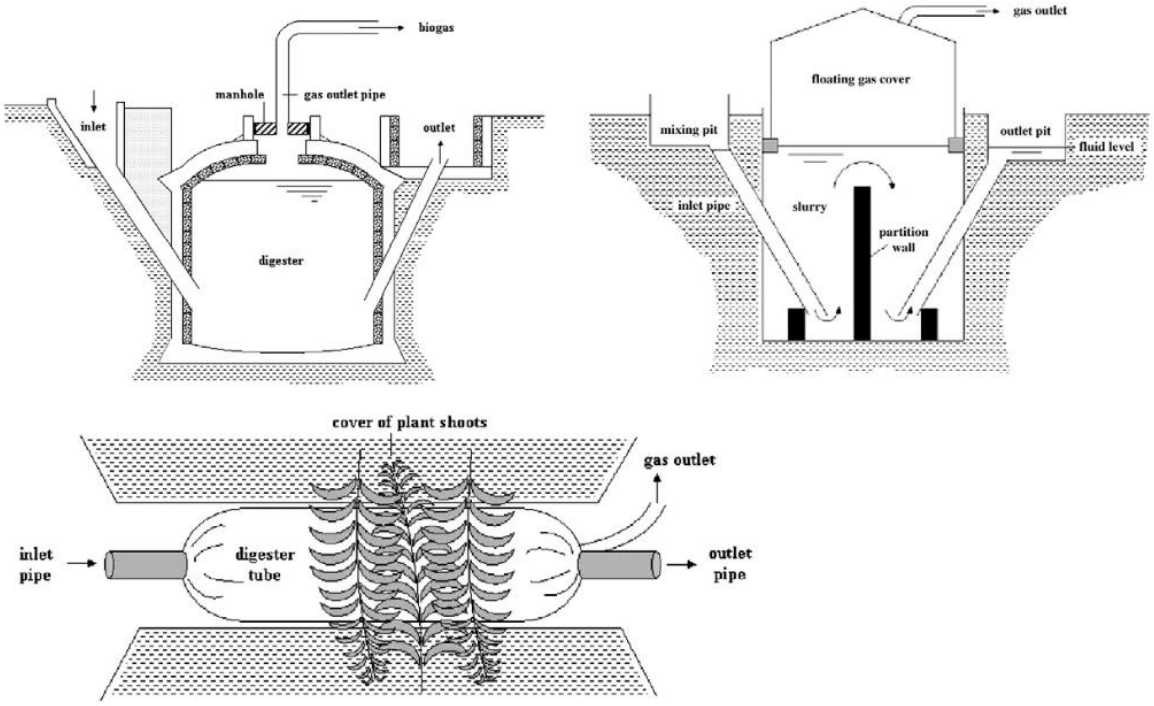


Figure 2.7 Common digester designs Top left: Chinese fixed dome digester. Top right: Indian floating cover digester. Below: balloon(tube) digester.

In the beginning, these digesters were fed by household and animal waste. Generally, these digester volumes are 2-10 m3 and produce 0.5 biogas/m^3 digester volume.(Bond & Templeton, 2011).The working Principle of these traditional methods is very much the same. Feedstock directly enters through the inlet and is kept for several days for digestion. This retention time depends on several factors and usually, it takes 20 to 100 days (Sasse, 2021). Produced biogas is collected above the slurry and exits through an outlet pipe for usage.

Several traditional methods are available for Biogas production. However, those methods will not be described in this report because the focus is on reducing emissions through the developing Biogas process.

Biogas production in combination with pyrolysis(AD-PY)

The process of exposing a feedstock to high temperatures in an oxygen-free environment is called pyrolysis (Py). The properties of Raw materials and the pyrolysis techniques mainly depend on the properties of final products from pyrolysis. Different pyrolysis processes are available in the market. Slow, fast and flash methods are highly focused on char and liquid production.

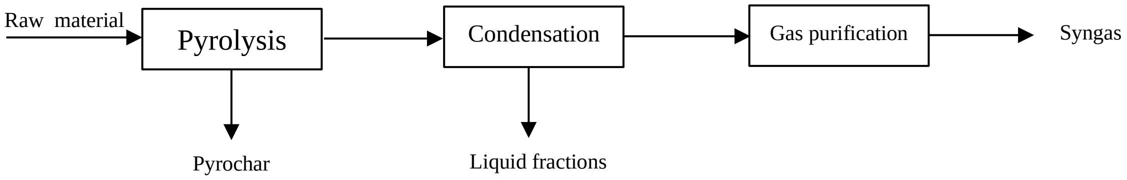


Figure 2.8 Basic pyrolysis process (Pecchi & Baratieri, 2019)

The products contain a combustible stream of syngas, Pyrolysis liquid (oily phase called pyrolytic-oil, bio-oil, pyro-oil, or pyrolysis oil and an aqueous phase called Aqueous Pyrolytic Liquid(APL), and char. (Pecchi & Baratieri, 2019). The basic pyrolysis process is shown in Figure 2.3. Char consists of solid carbonaceous material and the char types depend on the raw material properties. It is called biochar/biochar/pyrolytic char etc (Acharya et al., 2015). Syngas contains carbon monoxide, Hydrogen Methane and hydrocarbons.APL mixture containing complex aqueous chemicals with lower molecular weight depending on raw materials(Christian, 2000).

Typically pyrolysis liquid fraction product has two phases. Pyrolysis oil is directly used as a product and APL is removed as a waste. It consists of organic oxygenated compounds. This APL removal is one of the big challenges in the pyrolysis process. In this stage, Anaerobic Digestion plays a major role to decompose this APL and produce high-quality Biogas from low-quality APL. To reduce the impact of digestate land spreading, it can be used back on Py.

Combining Py and AD is a huge process. figure 2.4 shows the combined process of Py and AD process. As the literatures, there are many advantages. Most of the combined processes are in pilot stage and research stage.several Norwegian biogas plants are recearching these combine process for increase efficiency.

With this combine of AD and PY increases several advantages of pyrolysis and AD products. In this method, It handles raw materials. They are easily biodegradable, it can directly be sent to an anaerobic digester for methane production also the raw materials are too much solids it can be used for the Pyrolysis process. Another option is that Pyrolysis Oil and aqueous pyrolytic liquid from the Py process can be used as raw material for the AD process to enhance biogas yield. The biochar from pyrolysis also can be used to AD or upgrading processes to increase methane content on production.

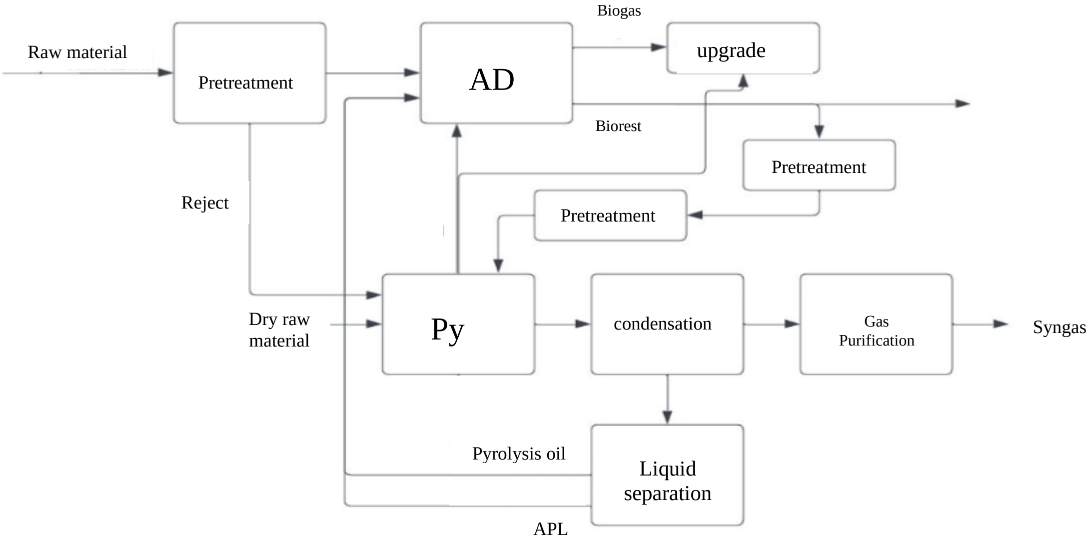


Figure 2.9 Combined AD- PY process

2.2.5 LCA of Biogas Production

Global developments have caused to significant environmental concerns, such as global warming, fossil fuel depletion, Water consumption etc. With that renewable energy sources and environmentally friendly energy sources are highly demand topics in the world. Biogas is also a highly demanded sector in renewable energy. Currently several novel technologies and different types of research working on this biogas sector. Evaluation of environmental impact related to biogas production by LCA and if provides very important aspects of impact identification(Bacenetti et al., 2016).

Life cycle Assessments for AD were done with several parties and people around the world.(Di Maria & Micale, 2015),(Cherubini et al., 2009),(Gunamantha & Sarto, 2012)(Evangelisti et al., 2014),(Tagliaferri et al., 2016),(Cremiato et al., 2018) have conducted LCA for AD Plants that use municipal solid waste as feedstock. various MSW management techniques are evaluated through LCA studies. Most of the studies considered impact categories are global warming potential(GWP), ozone layer depletion, acidification potential, and eutrophication potential. Used life cycle impact assessment methods such as Eco indicator 95, EDIP, Cumulative Energy Demand(CED), and CML were used. Above mentioned reports refer to several locations in the world: China/UK/Thailand/and Turkey.

According to the utilization of food waste to AD, several LCA studies done by various locations.(Khoo et al., 2010),(Righi et al., 2013a),(Vandermeersch et al., 2014),(Bernstad Saraiva Schott & Andersson, 2015),(Jin et al., 2015),(Ruiz et al., 2018) conduct several LCA studies of food waste to Biogas. Above mentioned LCA was done using different LCIA methods such as RECiPE, CED, ILCD, CML, GWP and EDIP. Moreover, some research was conducted on AD Plants that are handled with livestock manure. (Ramírez-Arpide et al., 2018),(Burg et al., 2018),(Budde et al., 2016),(Hahn et al., 2015), and (Whiting & Azapagic, 2014) report impacts from Livestock manure biogas production through LCA.

Based on the literature cited above, all studies can be summarized as, all studies focus on Global warming potential, Cumulative Energy Demand, Acidification potential, and ozone layer depletion impact categories and few studies considered human toxicity and ecotoxicity.

In table 2.7 selected references literature about LCA of AD mentioned below. Looking into table data; Funtional units have differences between among others and most of the units are based on waste input values and energy produced values. concerning LCIA methods, the RECiPE method is used rather than other methods and the investigation focuses on different types of Impact categories including Global warming potential, Cumulative Energy Demand, Acidification potential, ozone layer depletion etc.

This study tries to figure out the impact of biogas production by combining the pyrolysis process into a novel method to reduce digested waste up to a much lower level compared to input waste volume. By summarizing, available LCA gives a clear background vision of LCA methodology.

Table 2.2 Table 2.5 Selected works of literature summary about LCA of AD

Feedstock	Functional unit	System boundary	LCA Software	LCIA Method	Impact Catagories	References
Sewage sludge	1 m3 of biogas and 1 kg digestate	Gate-to gate	SimaPro	ReCiPe midpoint	C, OD, HT, FEC, FEU, TA, WD, MD, FD	(Singh et al., 2020)
Mix from different waste source	The use of 1 m3 of biogas produced	biogas produced Cradle-togate	Sima pro	ReCiPe 2016 midpoint	CC, OD, HT, FEU, TA, WD, FD	(Florio et al., 2019)
Food waste	sufficient fuel to achieve 1 km of passenger vehicle transportation	Gate-to gate	Sima pro	Ecoindicator 99 H/ A	CRG, RI, ECT, Fossil RES, CC	(Patterson et al., 2013)
Cattle manure	The production of 1 m3 biogas	Gate to gate	Sima pro 9.0	ReCiPe 2008	CC, OD, TA, FE, ME, HT, POF, PMF, TE, FEC, MEC, IR, ALO, ULO,NLT, WD, MRD, FD	(Ioannou-Ttofa et al., 2021)
Organic Fraction of Municipal Solid Wastes	Energy recovery from 1 kg of volatile solids entering the	Cradle-to grave	Sima pro 7.0	ReCiPe midpoint	CC, HH, FD, FE, HT, MD, OD, PMF, POF, TA, TE	(Masilela & Pradhan, 2021)

	bioconversion proces					
Sludge generated from the treatment of urban wastewater	Management of 1t of thickened mixed sludge	Gate to gate	SimaPro 5.1	CML	GWP,EP,ODP, AP, POF,ADP,HT	(Hospido et al., 2005)
Sewage sludge and food waste	Management of 3000 t of biodegradable waste fractions	Gate to gate	GaBi 4 software	CML	GWP,AP,ODP,POCP GaBi 4 software	(Righi et al., 2013b)

3 Methodology

This part refers to what data was used and how they were gathered, while major underlying assumptions are outlined. It lays out all aspects of the research design, contains the criteria for selecting the participants, the data collection methods and techniques and the analysis procedures. Furthermore, it covers the system under observation, describing its parts, limits and how they interact with the scope.

3.1 Goal & Scope

3.1.1 Goal

Comprehensive life cycle assessment (LCA) of anaerobic digestion as the method of treatment of primary sludge to find out if it is more or less effective in waste reduction and methane production throughout its lifespan. The analysis will deal with the issues of resource consumption, and waste generation in anaerobic digestion. The final goal is to determine how and which processes could have been optimized for Environment-friendly waste management.

3.1.2 Scope of work

In this study, the scope focuses on the entire sewage sludge treatment lifecycle and the work consists of two process flows of Biogas production**.** One process is based on an actual biogas plant in Norway and the other one is an optimized system for that. LCA was done using a Cradle-to-gate analysis basis covering from raw material generation to production process. Boundaries are selected based on available data and two processes are used for LCA analysis to compare which process is the best. Both processes are based on the Anaerobic digestion process. Sludge transportation to the plant and biogas utilization are not included in the system boundaries. This LCA calculation is done by assessing only the biogas production process up to the storage step without considering infrastructures. This study of Life cycle assessment lays on cradle to gate principle stage and calculations follow the Recipe 2016 midpoint (H).

3.1.3 Functional Unit

The LCA's functional unit is meant to serve as a point of reference for different systems. The results of all LCAs are provided in terms of the functional unit.

The production of biogas from the anaerobic digestion of 180 cubic meters of municipal sludge per day, Using 2 process scenarios, resulting in X cubic meters of biogas with Y% methane content, and generating W cubic meters of digestate suitable for use as fertilizer."

3.1.4 System Boundaries

The system boundaries for the study were selected by two systems For a better understanding, System boundaries are shown in Figures 3.1 and 3.2.

Scenario 1: Industry base traditional Biogas production process

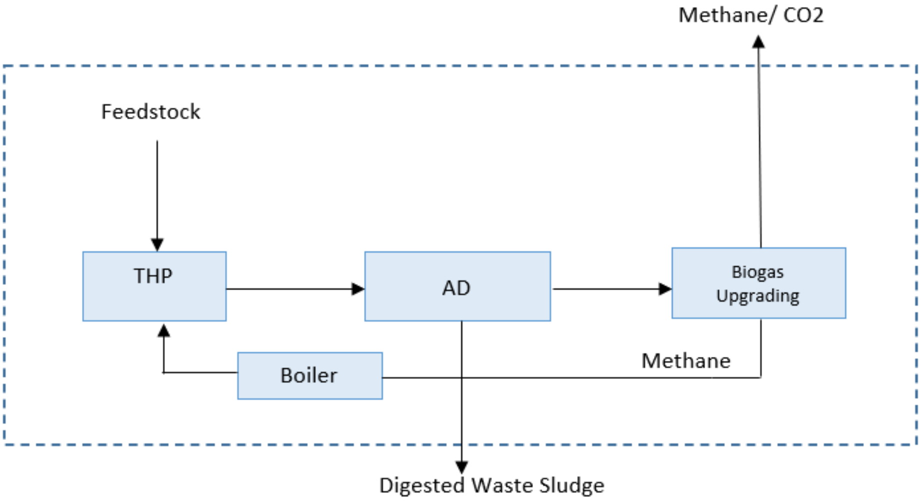


Figure 3.1 Industry base Biogas process

Scenario 2: Combined Biogas production with Pyrolysis process to minimize digested waste sludge

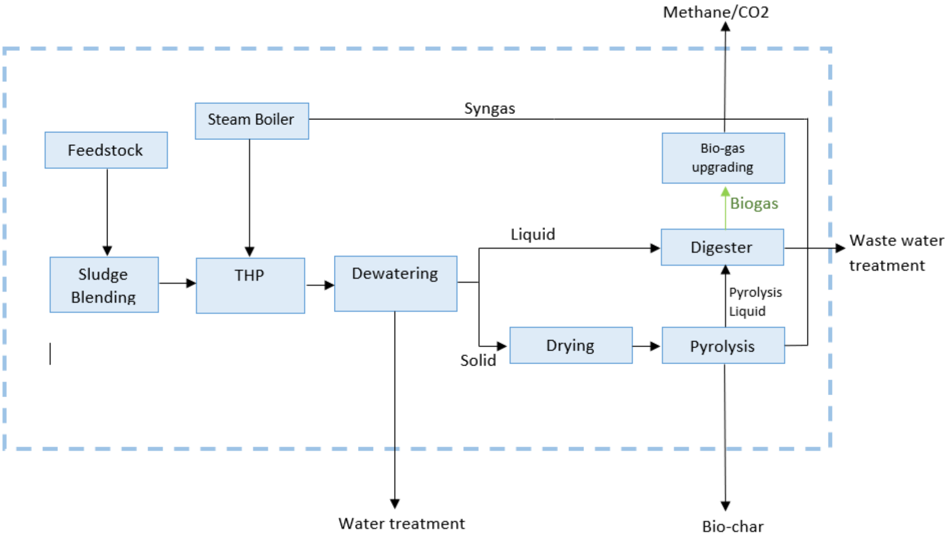


Figure 3.2 Biogas process integrated with pyrolysis process

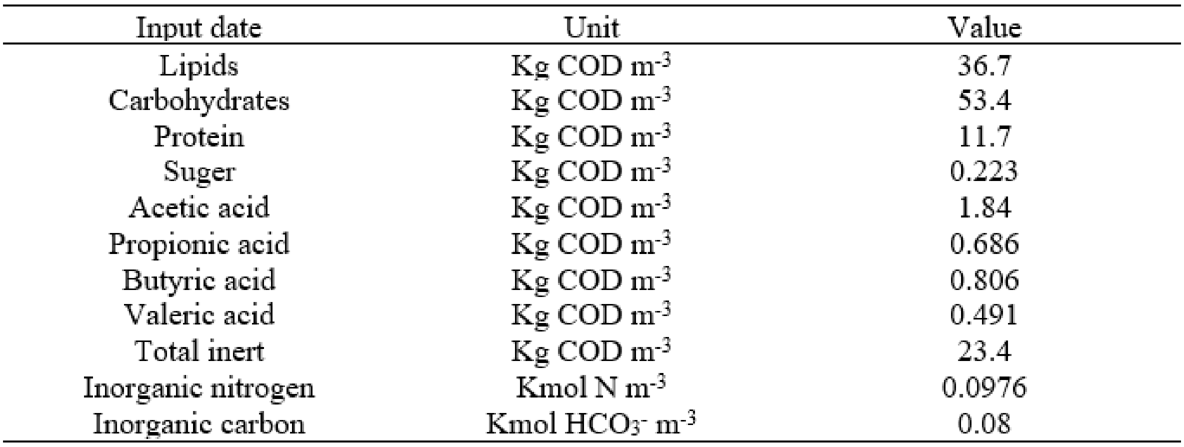
The system boundaries for both the industry-based biogas process and the lab-scale process are delineated primarily around the main steps of biogas production. As illustrated in Figure 3.1, the LCA boundaries for the actual biogas process encompass the production stages, including biogas production itself, while excluding peripheral processes such as sludge transportation, sludge generation, digestate treatment, and product use phases. Similarly, the lab-scale process boundaries align with this approach, focusing solely on the production stage of biogas generation.

3.2 Life Cycle Inventory (LCI) Analysis

Data Collection was mainly concerned with quality in terms of accuracy and country-specificity. The territorial data obtained in this project is a mixture of original and secondary research sources that include: theoretical-technical specifications, on-site data, default estimations and experimental values. Foreground data are sometimes dynamic process data from the Ecoinvent database. It is choosen on most of the factors which are related to the data presented by literature.

The main input material is municipal sludge from Norway. As per the literature, this sludge consists of various organic compounds. As the Gudny research of this biogas plant, the input substrate composition data is shown in Table 3.1 The total solid organic matter contribution sums up to 130 kgm-3 chemical oxygen demand (COD). The dissolved input data that occurs through amino acids, inert and long chain fatty acids is not presented. (Flatabø & Bergland, 2022)

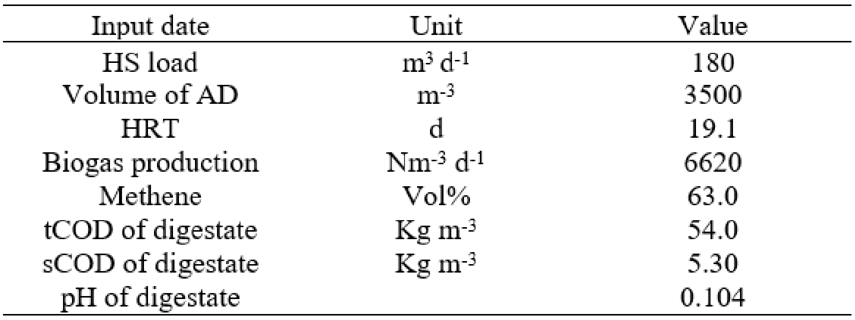
Table 3.1 Substrate Composition (Flatabø & Bergland, 2022)



Input date	Unit	Value
Lipids	Kg COD m^{-3}	36.7
Carbohydrates	Kg COD m^{-3}	53.4
Protein	Kg COD m^{-3}	11.7
Suger	Kg COD m^{-3}	0.223
Acetic acid	Kg COD m^{-3}	1.84
Propionic acid	Kg COD m^{-3}	0.686
Butyric acid	Kg COD m^{-3}	0.806
Valeric acid	Kg COD m^{-3}	0.491
Total inert	Kg COD m^{-3}	23.4
Inorganic nitrogen	Kmol N m^{-3}	0.0976
Inorganic carbon	Kmol HCO_3^- m^{-3}	0.08

For the study, the production data was supplied from the Lindum biogas plant. one year of production data was taken to get average daily production values. These values directly comes form the system from the plant, so all variations of data will include final average production values.

Table 3.2Avarage production data (Flatabø & Bergland, 2022)



Input date	Unit	Value
HS load	$m^3\ d^{-1}$	180
Volume of AD	m^{-3}	3500
HRT	d	19.1
Biogas production	$Nm^{-3}\ d^{-1}$	6620
Methene	Vol%	63.0
tCOD of digestate	$Kg\ m^{-3}$	54.0
sCOD of digestate	$Kg\ m^{-3}$	5.30
pH of digestate		0.104

HS= Hydrolyzed sludge/ HRT= Hydraulic Retention time / d= Days

The production process hydrolyzed sludge input is the same for scenario 1 and scenario 2 biogas production.the process-wise input flows and output flow data were taken from different sources. Industrial base biogas production process data completely taken through the current functioning biogas plant in Drammen. Labscale biogas optimization project data taken from current PHD experiments, past PHD literature and using theoretical calculations.For the better life cycle result, it should be input process wise input and output data related to each flows.Tables 3.3 and 3.4 show input-output data of each process in Industrial base biogas production and 3.5. /3.6 tables show input and output data of each process of lab-scale biogas production

Table 3.3 Scenario 01 process inputs flows

Process	Input flow	unit	value
Thermal Hydrolysis process	Raw sludge	m^3	174.6
	Steam	m^3	5.4
	Electricity	kWh	0
Anaerobic digester	Thermal hydrolyzed sludge	m^3	180
	Electricity	kWh	Sensitivity analyzed
Biogas Upgrading	Biogas	m^3	6620
	Electricity power	kWh	0-0.5
Biogas Storage	Methane	m^3	4170
Boiler operation	Methane	m^3	2085
	Tap water	kg	1000

Table 3.4 Scenario 1 Process output flows

Process	**output flow**	**unit**	**value**
Thermal Hydrolysis process	Thermal hydrolyzed Sludge	m^3	180
Dewatering Process	Thermal hydrolyzed solid Sludge	m^3	18.54
	Thermal hydrolyzed Liquid Sludge	m^3	161.45
Anerobic digester	Biogas	m^3	2888
Biogas Upgrading	Methane	m^3	1820
	Carbon Dioxide	kg	2116
Biogas Storage	Methane	m^3	4170
Boiler process	steam	m^3	5.4

Table 3.5 Scenario 2 process output flows

Process	**output flow**	**unit**	**value**
Thermal Hydrolysis process	Thermal hydrolyzed Sludge	m^3	180
Anerobic digester	Biogas	m^3	6620
Biogas Upgrading	Biogas	m^3	6620
	Carbon dioxide	kg	4849
Biogas Storage	Methane	m^3	4170
Boiler process	steam	m^3	5.4

Table 3.6 Scenario 2 production process input flows

Process	Input flow	unit	value
Thermal Hydrolysis process	Raw sludge	m^3	174.6
	Steam	m^3	5.4
	Electricity	kWh	0
Dewatering process	Thermal hydrolyzed sludge	m^3	180
	Electricity	kWh	0
Drying process	Thermal hydrolyzed solid sludge	m^3	18.54
	Electricity	kWh	Sensitivity analyzed
Pyrolysis Process	Thermal hydrolyzed solid sludge	m^3	18.54
Anaerobic Digester	Thermal hydrolyzed liquid sludge	m^3	161.46
	Pyrolysis liquid	m^3	1.033
	Electricity	kWh	Sensitivity analyzed
Biogas Upgrading	Biogas	m^3	6620
	Electricity power	kWh	0-0.5
Biogas Storage	Methane	m^3	4170
Boiler operation	Methane	m^3	2085
	Tap water	Kg	1000

3.3 Life Cycle Impact Assessment (LCIA) and Interpretation

Life cycle impact assessment includes the determination of the environmental impacts associated with all stages related to a product or process through its entire life cycle. The evaluation comes with factors like resource consumption, energy generation, emissions and waste effluence. This study focuses on several environmental impacts of biogas production.

Impact assessment analysis and interpretations were done in the discussion section below. According to the literature reviews most of the Life cycle impact assessment was done using the Recipe 2016 LCIA method and impact calculation categories are more related to biogas production process impacts. This method also calculates Impact for several impact categories including global warming potential, eutrophication potential, water consumption etc using the Recipe 2016 midpoint (H) Impact assessment method. Calculations lays on Cradle to gate stage and the OpenLCA platform was used to develop this LCA study and the Ecovinent 2.0 database was used as a data source. Open LCA application used to create these two process models for LCIA. Developed process flows are shown in Figures 3.3 and 3.4.

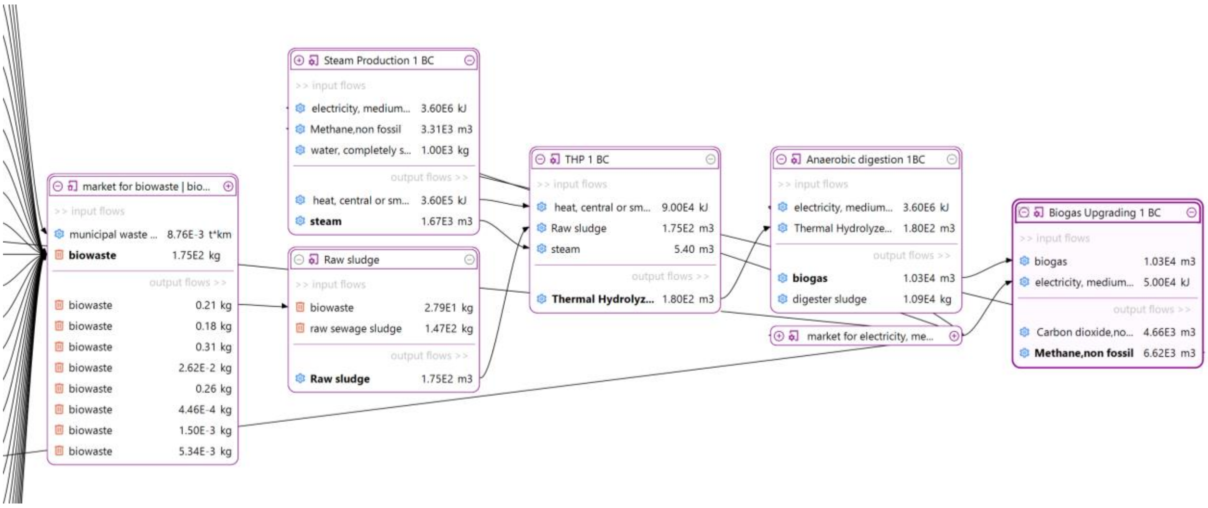


Figure 3.3 Senario 2 Open LCA Model Graph of Biogas production

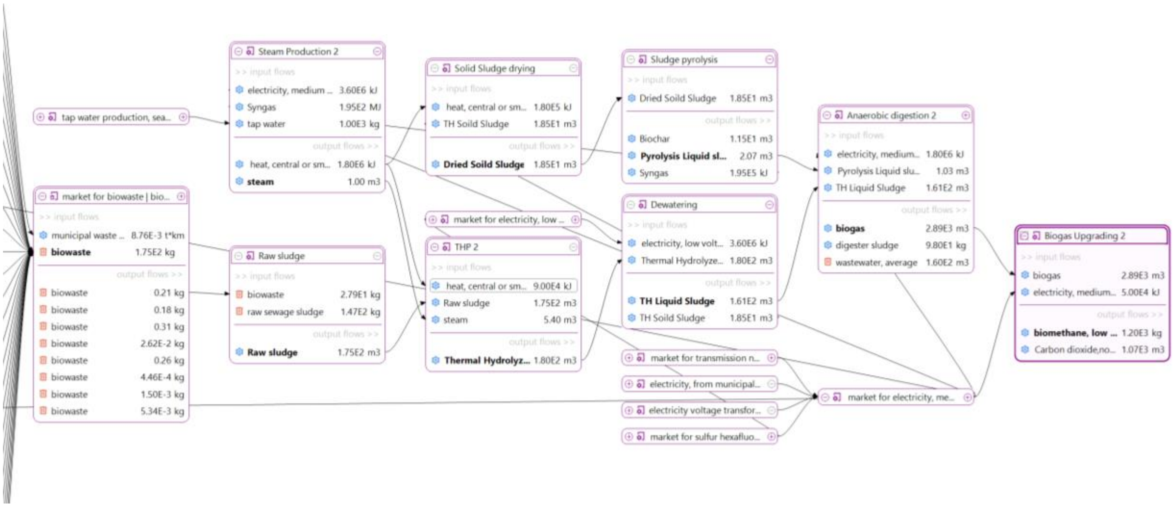


Figure 3.4Senario 2 Open LCA Model Graph of AD-PY Biogas production

3.3.1 ReCiPe 2016 LCIA Method

Goedkoop have established a life cycle impact assessment method known as ReCiPe 2008 that offers midpoint and endpoint characterization factors and an updated version was published in 2016 known as ReCiPe 2016(Goedkoop et al., 2009). The update of ReCiPe offers characterization factors that are valid for the global level rather than the European level, although it is still possible to use characterization factors at the country and continental level for some impact categories.

ReCiPe LCIA Method includes two groups of impact categories with the corresponding groups of characterisation factors. At the midpoint level, eighteen impact categories are considered. At the endpoint level, most of these midpoint impact categories are further converted and aggregated into the three endpoint categories. Figure 3.1 illustrates an overview of these impact categories and relationships. In the ReCiPe 2016 method LCIA calculation can be done by three different perspectives(Huijbregts et al., 2016).

1. **Individualistic (I)** perspective
   Based on uncontroversial impact types, short-term, and technological adaptation of humans.
2. **Hierarchist(H)** perspective
   Hierarchist perspective is a scientific consensus regarding the time scale and likelihood of the impact mechanisms.
3. **Egalitarian(E)** perspective
   it considers as most precautionary perspective with the longest time horizon and all the pathways of impact for which information is available.

These 3 different perspectives provide different Value choices in the derivation of characterization factors. For more information refer (Huijbregts et al., 2016) on page 18.

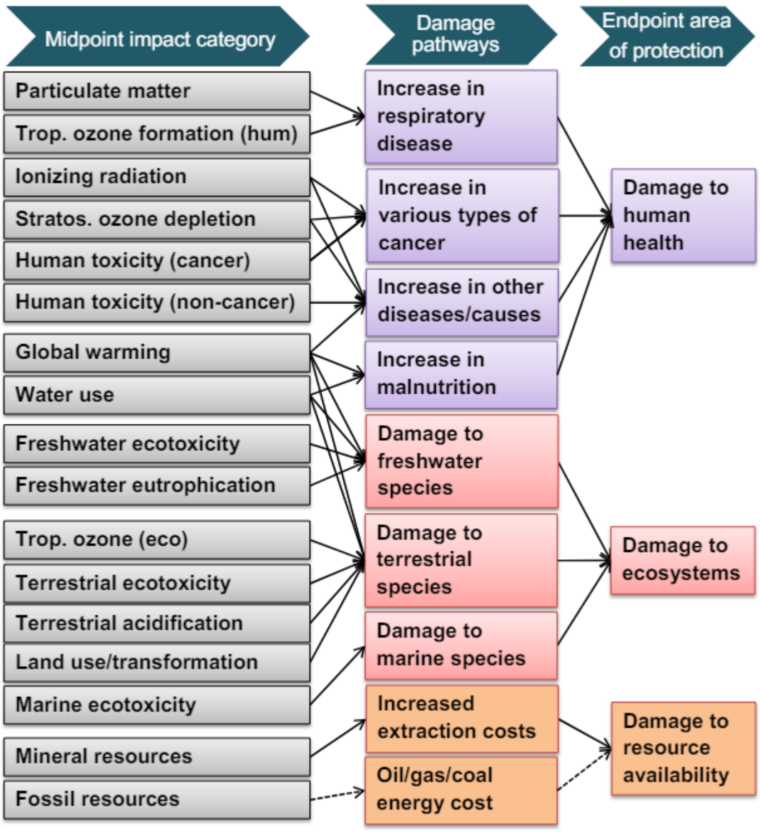


Figure 3.5 overview of recipe 2016 Midpoint and Endpoint impact categories (Huijbregts et al., 2016)

In this study, the ReCiPe (2016) Midpoint (H) method is used for the following reasons:

Comprehensive Coverage: The impact assessment tool ReCiPe (2016) includes 18 impact categories that address numerous environmental concerns.

Relevance to Biogas Production: This method is appropriate for the assessment of impacts that are related to biogas production such as global warming potential, human toxicity, terrestrial ecotoxicity, and water consumption.

Established Methodology: ReCiPe is the most commonly applied and acknowledged impact assessment method in LCA studies.

This study will use the ReCiPe (2016) Midpoint (H) method to calculate the environmental impacts of high-rate anaerobic digestion and thermal hydrolysis of municipal sludge. This approach helps to determine the main impact areas and develop strategies to reduce the negative impact on the environment. furthermore, A comparison between the two biogas production processes was done through a detailed framework for full-scale Life Cycle Assessment (LCA). In interpretation, step includes result analysis and elaboration of impacts throughout the system

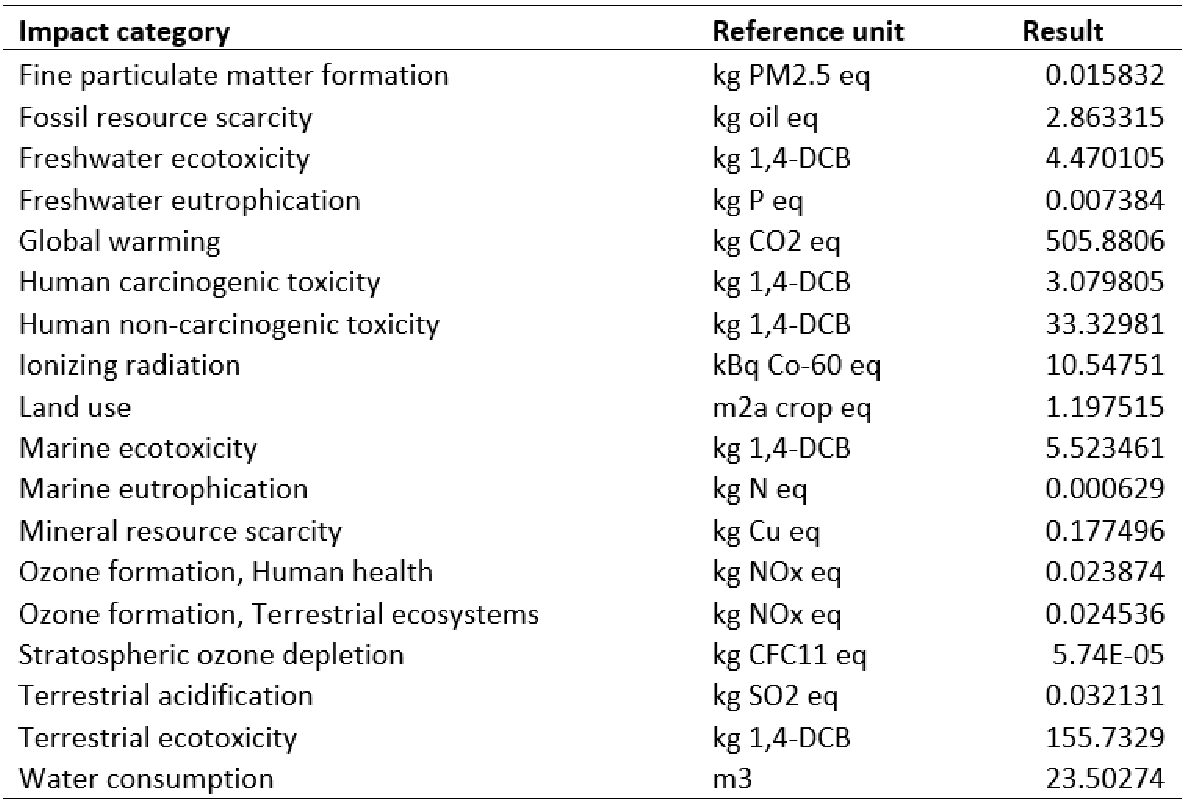
4 Results

This section illustrates the result of the whole study which is based on the ReCiPe 2016 midpoint (H) impact analysis method. Two process scenarios are studied through this life cycle assessment and all results are clearly shown in the tables.

Table 4.1 illustrates the overall impact calculation result of Industrial biogas production using the Recipe 2016 Midpoint (H) method.

Scenario 01(Baseline)- 100kW electricity input and 0.3 % emission output per day

Table 4.1 Industrial base LCA overall Impact results

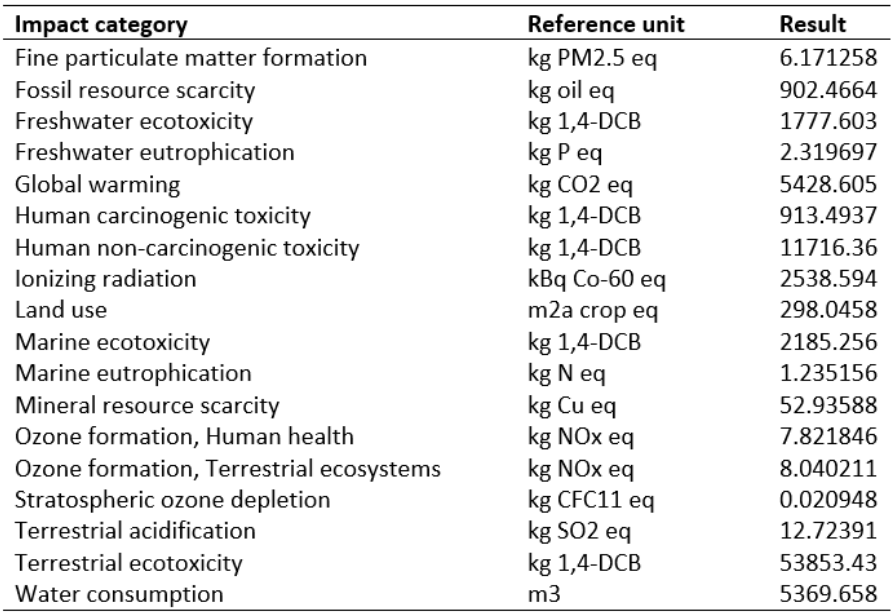


Impact category	Reference unit	Result
Fine particulate matter formation	kg PM2.5 eq	0.015832
Fossil resource scarcity	kg oil eq	2.863315
Freshwater ecotoxicity	kg 1,4-DCB	4.470105
Freshwater eutrophication	kg P eq	0.007384
Global warming	kg CO2 eq	505.8806
Human carcinogenic toxicity	kg 1,4-DCB	3.079805
Human non-carcinogenic toxicity	kg 1,4-DCB	33.32981
Ionizing radiation	kBq Co-60 eq	10.54751
Land use	m2a crop eq	1.197515
Marine ecotoxicity	kg 1,4-DCB	5.523461
Marine eutrophication	kg N eq	0.000629
Mineral resource scarcity	kg Cu eq	0.177496
Ozone formation, Human health	kg NOx eq	0.023874
Ozone formation, Terrestrial ecosystems	kg NOx eq	0.024536
Stratospheric ozone depletion	kg CFC11 eq	5.74E-05
Terrestrial acidification	kg SO2 eq	0.032131
Terrestrial ecotoxicity	kg 1,4-DCB	155.7329
Water consumption	m3	23.50274

Table 4.1 illustrates the overall impact calculation result of Scenario 1 using the ReCiPe 2016 Midpoint (H) method.

Scenario 02 (Baseline)- 100kW electricity input and 0.3 % emission output per day

Table 4.2 Lab scale base LCA overall impact results



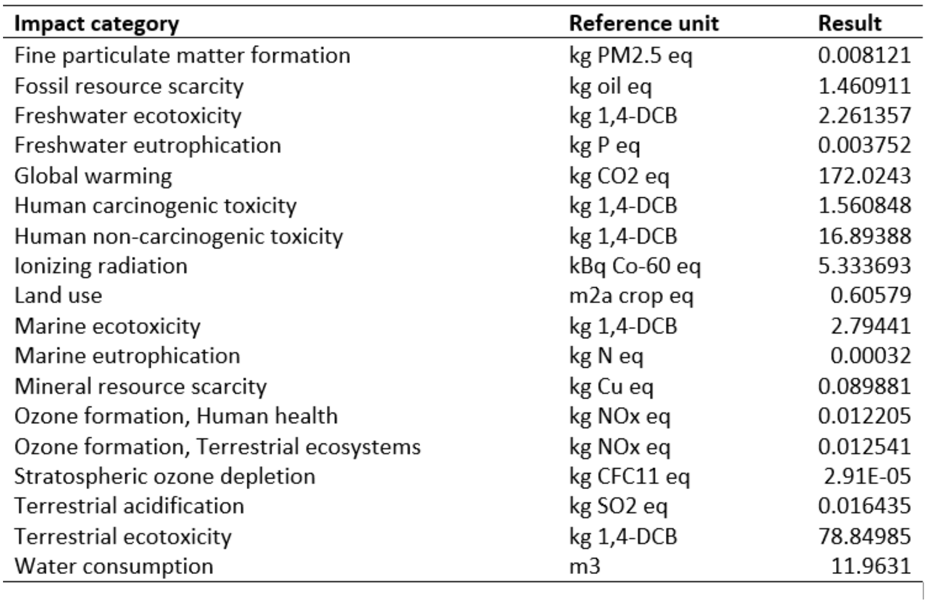
Impact category	Reference unit	Result
Fine particulate matter formation	kg PM2.5 eq	6.171258
Fossil resource scarcity	kg oil eq	902.4664
Freshwater ecotoxicity	kg 1,4-DCB	1777.603
Freshwater eutrophication	kg P eq	2.319697
Global warming	kg CO2 eq	5428.605
Human carcinogenic toxicity	kg 1,4-DCB	913.4937
Human non-carcinogenic toxicity	kg 1,4-DCB	11716.36
Ionizing radiation	kBq Co-60 eq	2538.594
Land use	m2a crop eq	298.0458
Marine ecotoxicity	kg 1,4-DCB	2185.256
Marine eutrophication	kg N eq	1.235156
Mineral resource scarcity	kg Cu eq	52.93588
Ozone formation, Human health	kg NOx eq	7.821846
Ozone formation, Terrestrial ecosystems	kg NOx eq	8.040211
Stratospheric ozone depletion	kg CFC11 eq	0.020948
Terrestrial acidification	kg SO2 eq	12.72391
Terrestrial ecotoxicity	kg 1,4-DCB	53853.43
Water consumption	m3	5369.658

4.1 Sensitivity Analysis Results.

Electricity can be varied with different climate situations/ equipment efficiencies and input sludge quality etc. Due to that, sensitivity analysis was done by changing electricity inputs and emission outputs to identify the impact through this variable electricity input. All sensitivity results are illustrated in the tables below Table 4.3 to 4.6.

Scenario 1(Lower Bound)- 50kW electricity input and 0.1 % emission output per day

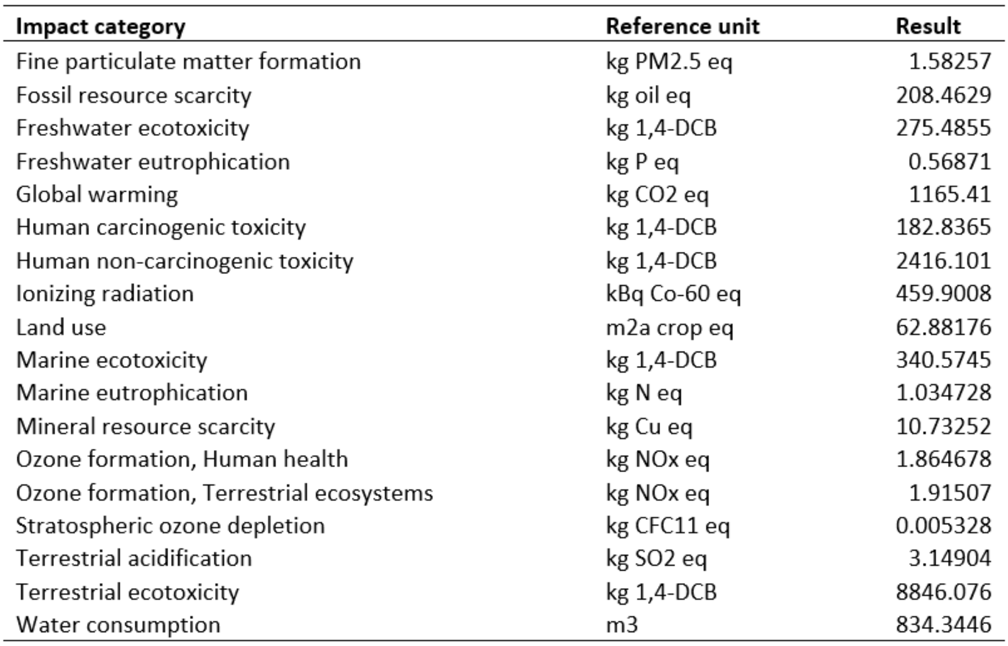
Table 4.3 Overall result for scenario 01 Biogas production process with 0.1% emission and 50 kW/d Electricity Usage



Impact category	Reference unit	Result
Fine particulate matter formation	kg PM2.5 eq	0.008121
Fossil resource scarcity	kg oil eq	1.460911
Freshwater ecotoxicity	kg 1,4-DCB	2.261357
Freshwater eutrophication	kg P eq	0.003752
Global warming	kg CO2 eq	172.0243
Human carcinogenic toxicity	kg 1,4-DCB	1.560848
Human non-carcinogenic toxicity	kg 1,4-DCB	16.89388
Ionizing radiation	kBq Co-60 eq	5.333693
Land use	m2a crop eq	0.60579
Marine ecotoxicity	kg 1,4-DCB	2.79441
Marine eutrophication	kg N eq	0.00032
Mineral resource scarcity	kg Cu eq	0.089881
Ozone formation, Human health	kg NOx eq	0.012205
Ozone formation, Terrestrial ecosystems	kg NOx eq	0.012541
Stratospheric ozone depletion	kg CFC11 eq	2.91E-05
Terrestrial acidification	kg SO2 eq	0.016435
Terrestrial ecotoxicity	kg 1,4-DCB	78.84985
Water consumption	m3	11.9631

Scenario 02 (Lower Bound) -50kW electricity input and 0.1 % emission output per day

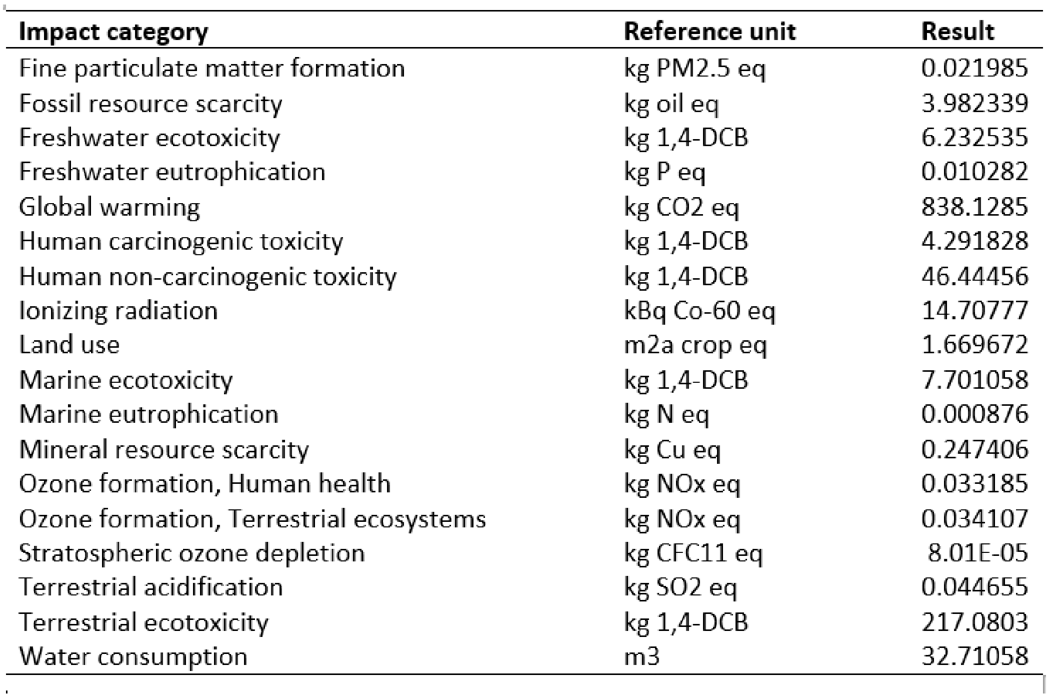
Table 4.4 Sensitivity analysis overall result for scenario 2 production process with 50 kWh



Impact category	Reference unit	Result
Fine particulate matter formation	kg PM2.5 eq	1.58257
Fossil resource scarcity	kg oil eq	208.4629
Freshwater ecotoxicity	kg 1,4-DCB	275.4855
Freshwater eutrophication	kg P eq	0.56871
Global warming	kg CO2 eq	1165.41
Human carcinogenic toxicity	kg 1,4-DCB	182.8365
Human non-carcinogenic toxicity	kg 1,4-DCB	2416.101
Ionizing radiation	kBq Co-60 eq	459.9008
Land use	m2a crop eq	62.88176
Marine ecotoxicity	kg 1,4-DCB	340.5745
Marine eutrophication	kg N eq	1.034728
Mineral resource scarcity	kg Cu eq	10.73252
Ozone formation, Human health	kg NOx eq	1.864678
Ozone formation, Terrestrial ecosystems	kg NOx eq	1.91507
Stratospheric ozone depletion	kg CFC11 eq	0.005328
Terrestrial acidification	kg SO2 eq	3.14904
Terrestrial ecotoxicity	kg 1,4-DCB	8846.076
Water consumption	m3	834.3446

Scenario 1 (Upper Bound)- 150kW electricity input and 0.5 % emission output per day

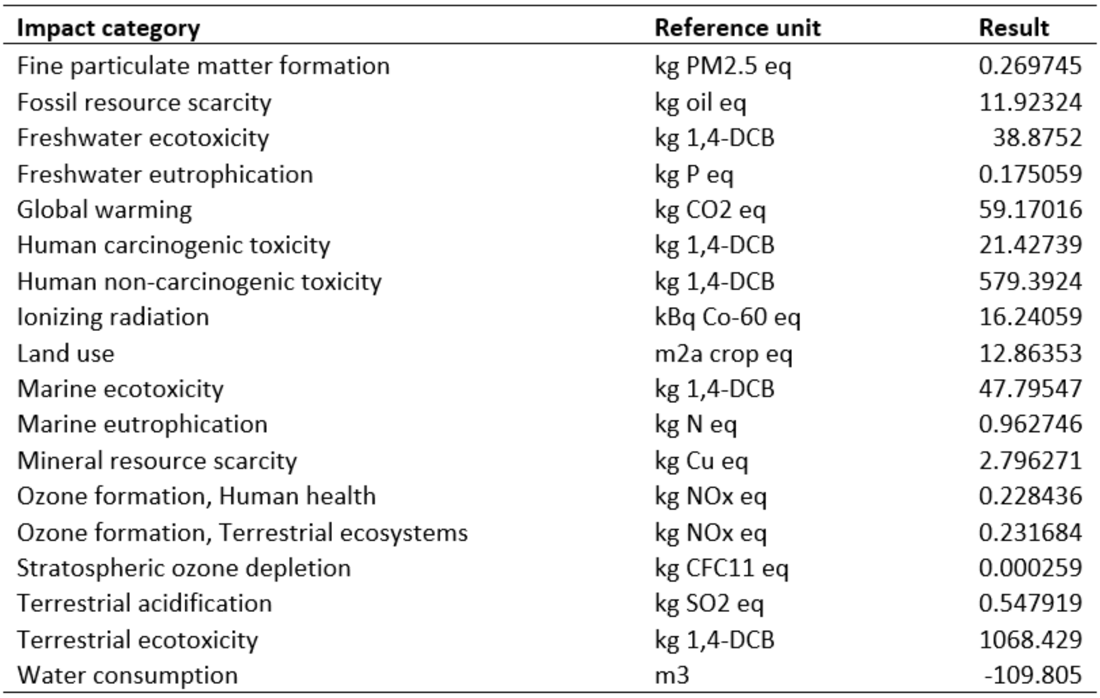
Table 4.5 Sensitivity analysis of overall result for Scenario 1 Biogas production process with 150 kWh



Impact category	Reference unit	Result
Fine particulate matter formation	kg PM2.5 eq	0.021985
Fossil resource scarcity	kg oil eq	3.982339
Freshwater ecotoxicity	kg 1,4-DCB	6.232535
Freshwater eutrophication	kg P eq	0.010282
Global warming	kg CO2 eq	838.1285
Human carcinogenic toxicity	kg 1,4-DCB	4.291828
Human non-carcinogenic toxicity	kg 1,4-DCB	46.44456
Ionizing radiation	kBq Co-60 eq	14.70777
Land use	m2a crop eq	1.669672
Marine ecotoxicity	kg 1,4-DCB	7.701058
Marine eutrophication	kg N eq	0.000876
Mineral resource scarcity	kg Cu eq	0.247406
Ozone formation, Human health	kg NOx eq	0.033185
Ozone formation, Terrestrial ecosystems	kg NOx eq	0.034107
Stratospheric ozone depletion	kg CFC11 eq	8.01E-05
Terrestrial acidification	kg SO2 eq	0.044655
Terrestrial ecotoxicity	kg 1,4-DCB	217.0803
Water consumption	m3	32.71058

Scenario 02(Upper Bound)- 150kW electricity input and 0.5 % emission output per day

Table 4.6 Sensitivity analysis overall result for Senario 2 Biogas production process with 50 kWh



Impact category	Reference unit	Result
Fine particulate matter formation	kg PM2.5 eq	0.269745
Fossil resource scarcity	kg oil eq	11.92324
Freshwater ecotoxicity	kg 1,4-DCB	38.8752
Freshwater eutrophication	kg P eq	0.175059
Global warming	kg CO2 eq	59.17016
Human carcinogenic toxicity	kg 1,4-DCB	21.42739
Human non-carcinogenic toxicity	kg 1,4-DCB	579.3924
Ionizing radiation	kBq Co-60 eq	16.24059
Land use	m2a crop eq	12.86353
Marine ecotoxicity	kg 1,4-DCB	47.79547
Marine eutrophication	kg N eq	0.962746
Mineral resource scarcity	kg Cu eq	2.796271
Ozone formation, Human health	kg NOx eq	0.228436
Ozone formation, Terrestrial ecosystems	kg NOx eq	0.231684
Stratospheric ozone depletion	kg CFC11 eq	0.000259
Terrestrial acidification	kg SO2 eq	0.547919
Terrestrial ecotoxicity	kg 1,4-DCB	1068.429
Water consumption	m3	-109.805

5 Discussion

This section includes the findings mentioned in section 4. This will provide an overall analysis of current results and a discussion of significant changes in impact between the two processes while comparing process-wise impacts. Finally, the discussion part integrates the whole study results and puts it into the broader context of comprehensive knowledge which offers meaningful guidelines for future research or decision-making processes.

Section 4 results show ReCiPe 2016 midpoint (H) impact analysis method calculation data based on 18 different impact categories. For this analysis taken to covers the effects of the biogas production process on human health, water resources, the atmosphere, and the land, with an analysis and comparison of the impacts across different situations.

This study mainly focuses on Global warming(GW), Human non-carcinogenic toxicity (HNCT), Terrestrial ecotoxicity and water consumption related to the above-mentioned areas. Tables 4.1 and 4.2 illustrate the overall impact calculation result of scenario 1 and scenario 2. The impact-wise analysis and comparison are shown below.

5.1 Global Warming Potential

This section discusses the results from the Life Cycle Assessment of two biogas production scenarios in terms of Global Warming Potential(GWP).

5.1.1 Senario 01; GWP

According to the study, the top 5 contributions to global warming by this biogas production scenario in 100KW electricity input and 0.3 Emission results, are shown in Figure 5.1

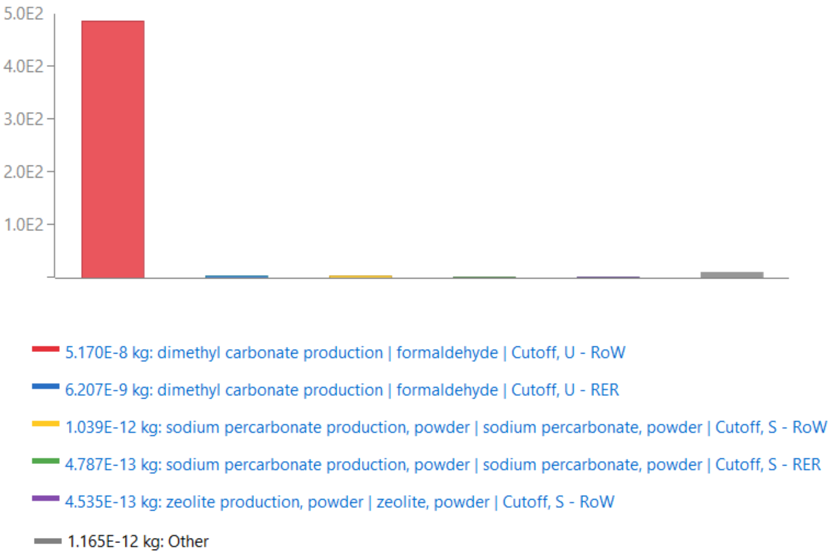


Figure 5.1 top 5 Contributions to Global Warming

The bar chart visualizes the contribution of different biogas production factors to the impact of global warming, with the highest value assigned to digestate CO2 emissions and electricity generation emissions.

Digestate CO2 Emissions: This category represents the carbon dioxide emissions due to the treatment and disposal of digestate, which is the biogas production's by-product. In most cases, the digestate is constituted of organic matter which is subjected to fermentation releasing carbon dioxide into the atmosphere. The high ranking suggests that digestate management practices are likely to cause a lot of harm to global warming through carbon dioxide emissions. Currently Lindum plant are finding alternative methods for treating and management of this digestate in ecofriendly way. Scenario 2 process mainly focus on minimization of digestate sludge by the biogas production process.

Electricity Generation Emissions: This type of emissions is caused by greenhouse gases that occur during the generation of electricity needed in biogas plants. Electricity may be used to perform a variety of processes including heating, mixing, and processing equipment. The high value signifies that a considerable amount of energy is spent on electricity generation as well and thus contributes significantly to the overall global warming impact of biogas production.

5.1.2 Senario 2; Global Warming

The impact of the biogas production by this method is shown in Figure 5.2 This method is a combined process of AD and PY to reduce digested sludge. With the experimental data, it produces sludge with less amount of total solids through the AD process. Due to that emissions from digestate sludge has very little amount of total solids.

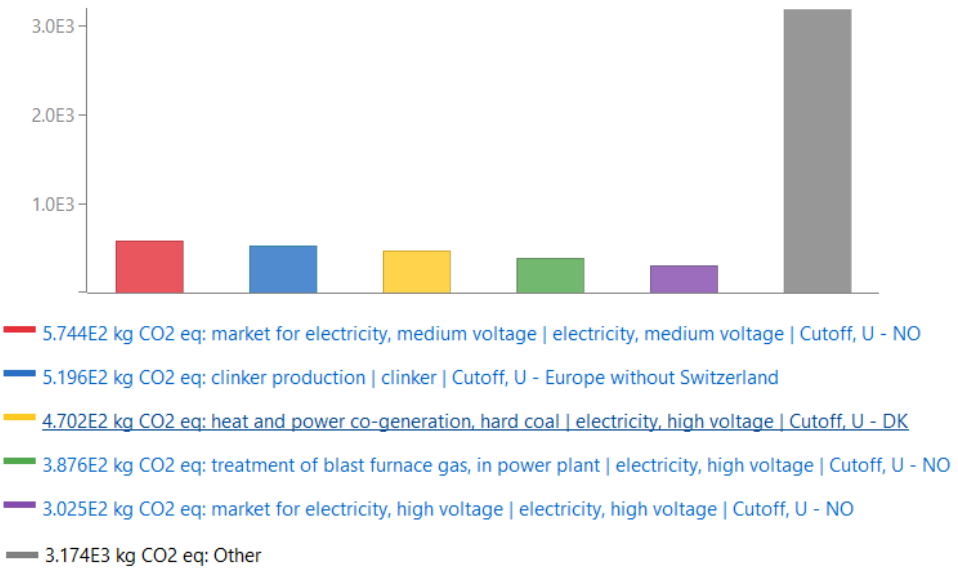


Figure 5.2 Top 5 contribution for Global warming, scenario 02

In this process, electricity is used for several dewatering drying and heating processes. it consumes electricity. Due to that electricity has to impact on global warming 5.744E2 KgCO2 eq value is the highest impact value from electricity. The grey bar shows other all global warming impact total value. It consist with huge number of process thoughout whole life cycle.for the better understanding contribution tree of globle warming shown in figure 5.3.this figure show upto 25 processes in biogas production and arrows weight shows contribution level and direction.

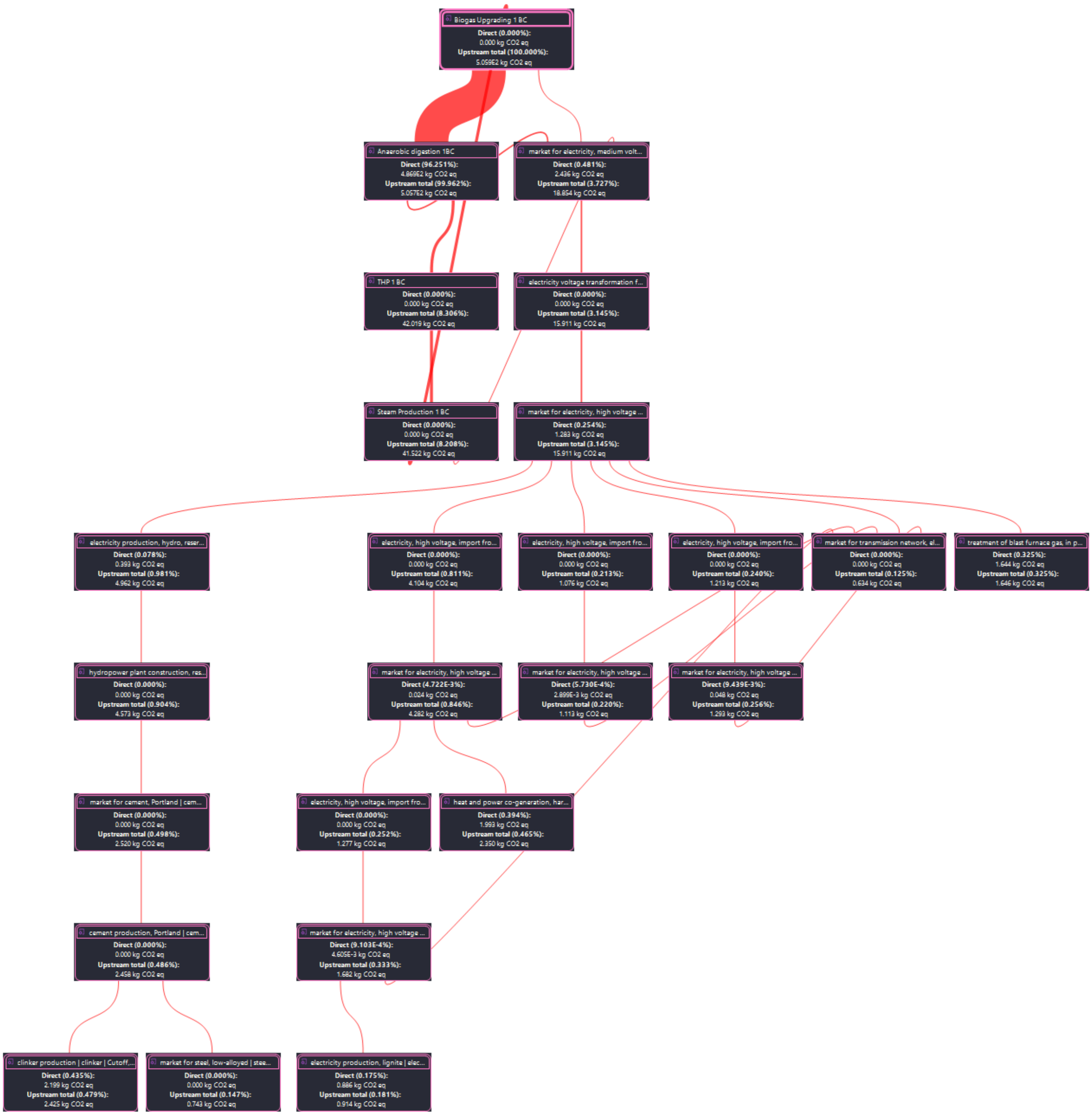


Figure 5.3 shankey diagram for Globle warming impact category in scenario 2

5.1.3 Global warming Comparison between Scenario 1 and Scenario 2.

For the comparison, Figure 5.1 and Figure 5.2 bar charts are shown in below. The comparison between Figure 5. 1 and Figure 5. The 2 bar charts clearly show that Scenario 1 has a higher global warming impact when compared to Scenario 2. This variation may be caused by the large amount of waste sludge that is transported to the environment in Scenario 1.

The scenario 1 contains carbon dioxide (CO2) and methane (CH4) emissions that are a result of digested waste sludge. The digested sludge after the AD process, which contains organic matter, is released into the environment for decomposition processes and releases CO2 as a byproduct. Furthermore, atmosperic conditions, that digested sludge management process can result in the production of methane, which is a highly potent greenhouse gas, with a much higher global warming potential over a given timeframe than CO2. Because of this, the continuous emission of CO2 and CH4 from the digested waste sludge in Scenario 1 also significantly contributes to the global warming impact of the system. This increased impact is portrayed in the bar chart for Scenario 1, where the total global warming contributions from digested waste sludge, and other factors, are higher than in Scenario 2.

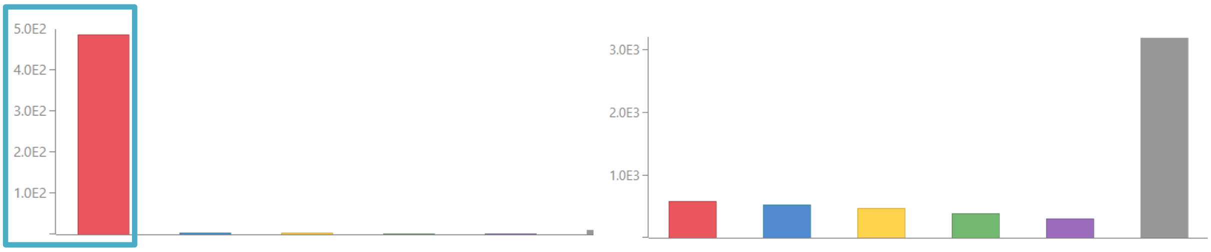


Figure 5.4 Senario 1 & 2 Globale warming impact result top 5 contribution grap

In this calculation shows a 0.3% emission impact on the Environment through scenario 1. Currently, a small no. of researchers are working on this digested sludge emission. Due to that in this case assume,0.3% of emission will be emitted into the air. In addition to that it shows 4.890E2 kgCO2 eq impact on the Figure 5.4 blue square. In scenario 2 only remove wastewater from the AD due to that, above 0.3% emission will on added to scenario 2.

By looking at the grey bars in the two graphs, these bars are the sum of other processes contributing to global warming. These processes include many stages and activities which make up the system in its whole, such as feedstock handling, energy consumption, transport, and other auxiliary processes. According to the system boundary, these valves are not affected in this study.

5.2 Human non-carcinogenic toxicity

Human carcinogenic toxicity is the feature of some substances or agents that can cause cancer in humans. Human non-carcinogenic toxicity is the term used to describe the harmful health effects that a person may experience as a result of exposure to substances or agents that do not cause cancer but can still damage human health through other means. Non-carcinogenic toxicity can be a consequence of the exposure to a large number of substances namely heavy metals, pesticides, industrial chemicals, air pollutants, food additives, pharmaceuticals, and biological toxins. These toxicants can be ingested, inhaled, or contacted through skin or other routes of exposure and can accumulate in the tissues or organs, thus, causing acute or chronic health effects.

The human non-carcinogenic toxicity linked to biogas production is mostly related to exposure to different chemicals and substances used in the production process. Although biogas is a much cleaner energy source than fossil fuels, the health risks connected with the production and handling of biogas and its by-products are still present. Based on the overall result of scenario 1 and scenario 2 with 100KW electricity input and 0.3 % emission related to Human non-carcinogenic toxicity shown below.

5.2.1 Scenario 1: Human non-carcinogenic toxicity

Figure 5.5 illustrates the Top 5 contributions of Human non-carcinogenic toxicity impact through scenario 1. The highest amount of impact value is marked in copper mine operation which is not related to the selected system boundary but it will have an indirect impact on this study. The ash colour bar shows the sum of other all contributions regarding with other process.

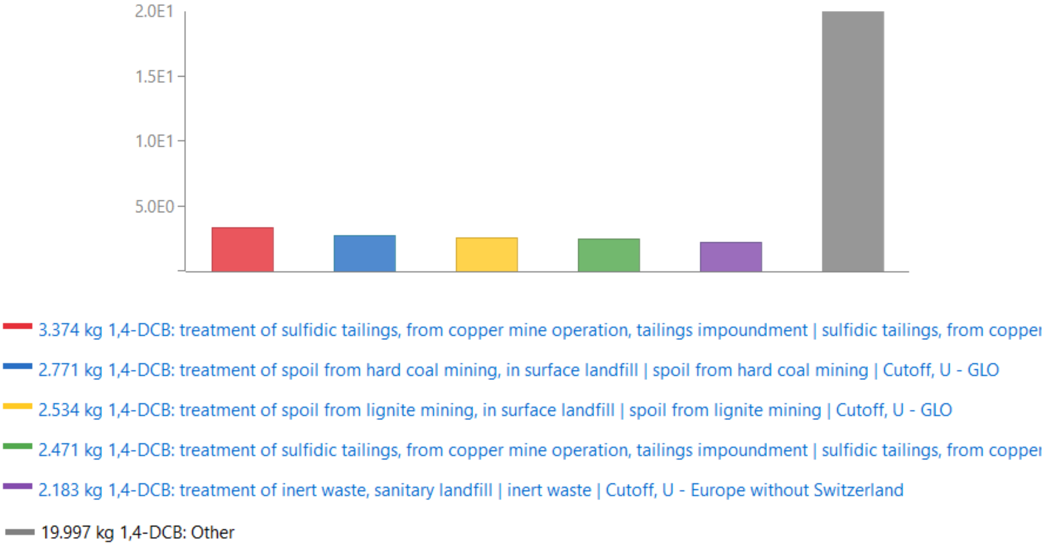


Figure 5.5 Human non-carcinogenic toxicity

5.2.2 Scenario 2: Human non-carcinogenic toxicity

Figure 5.5 illustrates the Top 5 contributions of Human non-carcinogenic toxicity impact through scenario 2 with 100KW electricity and 0.3% emission. In this process also highest impact contribution is contributed by out of boundry and it will indirect impact to the whole life cycle.

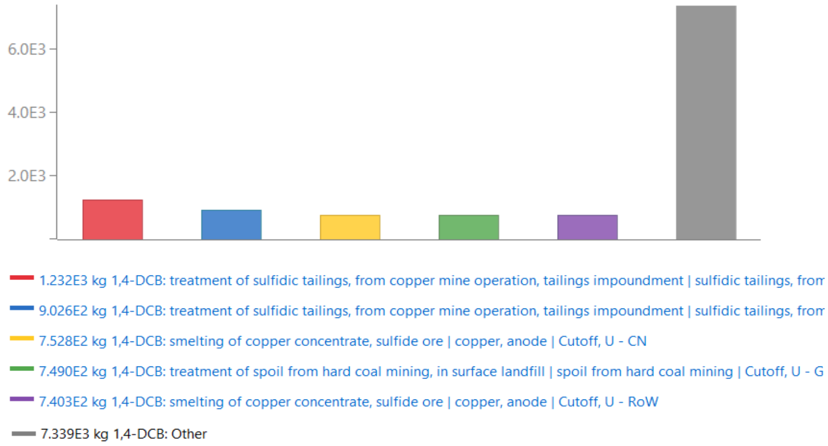


Figure 5.6 Top 5 contributions of Human non-carcinogenic toxicity

Human non-carcinogenic toxicity impact depends on several factors. In the Biogas production process, AD process, Gas handling and storage and Digestate management will cause to this impact. During the anaerobic digestion, the organic material has microbial decomposition and it produces biogas. The safety of the process is considered to be high, though there is a possible risk of exposure to pathogens present in the feedstock materials, like sludge from sewage or organic waste. The by-product of anaerobic digestion called digestate may contain pathogens, heavy metals, and other contaminants that can be hazardous to one's health if not handled properly. Improper treatment of digestate or its inadequate disposal can result in soil and water resources contamination, which can negatively affect human health and the environment.

5.2.3 Human non-carcinogenic toxicity Comparison between scenario 1 and scenario 2

Comparing traditional biogas production to optimized biogas production in terms of human non-carcinogenic toxicity, traditional biogas production is normally associated with a lower level of impact. figure 5.7 shows the difference between Human non-carcinogenic toxicity Impact results between scenario 1 and scenario 2.

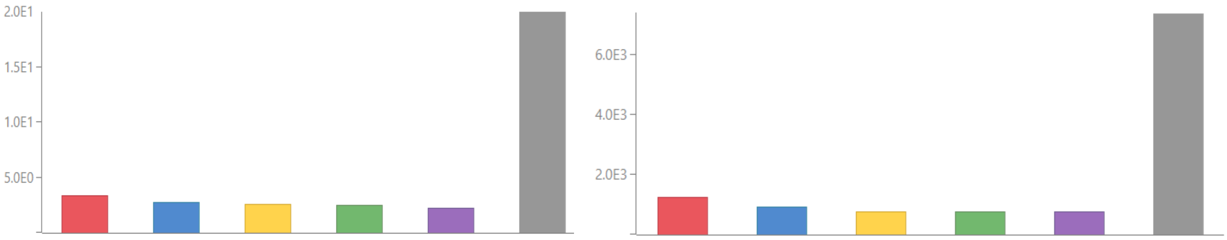


Figure 5.7 Human non-carcinogenic toxicity Impact results between scenario 1 and scenario 2

According to Figure 5.7 Red colour bar shows the highest contribution process for HNCT impact in both cases.In scenario 1 it belongs to the treatment of sulfidic tailings, from copper mine operation, tailings impoundment process with 3.374 kg 1,4-DC value. Scenario 2 shows a 1.232E3 kg 1,4-DC value for the same process. Therefore, scenario 2 impact will have cause higher impact on human health than scenario 1. However, these all process are sub process that help to fulfil the main process in the system boundary. Due to that, this impact contribution can be known as an indirect impact contribution to the selected system boundary.

5.3 Terrestrial Ecotoxicity

Terrestrial ecotoxicity represents the possibility of harmful impacts of substances or pollutants on terrestrial ecosystems, including soil, plants, and animals. This impact category evaluates the toxicity of substances to terrestrial organisms and ecosystems.

5.3.1 Scenario 1: Terrestrial Ecotoxicity

Figure 5.8 illustrates the top 5 contributions for Terrestrial ecotoxicity related to scenario 1. In scenario 1 calculated contributions belong to the sub-process of the out-of-boundary.

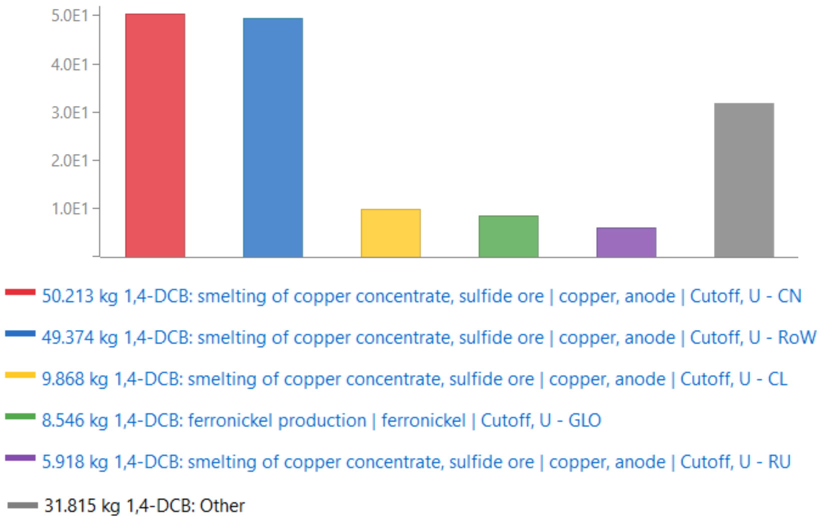


Figure 5.8 Top 5 contribution result chart for Terrestrial Ecotoxicity in scenario 1

According to the graph, these impacts can be grouped into indirect emissions due to these processes are sub-process life cycles in biogas production. The red colour bar- 50.213 Kg1,4-DCB and blue colour bar- 49.374 Kg1,4-DCB show higher impact values than total impact from all other processes (ash colour bar- 31.815 Kg1,4-DCB. When considering full life cycle analysis, this impact needs to be managed due to a higher amount of impact on the land. In scenario 1 there is one direct impact to Terrestrial ecotoxicity. Removing digested sludge is one of the critical impacts of this category. In this case that impact cannot added to the calculations due to the unavailability of data. In addition to that, this digested sludge is used in agricultural land as a fertilizer. Before utilising this, it needs to be diluted. this dilution process takes more than 20 weeks on an outdoor dump site. At that time there will be a significant impact on the environment.

5.3.2 Scenario 2: Terrestrial Ecotoxicity

Figure 5.9 illustrates the top 5 contributions for Terrestrial ecotoxicity related to scenario 2. This impact is also similar to scenario 1 impact contribution.

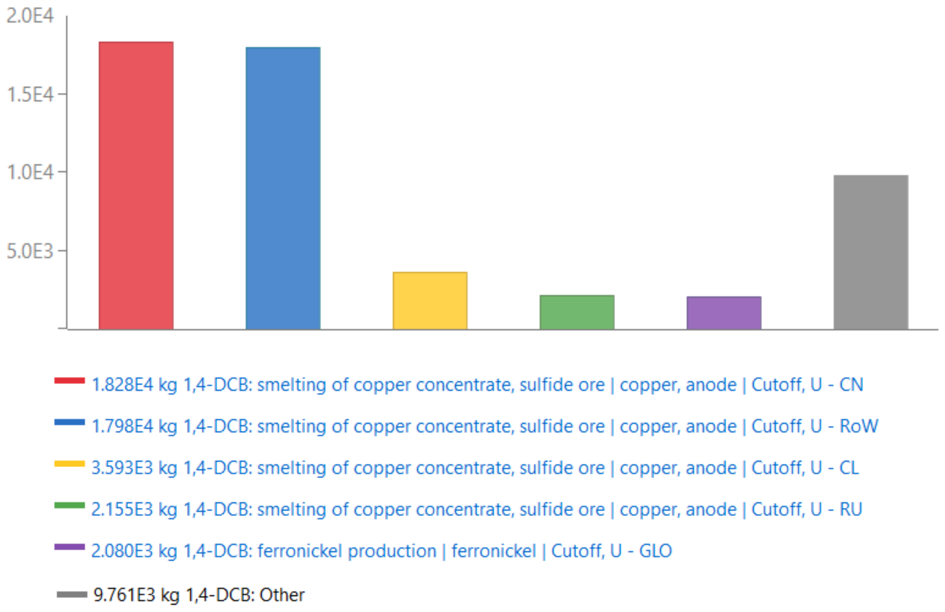


Figure 5.9 top 5 contributions for Terrestrial ecotoxicity related to scenario 2.

According to Table 5.9, the top 4 contributions presented with the Smelting of copper concentrate process. Compared to scenario one, it has the same pattern of impact trend and proportionally increased the impact value. Moreover, the whole life cycle has to impact on Terrestrial ecotoxicity due to this subprocess contribution and digestate contribution. when considering digestate contribution, it depends on feedstock composition. the feedstock consists of organic materials from municipal sludge. these materials may have pollutants such as pesticides, heavy metals, or pathogens. If these contaminants are not well treated during biogas production, which is the main process of digesting the feedstock, they can potentially accumulate in the digestate that is formed or the bio-fertilizer. The use of digestate or biofertilizer produced from biogas processing as agricultural land fertilizers can be a source of contaminants and could lead to ecotoxicological effects. Similarly, heavy metals can accumulate in soils, which represent a danger for soil organisms, plants, and even entering the food chain. Therefore, terrestrial ecotoxicity impact calculation is very significant in LCA.

5.4 Impact of Water Consumption

Water consumption is a main component of the Life Cycle Assessment (LCA) and it is always considered together with other environmental impacts. water consumption is normally assessed within the framework of LCA and its impacts on the environment.

Water Withdrawal: LCA determines how much water is drawn from different sources in the natural environment of a product during its production process, such as raw material extraction, manufacturing, usage, and disposal. This assessment delivers direct water extraction by the plant and indirect water extraction as a result of the production and transport of raw materials and energy inputs.

Water Consumption: LCA varies from water consumption and water withdrawal. Water withdrawal relates to the total amount of water taken from natural sources while water consumption takes into account the amount of water that cannot be returned to the source due to evaporation, use in the production process and pollution. Excessive water consumption can lead to a decrease of water availability could be possible environmental effects such as habitat degradation, ecosystem disruption and biodiversity loss.

5.4.1 Scenario 1: Impact of water consumption

Electricity is the main power source used for this biogas production process. For mixing processes, drying processes, lightning and all other functions related to controlling powered by electricity. According to the International Energy Agency energy policy review in Norway 2022, 92% of electricity generation is covered by hydropower resources. Hydropower facility generally converts the kinetic energy of flowing water into electricity. The water consumption which is a result of reservoir filling, turbine operations and maintenance is a significant feature of hydroelectric power which is considered to be renewable.

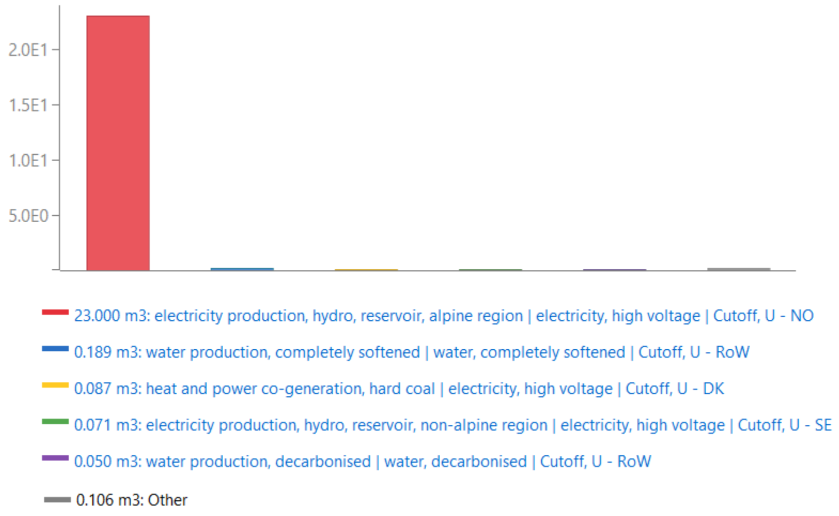


Figure 5.10 top 5 contibution process for water consumption in scenario 1

The highest amount of water consumption on this LCA is connected with electricity usage. The top 5 contribution processes for water consumption are shown in Figure 5.10. The figure clearly shows the highest contribution connected to hydropower electricity generation. The 23,000 cubic meters of water consumption for hydroelectricity generation is an obvious impact which can be explained by the need for water to run the turbines and maintain the reservoir levels. This degree of consumption can result in water scarcity, problems for aquatic ecosystems, and problems for downstream water users.

5.4.2 Scenario 2: Impact of water consumption

In scenario 2 top 5 contribution processes for water consumption results are shown in Figure 5.11.In this scenario. In this case shows minus values in the bar chart.

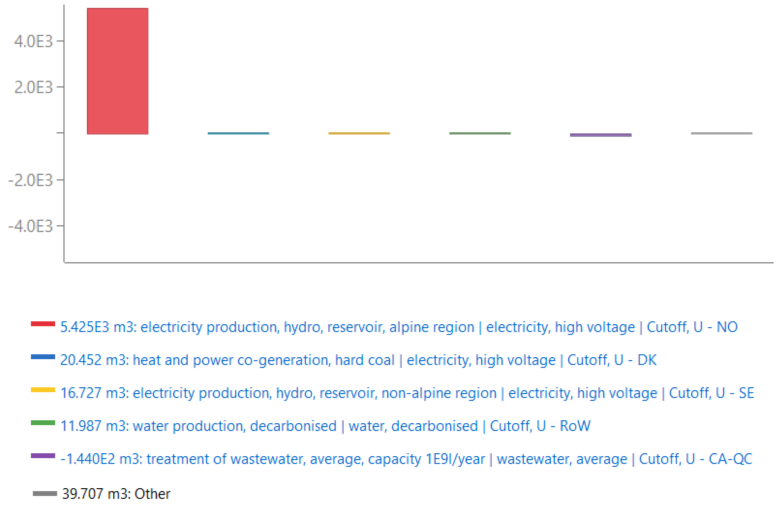


Figure 5.11 top 5 contribution processes for water consumption results

In this production, flow removes digested sludge as wastewater. In the dewatering process, the hydrolyzed sludge is divided into two parts liquid and solid and the liquid part directly feeds into AD. After this AD removes digested sludge as wastewater due to 1-3 percent TS. This water is measured as a positive impact on the environment. Due to that, this impact calculation is shown as minus impact in Figure 5.11. In this process, the highest amount of water is consumed for electricity generation similar to scenario 1.

Comparison between Scenario 1 and Scenario 2 water consumption impact

Both situations have a common fact of high water consumption from hydropower electricity production. This is highly important because a lot of water is used during the operation of the hydroelectric power plants. The impact level of the two scenarios differs because of the different amounts of electricity that is being used during the processes.

Another main difference in the water consumption of these two processes is shown through the digested sludge. In Scenario 1 there is a negative impact on the environment through water. The sludge treatment does not provide any positive impacts related to the water consumption or quality. Scenario 2, It provides a positive impact on the environment through wastewater converting to Normal water. figure 2.15 shows a summary result of both scenarios' water consumption impacts.

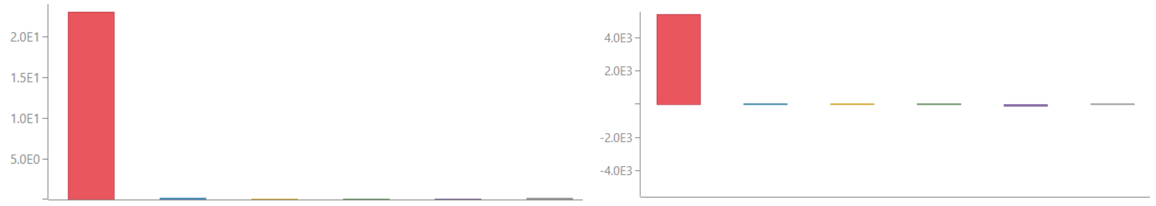


Figure 5.12 water consumption impact by scenario 1 and scenario 2

In the case of biogas production, the ReCiPe (2016) Midpoint (H) assessment technique is adopted to assess various environmental impacts. This study focuses on four specific impact categories: Global Warming, Human Non-Carcinogenic Toxicity, Terrestrial Ecotoxicity, and Water Consumption. These categories are selected due to their relevance to the primary environmental concerns associated with biogas production: global warming, soil, air, and water pollution. Above, each section (5. 1 to 5. 4) discusses the effects on humans, air, soil and water in detail. Moreover, this impacts calculations covering two different processes. The total result comparison and sensitivity analysis are illustrated below.

5.5 Sensitivity Analysis

Due to a lack of data, the impact calculations are done by changing most significant input and output that directly impact to the environment. Emission amounts vary with feedstock composition and Lack of Electricity usage data, this sensitivity analysis focuses on those criteria. By changing electricity and emission values, impact results were calculated to identify the minimum and highest possibilities of impact during the fluctuation of those inputs and outputs.

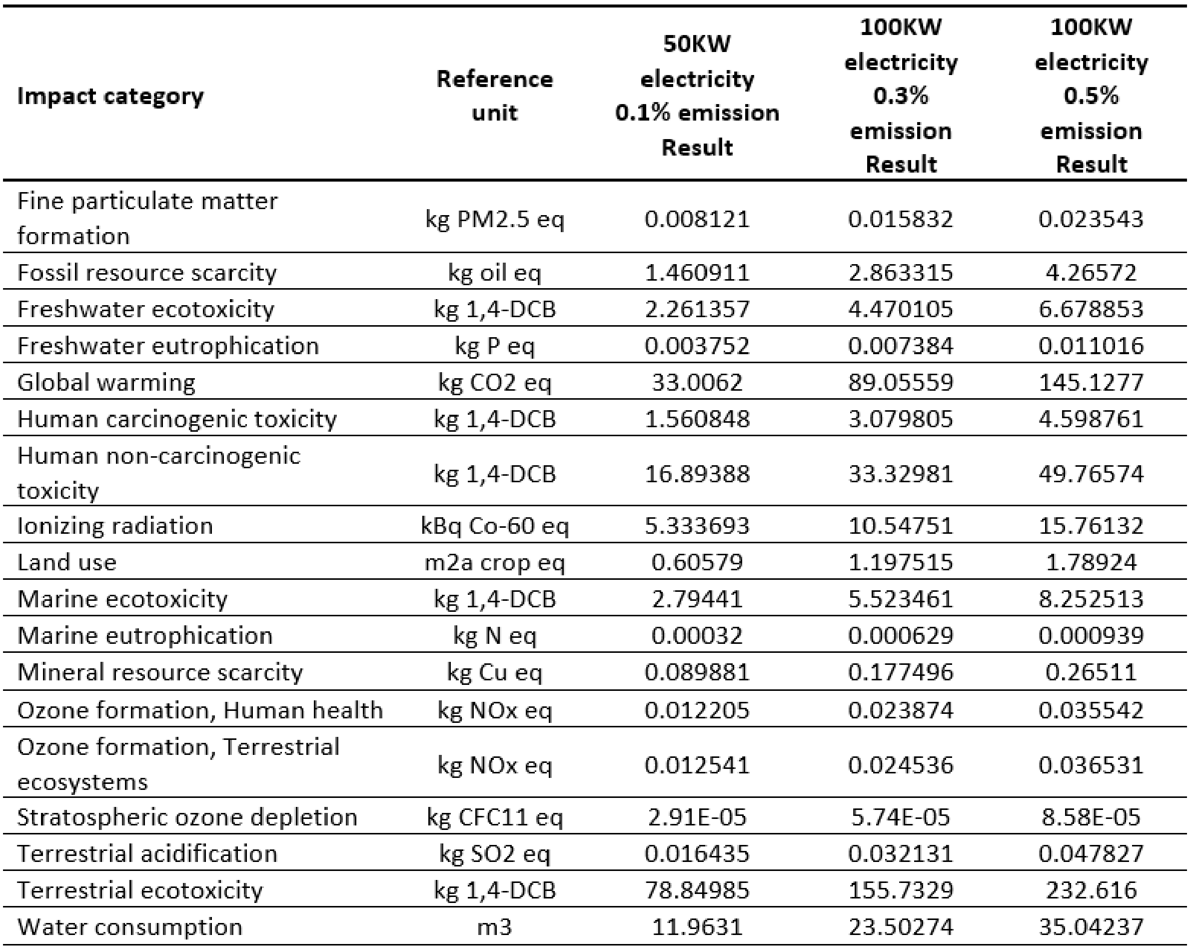
5.5.1 Scenario 1 Sensitivity Analysis

In scenario 1 sensitivity analysis baseline parameters are established by calculating the most suitable electrical equipment energy consumption requirements. In this analysis, 100KW electricity with 0.3 % emission criteria was used as a baseline parameter. Table 5.1 shows Sensitivity Analysis summary data in scenario 1

The upper bound and lower bound were fixed by adding 50 KW to the baseline For the upper bound and reducing 50 from the baseline for the lower bound. The Emission level baseline is assumed by the lowest probability of emission that can be emitted from the total biogas production

- Baseline – 100KW electricity input and 0.3 % emission output per day
- Lower bound – 50KW electricity input and 0.1 % emission output per day
- Upper bound – 150KW electricity input and 0.5 % emission output per day

Table 5.1 Scenario 1 Sensitivity Analysis Summary



Impact category	Reference unit	50KW electricity 0.1% emission Result	100KW electricity 0.3% emission Result	100KW electricity 0.5% emission Result
Fine particulate matter formation	kg PM2.5 eq	0.008121	0.015832	0.023543
Fossil resource scarcity	kg oil eq	1.460911	2.863315	4.26572
Freshwater ecotoxicity	kg 1,4-DCB	2.261357	4.470105	6.678853
Freshwater eutrophication	kg P eq	0.003752	0.007384	0.011016
Global warming	kg CO2 eq	33.0062	89.05559	145.1277
Human carcinogenic toxicity	kg 1,4-DCB	1.560848	3.079805	4.598761
Human non-carcinogenic toxicity	kg 1,4-DCB	16.89388	33.32981	49.76574
Ionizing radiation	kBq Co-60 eq	5.333693	10.54751	15.76132
Land use	m2a crop eq	0.60579	1.197515	1.78924
Marine ecotoxicity	kg 1,4-DCB	2.79441	5.523461	8.252513
Marine eutrophication	kg N eq	0.00032	0.000629	0.000939
Mineral resource scarcity	kg Cu eq	0.089881	0.177496	0.26511
Ozone formation, Human health	kg NOx eq	0.012205	0.023874	0.035542
Ozone formation, Terrestrial ecosystems	kg NOx eq	0.012541	0.024536	0.036531
Stratospheric ozone depletion	kg CFC11 eq	2.91E-05	5.74E-05	8.58E-05
Terrestrial acidification	kg SO2 eq	0.016435	0.032131	0.047827
Terrestrial ecotoxicity	kg 1,4-DCB	78.84985	155.7329	232.616
Water consumption	m3	11.9631	23.50274	35.04237

In this scenario Lower bound shows a lower impact and the upper bound shows a higher impact related to the other two bounds. No negative value in the summary list shown in Table 5.1 means no positive impact from these 3 different stages. The lower bound scenario shows the lowest environmental impact in all categories evaluated, as measured across all indicators. The upper bound scenario shows the highest environmental impact compared to the other two scenarios. The lowest bound scenario always produces the least environmental impact, and the upper bound scenario always produces the most significant impact. The baseline case is in between, representing moderate effects. This obvious trend demonstrates that the reduction of the consumption of electricity and the control of emissions can significantly reduce the environmental impacts of biogas production.

In addition to that all result increase with the incresement of energy and Emission values. therefore It can be consider, usage of electricitiy and the percentage of emission is increased the impact value will increase propotionally.

5.5.2 Scenario 2 Sensitivity Analysis

In scenario 2 sensitivity analysis follows the same baseline and lower and upper bound related to scenario 1.

- Baseline – 100KW electricity input and 0.3 % emission output per day
- Lower bound – 50KW electricity input and 0.1 % emission output per day
- Upper bound – 150KW electricity input and 0.5 % emission output per day

Table 5.2 illustrates the analysis data summary of the different levels. In this stage. According to the summary, it shows lower-bound results have a lower impact and upper-bound results with higher impact. These 3 levels of impact are increased with the electricity and emission variability. From 50 KW to 150KW range, the upper bound impact is 5 times higher than the lower bound. In this scenario water consumption impact is significantly high. It has as positive impact to the environment.

Table 5.2 Table 5.3 Scenario 1 Sensitivity Analysis Summary

Impact category	**Reference unit**	**50KW electricity 0.1% emission Result**	**100KW electricity 0.3% emission Result**	**150KW electricity 0.1% emission Result**
Fine particulate matter formation	kg PM2.5 eq	1.58257	6.171258	7.742828177
Fossil resource scarcity	kg oil eq	208.4629	902.4664	1188.28994
Freshwater ecotoxicity	kg 1,4-DCB	275.4855	1777.603	2227.766951
Freshwater eutrophication	kg P eq	0.56871	2.319697	3.059872635
Global warming	kg CO2 eq	1165.41	5428.605	7328.831391
Human carcinogenic toxicity	kg 1,4-DCB	182.8365	913.4937	1223.071654
Human non-carcinogenic toxicity	kg 1,4-DCB	2416.101	11716.36	15066.15526
Ionizing radiation	kBq Co-60 eq	459.9008	2538.594	3601.219706
Land use	m2a crop eq	62.88176	298.0458	418.6450822
Marine ecotoxicity	kg 1,4-DCB	340.5745	2185.256	2741.463233
Marine eutrophication	kg N eq	1.034728	1.235156	1.298203756
Mineral resource scarcity	kg Cu eq	10.73252	52.93588	70.792545
Ozone formation, Human health	kg NOx eq	1.864678	7.821846	10.20007127
Ozone formation, Terrestrial ecosystems	kg NOx eq	1.91507	8.040211	10.48495526
Stratospheric ozone depletion	kg CFC11 eq	0.005328	0.020948	0.026730201
Terrestrial acidification	kg SO2 eq	3.14904	12.72391	15.92289345

Terrestrial ecotoxicity	kg 1,4-DCB	8846.076	53853.43	69522.93084
Water consumption	m3	834.3446	5369.658	7721.546948

5.6 Comparison between Scenario 1 and Scenario 2.

Scenarios 1 and 2 both produce methane from municipal sludge using the same feedstock amount but with different production processes. In Scenario 1, a commissioned plant in Norway, a general biogas production process is applied. Scenario 2, however, comprises an alternative production process that takes into account the problems found in Scenario 1.

Key Differences between Scenario 1 and Scenario 2 related to Digester Sludge.

1. Digested Sludge Management:

Scenario 1: The most important problem in this case is the removal of digested sludge. The sludge generated requires proper management before it is allowed to be discharged into the environment. This management process requires approximately six months of treatment to reduce its ecological impact.

Scenario 2: This scenario has the effect of bringing the generation of digested sludge down to 1% due to the addition of a pyrolysis process with anaerobic digestion (AD). The pyrolysis process ensures that there are no total solids (TS) in the AD feed, which leads to minimal sludge production and the effective removal of wastewater from the AD unit.

2. Sludge Generation:

Scenario 1: Produces a larger volume of digested sludge that needs to be dealt with through treatment and disposal.

Scenario 2: It generates much less sludge (1% of the input) which is a result of the combined AD and pyrolysis process that hugely reduces the overall sludge burden.

Key Differences between Scenario 1 and Scenario 2 related to final production.

Both Scenarios 1 and 2 concentrate on the production of methane from municipal waste sludge, but they differ greatly in terms of the amount of methane and the process by-products due to the addition of the pyrolysis process in Scenario 2.

- Scenario 1:Methane Production: 3310 m^3 per day.
  Process: This scenario applies a general biogas production process, that is designed to maximize the production of methane from the given feedstock
- Scenario 2:Methane Production: 1195 m^3 per day.
  Process: In this case, the manufacturing process utilizes the combination of pyrolysis and anaerobic digestion (AD). The mixture of these two processes does not only deal with serious sludge problems but also produces less methane than in Scenario 1.

Key Differences between Scenario 1 and Scenario 2 related to LCA Results.

LCA results show a significant difference between the two scenarios. Sections 5.1 to 5.2 show detailed information about the main impacts of the methane production process. Figure 5.13 shows Recipe 2016 Midpoint (H) Impact analysis method 18 impact results summary of Scenario 1 and 2 with sensitivity analysis in methane production.For more information refer Appendix B

Scenario 1: The bar chart shows that Scenario 1, on average, shows lower environmental impacts than Scenario 2. This situation is based on enhancing the production of methane using a common biogas production process.

Scenario 2: Nevertheless, Scenario 2 is more advanced since it combines anaerobic digestion (AD) with pyrolysis, but it has higher effects in many categories. This is because the pyrolysis process requires more energy and emissions which are then multiplied by the number of by-products produced.

The LCA shows that Scenario 1 has generally lower environmental impacts in most categories when compared to Scenario 2. This is mainly because Scenario 1 involves fewer processing steps which results in lower energy consumption and emissions. Scenario 2 focuses on the main environmental issue of sludge management from digested sludge. The pyrolysis process not only reduces sludge production but also converts waste into valuable by-products. Even though Scenario 2 is more complex and demanding in terms of resources, this option provides the solution to the sludge management problem that Scenario 1 is unable to solve.

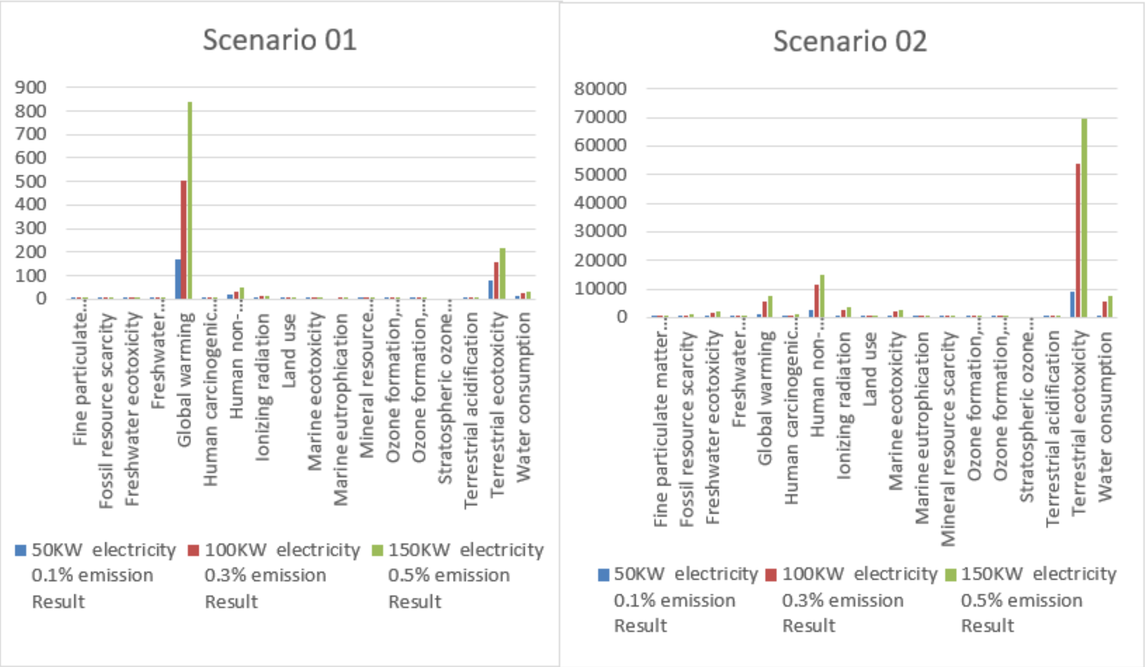


Figure 5.13 Recipe 2016 Midpoint (H) Impact analysis method 18 imapct results summary of Senario 1 and 2 with sensitivity analysis in methane production.

The sensitivity analysis reveals that scenario 1 is more resilient under different conditions of electricity consumption and emission rates. Scenario 2 on the other hand shows greater variability in effect as a result of its complex process and high resource intensity. This scenario’s ability to produce multiple by-products and how it deals with the sludge is a good demonstration of its environmental advantages. This life cycle assessment lays on cradle to cradle-to-gate principle. Due to that above result shows a significant difference and impact to the environment. Scenario 2 includes more processes than Scenario 1 and Scenario 2 process is more complicated than Scenario 1. By Scenario 2 production process directly addresses significant environmental problems and that solution creates a positive impact on the system. Table 5.3 shows the end product quantity summary of two scenarios. Table 5.3 clearly shows a higher amount of methane produced by Scenario 1 however, scenario 1 waste output is considerably higher than Scenario 1.

Table 5.4 End product quantity summary

	Methane (m$^{3/}$day)	CO$_2$ (m$^{3/}$day)	Digested waste Kg	Biochar (m$^{3/}$day)	Syngas (m$^{3/}$day)
Senario 1	3310.4	4663	10895	0	0
Senario 2	1820.44	415.97	98	11.494	2.91

Currently, this waste sludge management and impact from this waste sludge is a significant issue in biogas production. Moreover, scenario 2 produces biochar and syngas as a byproduct these products positively impact the LCA analysis. Biocahr acts as a carbon saver to the environment.Amount of this scenario 2 produced carbon equals to 17.40 m$^{3/}$day of carbone save.Due to these reasons scenario 2 impact can be reduce by calculating Cradle to grave model LCA.

6 Conclusion

This study identified the environmental impacts of two different biogas production scenarios using municipal sludge as the feedstock by Comparing the general anaerobic digestion process (Scenario 1) with the process that integrates pyrolysis–biogas production (Scenario 2). The main objective was to identify and quantify the environmental impacts of these two production pathways, with a particular focus on methane production and the management of digested sludge. To achieve this, the Life Cycle Assessment (LCA) approach enabled to systematic comparison of the environmental impact of both scenarios from cradle to gate.

This study addressed some issues such as the environmental impacts of methane production compared between the two scenarios, and the implications of digested sludge management in each scenario. LCA calculations illustrate that Scenario 2, which combines anaerobic digestion with pyrolysis, has an immediate environmental impact compared to Scenario 1. However, Scenario 1 results in a higher amount of digested sludge, which causes significant environmental impacts if not managed properly.

In Scenario 2 integration of the pyrolysis process leads to the production of biochar and syngas as valuable byproducts. These byproducts have the potential to provide long-term positive environmental benefits, such as carbon sequestration through biochar application and the generation of additional energy from syngas. Moreover, the initial environmental impact of Scenario 2 is higher, its end products contribute positively to environmental sustainability. The study's calculations focused exclusively on the production process impacts, indicating that the overall environmental footprint of Scenario 2 could be mitigated by considering the benefits of its byproducts.

In conclusion, this assessment analyze the importance of balancing process efficiency with environmental sustainability in biogas production. Although Scenario 2 appears to have a higher immediate environmental impact, its more complex process directly addresses significant environmental issues related to digested sludge management. The potential long-term benefits of integrating pyrolysis, such as reduced waste and valuable byproducts, suggest that Scenario 2 could become a more sustainable approach to biogas production with improvements in energy efficiency and emissions control. This highlights the need for ongoing innovation and optimization to achieve both efficient and environmentally friendly biogas production.

7 Future Works

Based on the above research outcomes, there are various ways through which further studies can greatly help to develop knowledge and advance in the optimization of the processes of biogas production.

Cradle-to-Grave Analysis

For future work, it is significant to evaluate the Full Cradle Grave Life Cycle Assessment (LCA) of methane production in association with the pyrolysis process. This would involve a deeper analysis that is beyond the cradle-to-gate system investigated in the current study and also involves the use, end-of-life processes, recycling or disposal of byproducts. That way, the assessment would focus on the positive effects on the environment and negativity, which would make it easier to depict the extent of sustainable implementation of pyrolysis with anaerobic digestion.

Pyrolysis and Nutrient Retention

One more great direction for future research is to examine the LCA for the idea of pyrolyzing the solid fraction of the digestate and utilizing the liquid fraction with the help of nutrient retention improvements. In particular, the study will look at how pyrolysis can transform the solid digestate into biochar and how the liquid fraction of it can help retain the nutrients, as to determine whether it can improve the nutrient cycle and soil condition for a better environment, eliminating the need for chemical fertilizer, and therefore benefiting the environmental aspect of the biogas production process.

Emissions from Waste Sludge

Furthermore, it would also be beneficial to investigate the quantity of methane and carbon dioxide released from waste sludge when this material is taken out from the AD. Analyzing the emission characteristics of the waste sludge at the post-AD treatment phase is important to establish the possibility of the waste sludge having an adverse effect on the environment as well as the odds of minimizing the wastes' emissions. This could include exploring the options open for digested sludge management that involves storage, additional treatment, or land application in order to weigh their emissions impact.

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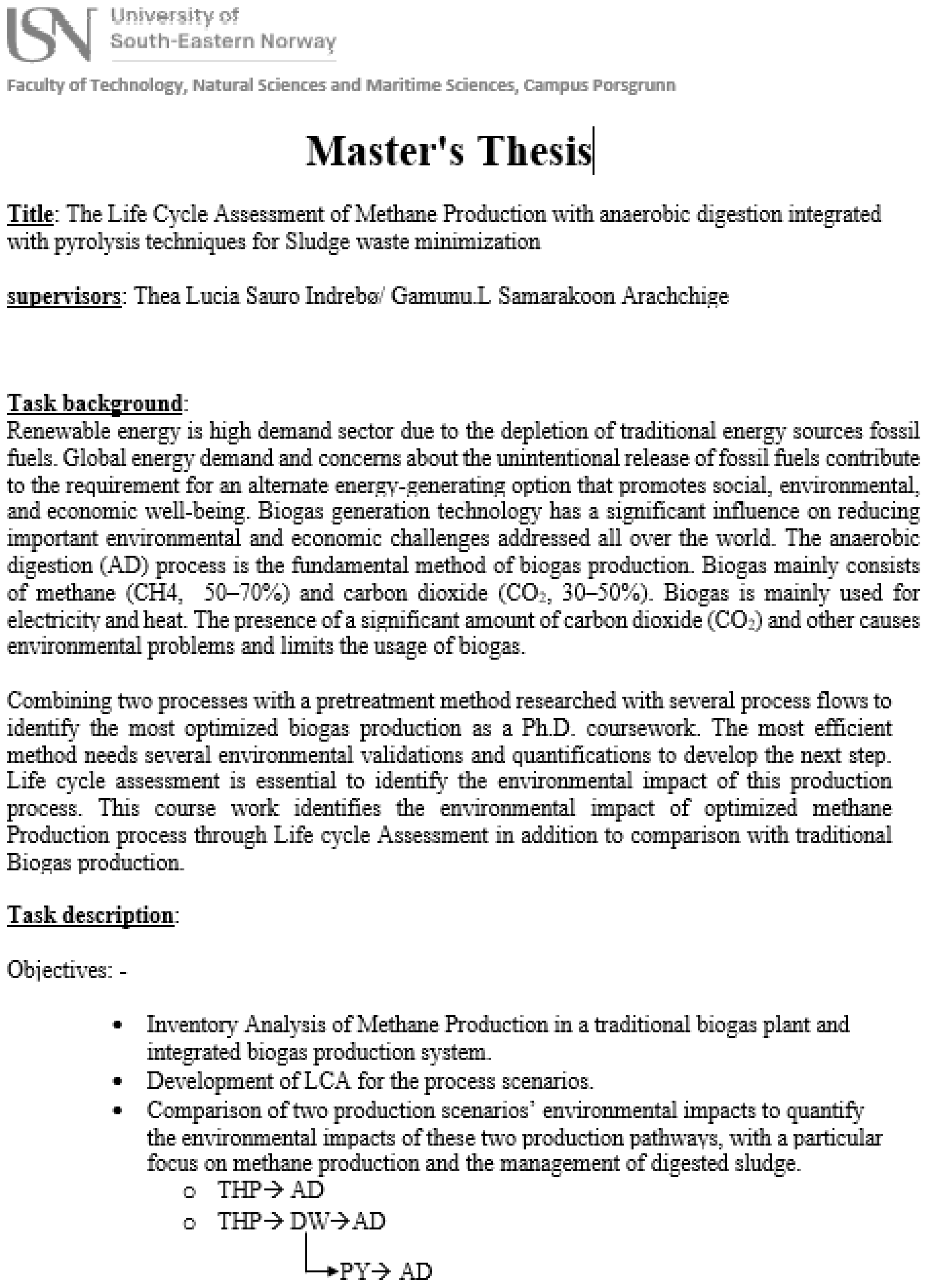
9 Appendices

9.1 Appendix A: Task Description



University of
South-Eastern Norway

Faculty of Technology, Natural Sciences and Maritime Sciences, Campus Porsgrunn

Master's Thesis

Title: The Life Cycle Assessment of Methane Production with anaerobic digestion integrated with pyrolysis techniques for Sludge waste minimization

supervisors: Thea Lucia Sauro Indrebø/ Gamunu.L Samarakoon Arachchige

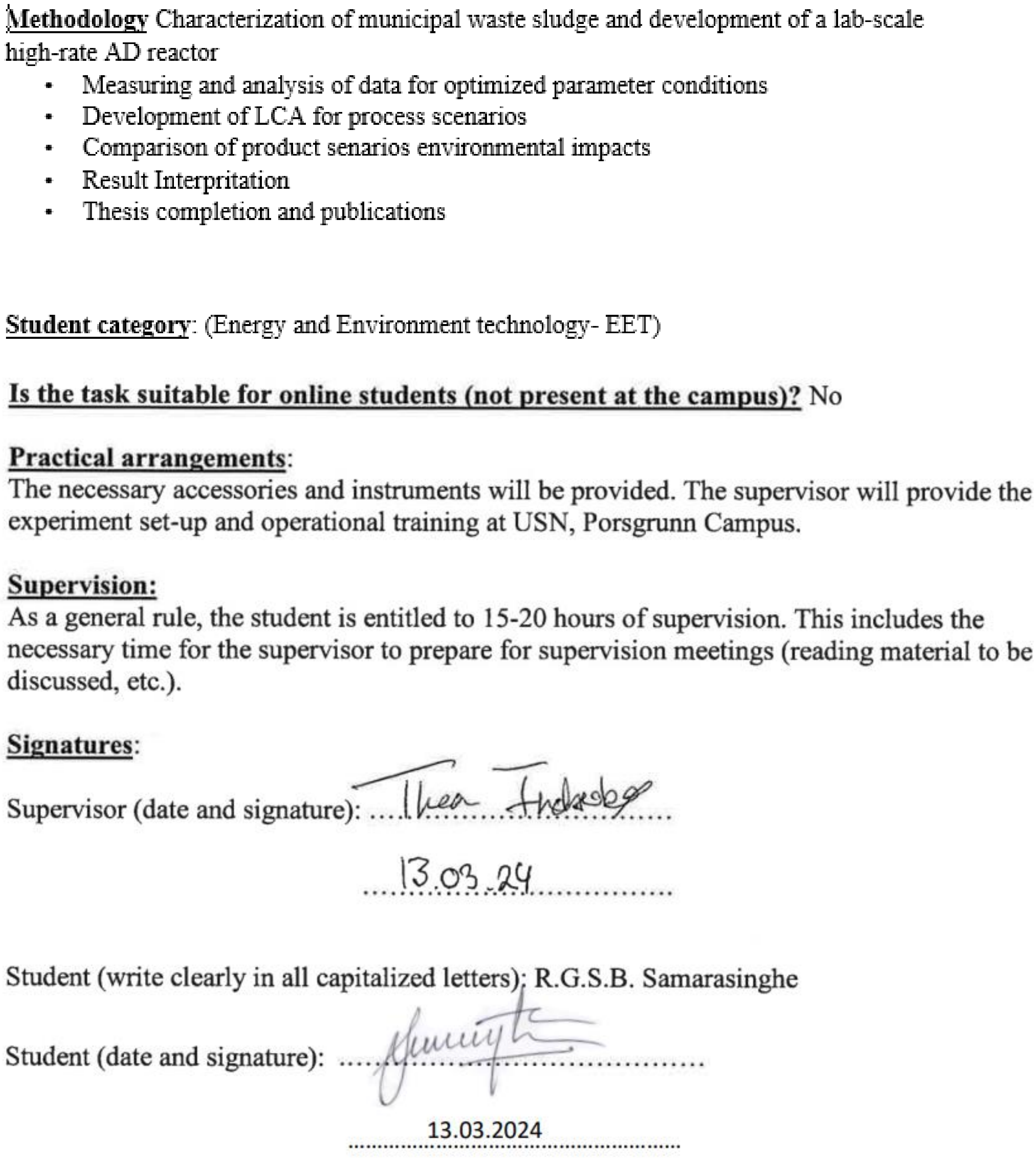
Task background:
Renewable energy is high demand sector due to the depletion of traditional energy sources fossil fuels. Global energy demand and concerns about the unintentional release of fossil fuels contribute to the requirement for an alternate energy-generating option that promotes social, environmental, and economic well-being. Biogas generation technology has a significant influence on reducing important environmental and economic challenges addressed all over the world. The anaerobic digestion (AD) process is the fundamental method of biogas production. Biogas mainly consists of methane (CH4, 50–70%) and carbon dioxide (CO_2, 30–50%). Biogas is mainly used for electricity and heat. The presence of a significant amount of carbon dioxide (CO_2) and other causes environmental problems and limits the usage of biogas.

Combining two processes with a pretreatment method researched with several process flows to identify the most optimized biogas production as a Ph.D. coursework. The most efficient method needs several environmental validations and quantifications to develop the next step. Life cycle assessment is essential to identify the environmental impact of this production process. This course work identifies the environmental impact of optimized methane Production process through Life cycle Assessment in addition to comparison with traditional Biogas production.

Task description:

Objectives: -

- Inventory Analysis of Methane Production in a traditional biogas plant and integrated biogas production system.
- Development of LCA for the process scenarios.
- Comparison of two production scenarios' environmental impacts to quantify the environmental impacts of these two production pathways, with a particular focus on methane production and the management of digested sludge.
    - THP→ AD
    - THP→ DW→AD
      └→PY→ AD



Methodology Characterization of municipal waste sludge and development of a lab-scale high-rate AD reactor

- Measuring and analysis of data for optimized parameter conditions
- Development of LCA for process scenarios
- Comparison of product senarios environmental impacts
- Result Interpritation
- Thesis completion and publications

Student category: (Energy and Environment technology- EET)

Is the task suitable for online students (not present at the campus)? No

Practical arrangements:
The necessary accessories and instruments will be provided. The supervisor will provide the experiment set-up and operational training at USN, Porsgrunn Campus.

Supervision:
As a general rule, the student is entitled to 15-20 hours of supervision. This includes the necessary time for the supervisor to prepare for supervision meetings (reading material to be discussed, etc.).

Signatures:

Supervisor (date and signature): Thea Indrebø

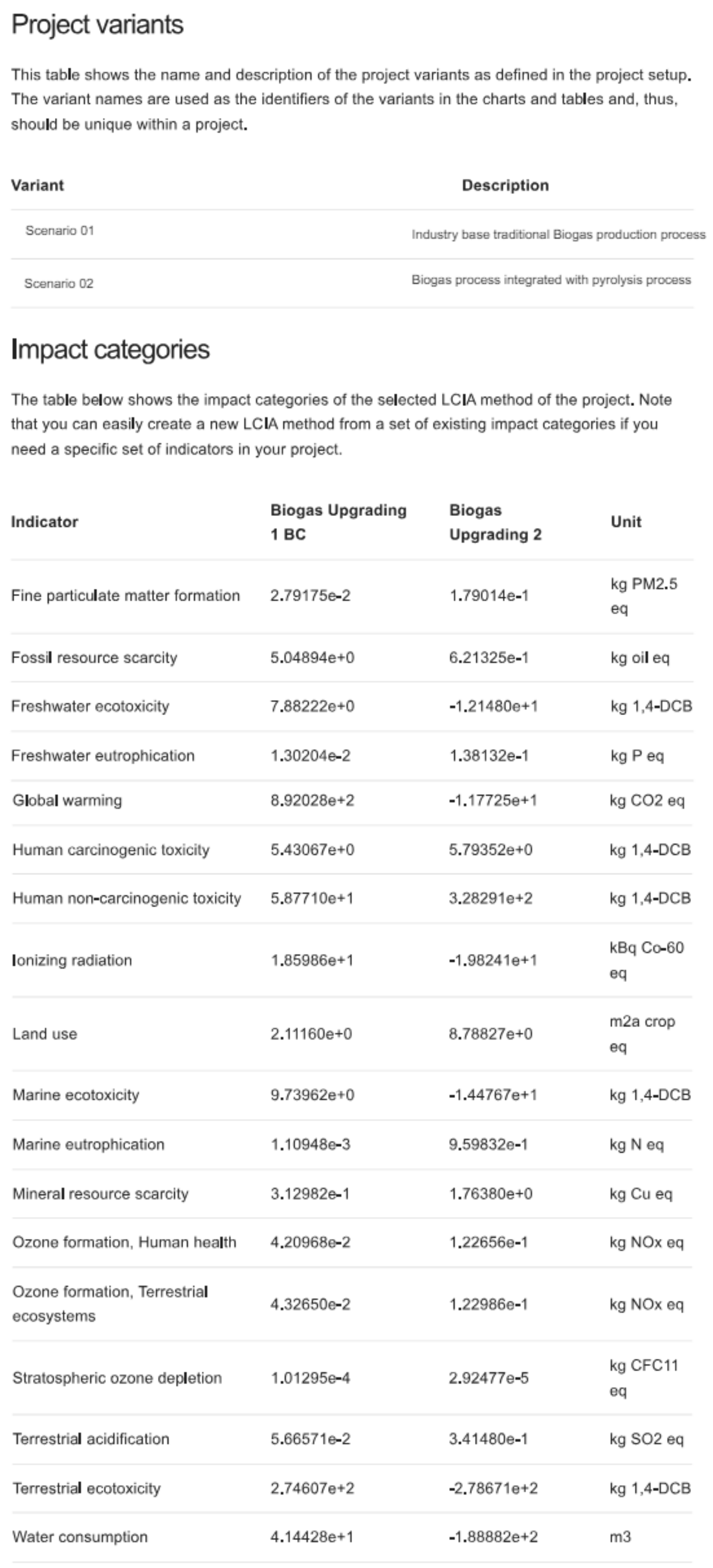
13.03.24

Student (write clearly in all capitalized letters): R.G.S.B. Samarasinghe

Student (date and signature):

13.03.2024

9.2 Appendix B: Scenario 1 and Scenario 2, 0.3 % emission impact calculated comparison report



Project variants

This table shows the name and description of the project variants as defined in the project setup. The variant names are used as the identifiers of the variants in the charts and tables and, thus, should be unique within a project.

Variant	Description
Scenario 01	Industry base traditional Biogas production process
Scenario 02	Biogas process integrated with pyrolysis process

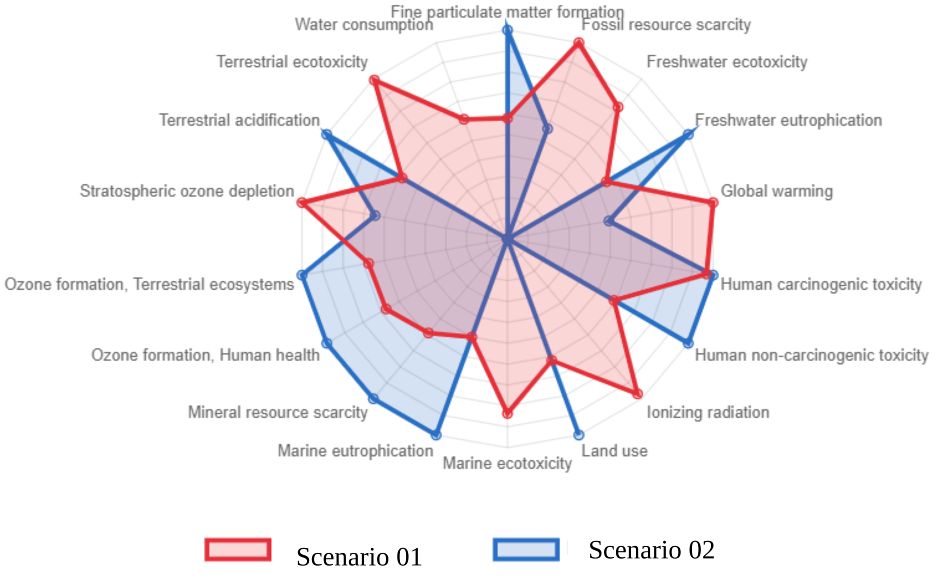
Impact categories

The table below shows the impact categories of the selected LCIA method of the project. Note that you can easily create a new LCIA method from a set of existing impact categories if you need a specific set of indicators in your project.

Indicator	Biogas Upgrading 1 BC	Biogas Upgrading 2	Unit
Fine particulate matter formation	2.79175e-2	1.79014e-1	kg PM2.5 eq
Fossil resource scarcity	5.04894e+0	6.21325e-1	kg oil eq
Freshwater ecotoxicity	7.88222e+0	-1.21480e+1	kg 1,4-DCB
Freshwater eutrophication	1.30204e-2	1.38132e-1	kg P eq
Global warming	8.92028e+2	-1.17725e+1	kg CO2 eq
Human carcinogenic toxicity	5.43067e+0	5.79352e+0	kg 1,4-DCB
Human non-carcinogenic toxicity	5.87710e+1	3.28291e+2	kg 1,4-DCB
Ionizing radiation	1.85986e+1	-1.98241e+1	kBq Co-60 eq
Land use	2.11160e+0	8.78827e+0	m2a crop eq
Marine ecotoxicity	9.73962e+0	-1.44767e+1	kg 1,4-DCB
Marine eutrophication	1.10948e-3	9.59832e-1	kg N eq
Mineral resource scarcity	3.12982e-1	1.76380e+0	kg Cu eq
Ozone formation, Human health	4.20968e-2	1.22656e-1	kg NOx eq
Ozone formation, Terrestrial ecosystems	4.32650e-2	1.22986e-1	kg NOx eq
Stratospheric ozone depletion	1.01295e-4	2.92477e-5	kg CFC11 eq
Terrestrial acidification	5.66571e-2	3.41480e-1	kg SO2 eq
Terrestrial ecotoxicity	2.74607e+2	-2.78671e+2	kg 1,4-DCB
Water consumption	4.14428e+1	-1.88882e+2	m3

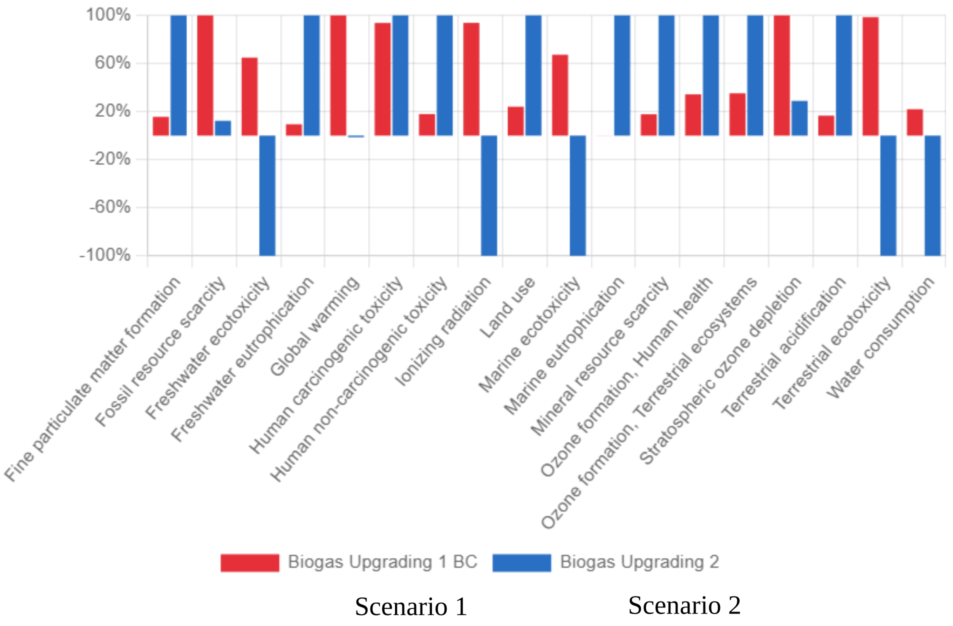
Impact assessment results

The table below shows the impact assessment results of the different project variants.



Relative results

The chart below shows the relative indicator results of the respective project variants. For each indicator, the maximum result is set to 100% and the results of the other variants are displayed in relation to this result.



9 Appendices