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Life Cycle Assessment of Bioelectrochemical System for Biogas Upgradation

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Summary:

The raise in population, technology and infrastructure development is directing the present towards the future of high energy demand. The reduce the consumption of the fossil fuel, renewable energy sector should be boosted for a green and clean future. Bioelectrochemical system has been proven an effective technology for biogas upgrading. Therefore, it is necessary to conduct life cycle assessment (LCA) studies based on the BES system for biogas upgrading to evaluate the potential for the purpose of commercialization.

In this study, two systematic literature reviews were performed i.e. BES system for biogas upgrading and the LCA of BES system, to understand the fundamental and gap of the BES system for biogas upgrading and LCA. Most of the research papers were found on Scopus and Web of Science using search strings.

The objective of this research is to conduct a life cycle assessment using for the bioelectrochemical system for biogas upgrading. The LCA is performed using OpenLCA software and Database from Eco-invent. The cradle to gate LCA study includes the impact categories such as Global warming potential (100a), Acidification, Eutrophication and Human Toxicity potential using CML-IA baseline method.

It is difficult to evaluate the LCA of lab scale-based experiments due to the small input quantities, therefore the input components were scaled up and normalized the system operation for a year. Platinum showed the major contributor to Global warming potential, acidification, eutrophication and human toxicity. A comparative LCA study was performed in between platinum and nickel contribution to the environmental impacts. Platinum has shown higher contribution to GWP, acidification, eutrophication and HTP as compared to Nickel.

Preface

The Master thesis with the title “Life Cycle Assessment of Bioelectrochemical System for Biogas Upgradation” was done to fulfill the requirement of the FMH606 Master's Thesis, exchange program at the University of South-Eastern Norway (USN), Porsgrunn and master’s thesis course at the Kathmandu University. The exchange program is funded by NORPART Re-Tech project.

I would like to extend my sincere gratitude to my supervisors, Anish Ghimire, Sunil Prasad Lohani, Nabin Aryal and Zahir Barahmand for their supervision, expert guidelines, and support throughout the thesis work.

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Porsgrunn, 26.01.2024

Rajani Neupane

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Nomenclature

LCA	Life Cycle Assessment
BES	Bioelectrochemical System
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
CH_4	Methane
CO_2	Carbon Dioxide
GWP	Global Warming Potential
HTP	Human Toxicity Potential
CTC	Cradle to Cradle
CTG	Cradle to Gate
AP	Acidification Potential
ROW	Rest of the World (As per Eco invent database)
RER	Rest of Europe Region (As per Eco invent database)
GLO	Global (As per Eco invent database)
AD	Abiotic depletion
EP	Eutrophication Potential
ILCD	International Life Cycle Data System
MFC	Microbial Fuel Cells
MEC	Microbial Electrolysis Cells
MES	Microbial Electrosynthesis
MSC	Microbial Solar Cells
MDC	Microbial Desalination Cells
SHE	Standard Hydrogen Electrode
AD	Anaerobic Digestion
H_2O	Water
H_2	Hydrogen
ISO	International Organization for Standardization
EPD	Environmental Product Decleations
H_2S	Hydrogen Sulfide
BOD	Biological Oxygen Demand
COD	Chemical Oxygen Demand
ILCD	The International Reference Life Cycle Data System
IrO_2	Iridium Oxide
Ti	Titanium
Pt	Platinum
C	Carbon
Ni	Nickel
FU	Functional Unit
ODP	Ozone Layer Depletion

HT	Human Toxicity
TE	Terrestial Ecotoxicity
FWAE	Freshwater Aquatic Ecotoxicity
MAE	Marine Aquatic Ecotoxicity
PO	Photochemical Oxidation
PM	Particulate Matter
IR	Ionising Radiation
POF	Photochemical Ozone Formation
GHG	Greenhouse Gas
FE	Freshwater Eutrophication
GW	Global Warming
TA	Terrestrial Acidification
FRS	Fossil Resource Scarcity
MRS	Mineral Resource Scarcity
HCT	Human Carcinogenic Toxicity
SOD	Stratospheric Ozone Depletion
CED	Cumulative Energy Demand
WC	Water Consumption
eq	Equivalent

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1 Introduction

1.1 Background

The high demand for energy consumption by the increasing population as well as the development activities like building infrastructure, upgrading technologies, etc. in the modern age and in the future requires high energy production. And depending on the fossil fuel to fulfill the requirements is not an environmentally friendly solution [1]. Thus, the sustainable energy solutions may be found in renewable energy sources like hydro, wind, solar, and biogas to issues like human health, the environment, and climate change [2]. Biogas has more advantages than others as a renewable energy source. This is because biogas can be generated during wastewater treatment, solid waste management, serving as an alternative to fossil fuels, greenhouse gas reduction, etc, [3]. Biogas consists the 50-70% methane (CH_4) and 30-50% carbon dioxide (CO_2) produced by the anaerobic digestion process. Production and utilization of biogas can bring a greener future. Fertilizers as waste generated by Biogas can be used for agriculture purposes [4] [5]. It is important to improve the biogas quality by removing impurities such as CO_2, H_2s, etc. to use pure biogas in automobiles, adding it to the natural gas network and fuel cells and so on [6]. The process of treating raw biogas to remove harmful substances is known as biogas upgrading. The conventional methods of biogas upgrading such as water scrubbing, pressure swing adsorption, membrane separation, etc. are used for the biogas upgrading [7].The operation cost of conventional methods of biogas treatment is higher and it also causes negative impacts on the environment. Therefore, researchers have studied and found a new sustainable and environmental solution which is a biological method for biogas upgradation [8]. In biological methods microbes and photosynthetic microalgae are effective for CO_2 utilization from biogas. The bioelectrochemical system (BES) is a developing technology that uses microorganisms which are capable of electrochemical reactions. These electrochemical reactions help in the conversion of organic compounds into rich energy products or valuable chemicals [7].

BES is an emerging technology which is useful for biogas upgrading. This system reduces CO_2 content and increases the methane concentration. It also helps to improve overall biogas quality. BES and biogas upgrading are still ongoing research [9]. Researchers are still working on these two areas i.e. BES and biogas upgrading and also working on its further advancement to optimize the system designs, electrode materials, and microbial communities for an efficient and scalable biogas upgrading process [10].

It is important to conduct further research on these systems to enhance performance and also make plans for scaling up the technology, checking its potential to end users. Life cycle assessment studies of these systems are limited therefore conducting LCA studies is important for sustainable solutions [11].

1.2 Statement of the problem

Researchers have made amazing progress in the development of laboratory-scale BES systems in the past few years. A systematic literature review is done for BES for biogas upgrading and

LCA in chapter number 3. These developments have demonstrated possibilities for biogas upgradation in a number of areas, including reactor design and the use of CO_2 fraction. Although BES technologies exhibit potential as economical and sustainable solutions for biogas upgrading, there aren't many thorough life cycle evaluations that study the environmental effects of BES throughout their whole life cycle. Our comprehension of the sustainability and possible trade-offs related to using BES for biogas upgrading is hampered by this information gap. Thus, to evaluate the environmental performance of the BES system, a comprehensive life cycle assessment study is required.

1.3 Research Questions

1. What are the environmental impacts of the Bioelectrochemical system for biogas upgrading throughout its cradle-to-gate?
2. What will be the Global warming potential, Acidification, Eutrophication, and Human toxicity potential using the CML-IA baseline method?
3. Which input component used during the operation phase will impact the environment comparatively more than other input components?

1.4 Objectives

General Objective:

a. To carry out a thorough evaluation of the environmental impacts produced by different components of the bioelectrochemical system for biogas upgrading throughout its operation phase.

Specific Objectives:

a. To identify the Acidification, Eutrophication, Human Toxicity and Global Warming Potential impacts generated by the scaled-up input components of the lab scale experiment using CML-IA baseline method.
b. To perform a comparative LCA study in between Platinum and Nickel using CML-IA baseline method.

1.5 Approach and Methodology

This study is conducted to evaluate the potential environmental impacts of the bioelectrochemical system used to produce treated biogas through a cradle-to-gate approach. BES system may become an effective system for large-scale treated methane production if the small-scale study shows negligible negative environmental impacts. The literature review is done utilizing the scoping method and most of the research papers are found on Scopus and Web of Science using search strings. Due to the limited life cycle studies on the BES system, only a few research papers were found using a different filter such as article title, English language, and the period from 2021 to 2023. This study involves performing a life cycle assessment based on an experimental paper, The procedure of conducting literature review is explained in chapter number 3.

1.6 Scope

This study focuses only on the operational stage of the BES system for biogas upgrading. It is difficult to perform the LCA study of the BES lab scale-based experiment due to its small input quantities. Therefore, the lab scale input quantities are scaled up and environmental impacts for 1 year operation is calculated.

1.7 Limitations

Accurate data that adequately describe the life cycle evaluation was hard to find for the lab scale-based investigation. When estimating actual environmental consequences in operational settings, there were uncertainties due to the dependence on lab-scale data. The scope was restricted to the operating phase, so excluding the manufacture, building, and decommissioning stages of a full life cycle evaluation. This restriction could have affected the environmental impact assessment's overall accuracy. The electrode waste or after use part is not included in this study. It was also not investigated if the bioelectrochemical system could be economically implemented on a wide scale.

1.8 Target Group

The result of this thesis will be useful for the researchers to carry out further studies on LCA of bioelectrochemical systems for biogas upgrading. Also, it will be useful for the industries to make plannings to establish large-scale treated biogas plant and also help them to make more informed decisions.

2 Theoretical Background

2.1 Bioelectrochemical System

In Bioelectrochemical systems (BES) anode and cathode are separated by an ion exchange membrane. The oxidation takes place at the anode and reduction at the cathode. BES is a novel technology that can be useful for a sustainable future [8]. The BES has various advantages such as wastewater treatment efficient conversion of waste CO_2 into energy, useful for the transportation, and renewable energy [7]. Figure number 3 shows that the refined methane can be used as fuel in the bus.

BES can be divided into various groups i.e. Microbial fuel cells (MFC), Microbial electrolysis cells (MEC), Microbial electrosynthesis (MES), Microbial solar cells (MSC), and Microbial desalination cells (MDC) based on their operational modes and end products [2].

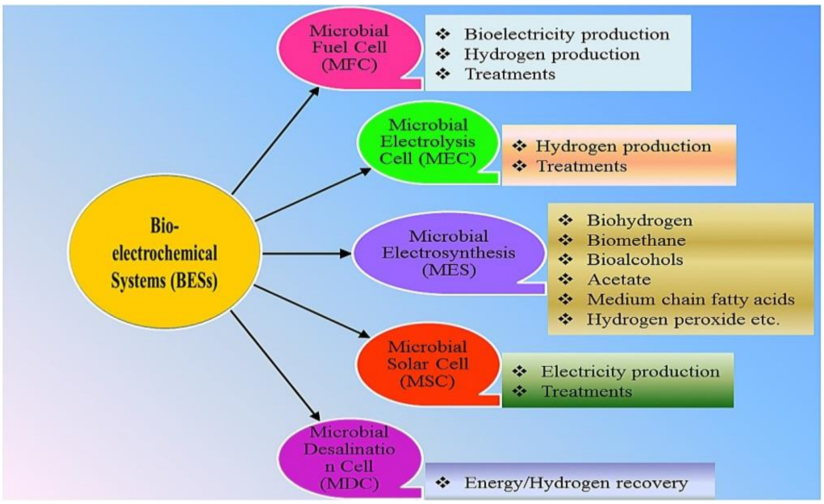


Figure 1: Schematic overview of various BES types [2]

BES types, based on the end products

i. Microbial Fuel Cell (MFC): The overall process of MFC is the conversion of organic matter into electrical energy [12].
ii. Microbial Electrolysis cells (MEC): The end products of MEC are hydrogen gas and hydrogen peroxide [12].
iii. Microbial Electrosynthesis (MES): The end products of MES are the renewable fuel and chemicals [12].
iv. Microbial solar cells (MSC): The end product of MSC is electrical energy generated from sunlight through the photosynthetic activity of microorganisms [12].
v. Microbial desalination cells (MDC): MDC is the process of removing salt from water and generate electrical energy [12].

2.1.1 Reactor design and configuration applied in BES biogas upgrading

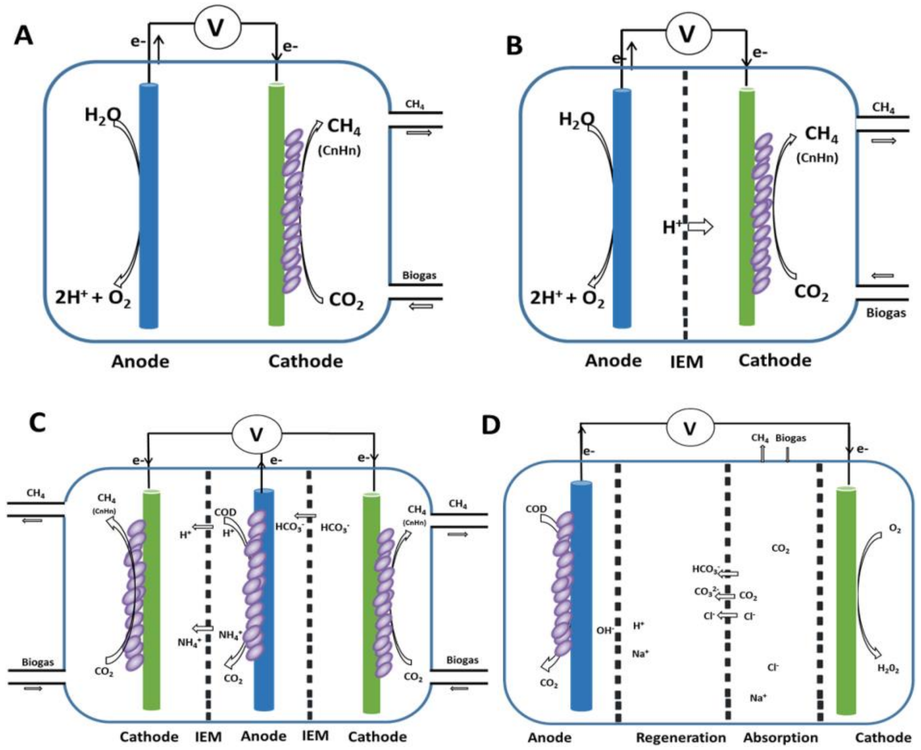


Figure 2: Reactor designs A) Single compartment configuration B) double compartments configuration C) triple compartments configuration and D) Four compartments configuration [7]

The survival of methanogens is significantly impacted by the oxygen (O_2) in the single-chamber system. The H-shaped reactor has two identical chambers which is the most widely used form of reactor in a compartment layout. Researchers developed three-compartment reactors to aid in the upscaling of BES with an accumulation chamber positioned between the anolyte and catholyte. Resource recovery is one of the advantages of multitasking with the multi-compartment system. However, there's a chance that this system would require more energy and that the reactor layout would become more complex [7].

Figure 3 : Upgraded biogas can be used as a vehicle fuel in buses (Source: photo captured at Porsgrunn Bus Station)

2.2 Introduction to Life Cycle Assessment and Software

Life Cycle Assessment (LCA) is a process that involves a systematic evaluation of a product or system's environmental impact throughout its entire life cycle. The literature review shows that there is a gap in a comprehensive LCA specific to the Bioelectrochemical system for biogas upgradation in chapter 3. Over the last couple of years, researchers have shown tremendous progress in laboratory-scale BES systems. This development has shown potential in various aspects such as CO_2 fraction utilization, reactor design, etc. for biogas upgradation [13]. However, the major challenge is the successful scaling up of BES technology from lab scale to the pilot large scale plant [14].

Life cycle study could play a vital role in the planning and decision making process of the large scale up plant. The life cycle assessment consists of four diffrent stages [15] (see figure number 4). The life cycle includes the difffrent stsges of the products or system’s entire cycle starting from the raw material extraction, manufacturing process, suppy chain, production phase, use and end phase.

The LCA has different approaches:

i. Cradle to Gate

ii. Cradle to Grave

iii. Cradle to Cradle

The cradle to gate consists of the chains from the extraction of raw material to the production of the product phase. The cradle to grave consists of from the raw material extraction, manufacturing, production, use to the disposal of the product phase and cradle to cradle consists from the end phase of disposal product to using it as a raw material.

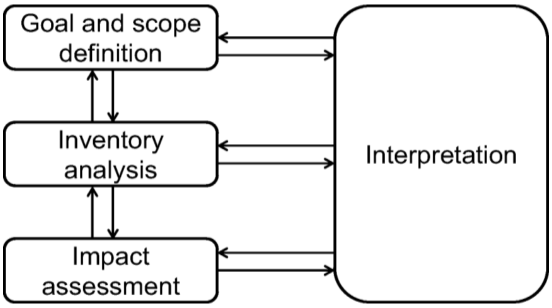


Figure 4: The four mandatory stages of a LCA, adapted from ISO (2006b)

The goal and scope include the objectives, system boundary and the functional unit of the LCA study. The next after defining the goal and scope is the inventory analysis which includes the inputs and outputs details related to the product or system. At the final stage i.e., interpretation consists a process of interpretating and identifying various environmental impacts like global warming potential, acidification, human toxicity etc. There are various impact methods in the LCA study such as CML-IA baseline, ReCiPe midpoint and endpoint etc. The impacts have various calculating unit e.g. Global warming potential is measured in kg CO_2 equivalent, Acidification is measured in kg SO_2 equivalent etc. Table number 1 consists of a list of impact categories of CML-IA baseline method. There are various tools such as GABI, SimaPro, OpenLCA to perform LCA study. OpenLCA is selected to perform LCA in this study.

Table 1: List of impact categories (CML-IA Methods [16]

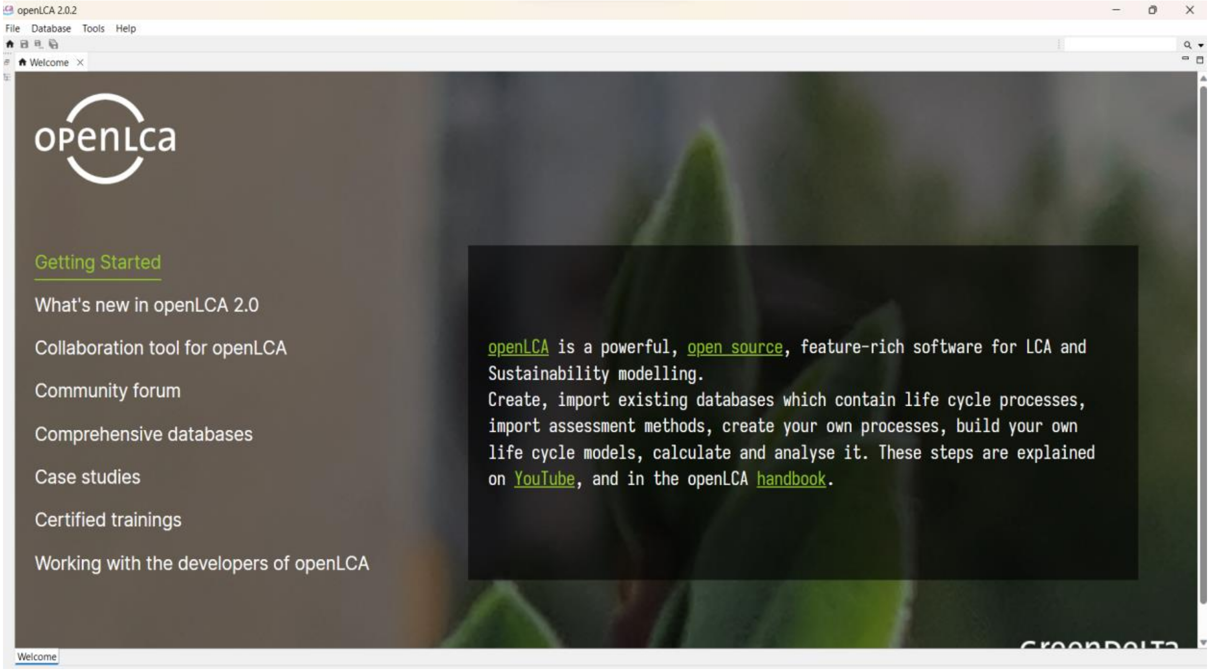
Impacts Category	Units
Global Warming Potential (GWP100a)	kg CO_2 equivalents
Acidification	kg SO_2 equivalents
Eutrophication	kg PO_4 equivalents
Human Potential Toxicity	kg 1.4 DB equivalents
Marine Aquatic Ecotoxicity	kg 1.4 DB equivalents
Abiotic Depletion	kg Sb. equivalents
Abiotic Depletion (fossil fuel)	MJ
Fresh Water Aquatic Ecotax.	kg 1,4 DB equivalents
Ozone Layer Depletion (ODP)	kg CFC- 11 equivalents
Photochemical	kg C_2H_4 equivalents
Terrestrial Ecotoxicity	kg 1,4 DB equivalents

2.2.1 OpenLCA

OpenLCA is an open access software by GreenDelta which is free for the sustainability modeling [16]. The OpenLCA is more functionally robust due to several important features. These consist of the following:

i. Choosing a backdrop database (EPDs)
ii. Developing the products and processes
iii. Attaching them to a life cycle
iv. Selecting a technique for impact assessment
v. Carrying out life cycle analysis; and
vi. Examining the outcomes.

The openLCA Nexus is an online resource for locating, choosing, obtaining, and downloading life cycle assessment and sustainability datasets from several well-known international sources. it has overall provided 300,000 data sets [17].



Getting Started
What's new in openLCA 2.0
Collaboration tool for openLCA
Community forum
Comprehensive databases
Case studies
Certified trainings
Working with the developers of openLCA

openLCA is a powerful, open source, feature-rich software for LCA and Sustainability modelling.
Create, import existing databases which contain life cycle processes, import assessment methods, create your own processes, build your own life cycle models, calculate and analyse it. These steps are explained on YouTube, and in the openLCA handbook.

Figure 5: OpenLCA welcome page [16]

2.2.2 Eco-invent

The Ecoinvent database helps to make the evaluation of products and processes' sustainability easier and helps to better understand how they affect the environment globally. The nonprofit organization Ecoinvent has its main office in Zurich, Switzerland [18].

3 Research Methodology

A literature study is required to have a better grasp of the subject matter. The literature review work started using the term ‘types of review’ in the Google search box.Google has offered many links of which the top ten are chosen and examined for further processing. Two systhematic literatue reviews are conducted i.e. BES for biogas upgrading and LCA of BES.

The links are given below:

1. https://guides.mclibrary.duke.edu/sysreview/types
2. https://support.covidence.org/help/types-of-review-explained
3. https://library.shu.edu/ReviewArticles/Types
4. https://www.phdontrack.net/review-and-write/types-of-reviews
5. https://unimelb.libguides.com/whichreview
6. https://uow.libguides.com/systematic-review/types-of-systematic-reviews
7. https://guides.lib.umich.edu/c.php?g=283340&p=9133330
8. https://www.ncbi.nlm.nih.gov/books/NBK481583/
9. https://libguides.library.ohio.edu/SR/review-types

Which review type should be selected for futher procedure?

After going through each URL, it is found that there are various types of reviews e.g. Systematic reviews, rapid reviews, and scoping reviews. Critical review, Meta review, etc. It is difficult to select one particular review type for further procedure. However, Scoping review is selected because of the following reasons:

i. To find the past and present research study
ii. To check the quantity and scope of available literature
iii. To check the amount of material, classify it, and identify any potential gaps [19] [20] [21]. [22] [23] [24] [25].

3.1 Literature Review 1

3.1.1 Search Procedure

In a reseach work it is investigated by defining the major processes involved in the scoping review search technique [26]. The steps involved in the study are:

i. Defining research objectives
ii. Finding relevant studies
iii. Plotting data
iv. Presenting results
v. Submitting consequences.

The search procedure also includes a carried out methods that researchers must follow to perform a comprehensive and productive review of the available literature.

1. A list of research questions was selected and defined at the beginning of the project development. These objectives formed the study approach's foundation as well as a roadmap for future studies.
    a. To gain a deeper grasp of the biological biogas upgrading process.
    b. The Bioelectrochemical system and its derivatives.
2. After multiple tries and errors using scientific platforms like Scopus and Web of Science found multiple articles with the following search strings:
    a. (bioelectrochemical OR microbial) AND upgrad* on Scopus.
3. There was a total of 28727 documents found on Scopus and 26310 documents on Web of Science without any limits.
4. Then 1419 documents were found on Scopus while searching with the "Article title, Abstract, Keywords''.
5. Atter using a limit to English language filter total of 1359 results were found on Scopus.
6. Limited the published year from 2019 to 2023 on both the platforms and found 747 documents on Scopus whereas 24 results were shown on Web of Science.
7. Other filters i.e. "Article Title" and 2021-2023 published year were used to make the search more precise 42 documents on Scopus and 15 documents were found on the Web of Science.
8. After screening the topic title and full-text study on Scopus, only 14 relevant documents were found whereas on Web of Science, only 3 documents were found for the thesis work.
9. Searching for relevant documents finally ended with studying a total of 13 publications briefly for the thesis work.

The screening was an impotant step for classifying the documents based on title, the objective of the study, scope, type of research paper, methods, resources, and publication year. And checking for duplicates if any and deleting them is also an essential step to perform. The screening review identified relevent research materials for thesis work.

Table 2: Flow diagram showing the screening process

Steps	Action	Reason	Result
1	Find research questions	To find a purpose of the study	Thesis work
2	Searched Relevant documents on Scopus and Web of science	To find the study related documents	Scopus = 28727 & Web of science = 26310
3	Used "“Article tittle, Abstract, Keywords’’ and Title filter on web of science	To search the precise documents	Scopus = 1419 & Web of science = 40
4	Used English language limit	To find relevant language	Scopus = 1359 & web of science = 40

Steps	Action	Reason	Result
5	Used published year (2019-2023) limit	To search the precise documents	Scopus = 747 & web of science = 24
6	Used Article title and year (2021-2023) filter	To search the recent papers	Scopus = 42 & web of science = 15
7	Screening	To remove the duplicates and select more precise papers	Scopus = 10 & web of science = 3

3.1.2 Literature Review of BES for Biogas upgrading

Sun et al. [27] established a microbial electrolysis cell (MEC) that simultaneously purified biogas and enhanced anaerobic digestion. The MEC upgraded biogas with PSB at the cathode and performed anaerobic digestion at the anode. The in-situ upgrading technique increased photosynthetic CO_2 fixation by 83.3% and methane production by 62.8%. It consumed only 0.37 kWh/Nm3 removed of electric energy, making it an eco-friendly and cost-effective solution for in-situ biogas upgrading.

In a 2021 study, Charles et al. [28] found that a novel MEF can continuously convert biogas to high-purity biomethane with over 98% CH_4. it is shown that the MEF's electrochemical process was not hindered by its operation as a trickling filter and It resulted in high efficiency also the computer feedback's pH control maximized CO_2 flux and provided stability for elective methanogenesis. The system can operate at a higher current and increase the CO_2 removal rate as the elevated pH is no longer an issue.

Direct CO_2 reduction by the cathode: $CO_2 + 8H^+ + 8\ e^- \rightarrow CH_4 + 2\ H_2O$

Indirect CO_2 reduction via cathodic H_2: $CO_2 + 4\ H_2 \rightarrow CH_4 + 2\ H_2O$

Kim et al. [29] discovered in 2023 that microbial electrosynthesis (MES) using a cathode electrode-attached cell may directly convert CO_2 to CH_4. A maximum methane generation rate of 10.55 L CH_4/m^2 cat/day with a final CH_4 concentration of 96% was achieved with a cathodic potential of -1.0 V. At 8.8 CH_4/m^2 cat/day and a final CH_4 content of 95%, the methane production rate and concentration in the actual AD biogas application were similar to those of synthetic gas.

Aryal et al. in 2021 [7] has given an outline of microbial electrochemical techniques for biogas upgrading technologies. There are various situations such as in-situ, ex-situ, batch, and continuous modes that are reviewed in this study. This study has also highlighted the challenges in obtaining low overpotential with great coulombic efficiency. This review has also covered a description of the CO_2 reduction to CH_4 procedure reactor design and electrode materials as well as the potential application of bioelectrochemical biogas upgrading with resource and nutrient recovery.

The study by Tsapekos et al. in 2022 [30] aimed to understand microbial ecology in biogas reactors fed with bio-waste. The microbial community in bio-waste was mostly eliminated during digestion. The AD microbiome consists of members from Clostridiales and Bacteroidales and it also adapts to operational conditions. The microbiome mediates the process and produces CH_4 at a rate of 9.99 ± 0.50 mL/L-reactor/h with a lag phase of 13.06 ± 0.65 h. Additional Fe/Ni/Co up to 10 ml/L significantly impacted methane production rate and lag phase. The raw digestate can be used as a sound source of micro- and macro-nutrients for biological methanation.

in 2021, Verma et al. [31] described the use of yeast as an anode biocatalyst in microbial fuel cells (MFCs). They also described about how yeast cells transmit electrons to the anode. It has also explained its beneits and drawbacks of using yeast in MFCs as well as the strategies for raising its efficiency. The research indicates that the best MFCs for cogenerating bioethanol and energy are yeast-based MFCs.

Ning et al. (2021) [32] compared anaerobic digestion (AD) with three bioelectrochemical technologies - P2G-AD, MEC-AD, and AD-MES - based on renewable electricity availability. The MEC-AD system was found to be the most efficient, with the highest modeled methane production (4943.3 Nm^3 per 100 t fresh weight grass silage normalized to 8% TS). This analysis can guide the integration of the electricity grid in advanced biofuel production, but more optimization is needed for industrial applications.

2021, Liu et al. [33] For in-situ biogas upgrading, a bioelectrochemical system with low energy input (applied cathode potential of -0.5 V vs. standard hydrogen electrode, SHE) was used in this study. When the system operated with an organic load of 1.7 kgCOD/(m^3 d), high-efficiency CO_2 conversion (318.5 mol/d/m^2) was achieved. The improved biogas included 97.0% methane and less than 3% CO_2, which is comparable to biogas upgraded utilizing more expensive and less sustainable physiochemical approaches.

Cristiani et al.'s work from 2021 [34], shows that a microbial electrolysis cell biocathode may be used to constantly extract CO_2 from a gas mixture. The requirement for water facilities was removed by a closed electron recycling loop made possible by an anion exchange membrane. Although the galvanostatic operation is more expensive, it has the benefit of not requiring transportation facilities. Only sustainable technologies like biogas or biodiesel, or renewable electric power sources, can be used in this procedure.

Corbellini et al. (2021) [35] looked at how different hydrogen concentrations affected the in situ biological biogas upgrading process. They discovered that hydrogenotrophic methanogenesis, which produces 90% of the methane in the biogas, transformed CO_2 into biomethane when the molar ratio of H_2/CO_2 was increased to 7:1. According to microbial research, the genera Methanobacterium and Methanolinea included the majority of hydrogenotrophic methanogens. To improve energy recovery from sludge treatment, this process has to be further engineered and optimized.

3.1.3 Discussion

With an emphasis on microbial electrolysis cells and bioelectrochemical systems, researchers evaluated a variety of tactics and technologies for biogas upgrading in various studies done between 2020 and 2023. To maximize CO_2 to methane conversion, these studies looked at elements including organic input rate, electrode potential management, pH levels, and microbial populations. Utilizing cutting-edge methods like microbial electrosynthesis and in-situ biological biogas upgrading, certain studies were able to produce methane at high rates and with excellent purity.

The following points were also investigated by researchers:

1. the upgrading of bioelectrochemical biogas in conjunction with usage as fertilizer and resource recovery.
2. The bioelectrochemical system's promise for environmentally acceptable and effective biogas upgrading.
3. It made room for wastewater treatment techniques and environmentally friendly energy sources.

3.2 Literature Review 2

3.2.1 Search Procedure

After completing the previous procedure, the literature review for the Life Cycle Assessment was finished. This time, the further research is conducted on the Web of Science platform.

1. The first step was to define the research questions which are listed below:
    a. What information is needed for any life cycle parameters?
    b. Which databases are required to perform LCA?
    c. What system boundaries have been used in previous studies?
2. Strings used is:

    ((life AND cycle) OR (environmental) OR LCA) AND (bioelectrochemical OR (microbial AND electro*)).
3. There were a total of 26310 documents on Web of Science.
4. 40 documents were found on the Web of Science while searching with the ‘’Title''
5. After using a limit to the English language filter, a total of 40 results were found using the same filter on Web of Science.
6. Limited the published year from 2019 to 2023 used and 24 results were shown on the Web of Science.
7. Other filters i.e. “Article Title” and 2021-2023 published year were used to make the search more precise and 15 documents were found on the Web of Science.
8. After screening the topic title and full-text study on Scopus, only 3 documents were found for the thesis work.

9. Additional 5 docments were studied along with the 3 documents and total of 8 documents were screened for literature review.

3.2.2 Literature Review of Life Cycle Assessment of BES

Table 3: Literature Reviews of LCA

S. No	Type Of Study	Life Cycle	Functional Unit	Life Span	Uncertainty Analysis	Reference
1	Simulation	LCA	one cubic meter of treated wastewater (1 m^3)	20 years		[36]
2	Simulation	LCA	1,000 tons per year of products synthesized from CO_2	10 years	SA	[37]
3	Simulation	LCA	1 L of wastewater treated	10 years	SA & USA	[38]
4	Simulation	LCA	1 kW/m^3 electrode for WWT & 1000 A/m^3 for product generation	1 year	SA	[10]
5	Simulation	LCA	1 m^3 of biogas produced		USA	[39]
6	Simulation	LCA	one MJ produced by combustion of CH_4 in a boiler	100 years	SA	[40]
7	Simulation	LCA	1 L water	10 years	SA	[41]
8	Simulation	LCA	100m^3 of upgraded biogas per hour.	20 years		[42]

There are eight documents in Table number 3, all of which concentrate on different sorts of simulation studies. The simulation study types are shown in the table's first column and are consistent throughout the eight documents. The life cycle study is described in the second column, with papers 1 and 6 looking at the effects on the environment and the economy. Functional units are also included in life cycle research. The sensitivity analyses of several texts are included in the columns dedicated to uncertainty analysis. Document 3 performs sensitivity and uncertainty studies to verify the viability of the system, for instance, on the wastewater BOD or COD removal rate and electricity mix variation in several BES configurations. The uncertainty associated with important foreground input/output and background processes/emissions is propagated along the assessed stages of the best-performing upgrading technology option in Document 5 using the Monte Carlo simulation technique. Document 6 contains sensitivity studies for the following topics: yearly operating time, 25 electricity prices, the composition of the electricity, and biogas upgrading technology. In contrast, the power density is examined in Document 7's sensitivity analysis.

The table number 5 shows methods, techniques etc applied in LCA research. There were various techniques which include cradle-to-grave and cradle-to-gate and tools such as SimaPro and Gabi was utilized for simulation. The table shows research that makes use of OpenLCA.

Therefore, OpenLCA software would be the first to be used in this research work. The Ecoinvent database is mostly used for database collection. The life cycle impacts such as AD, EP, GWP, ODP, HT, TE, and FW are calculated in the LC impact column. It is essential to set up the boundary. for the LCA study. The column method shows LCA methods CML-IA baseline and ReCiPe.

Table 4: Literature review of LCA

S. No	Approach	LCA Software	Database	Life Cycle Impact	Boundary	Method	Reference
1	cradle to gate	SimaPro ® 9.3	Ecoinvent 3.0	AD, EP, GWP, ODP, HT, TE, FWAE (HT), (MAE), (PO) (ADF), (AP)	construction and operation phase	CML-IA baseline	[36]
2	cradle to gate	Gabi	ILCD, Ecoinvent 3.0	GHG, ODP, HT, PM, IR, POF, AP, EP,	All MES plant unit		[37]
3		SimaPro 9.2	Ecoinvent v3.8	GWP, PM, HCT, EP, ME, FRS, MRS	Includes construction and operation stages	ReCiPe 2016	[38]
4	Cradle to grave	SimaPro 9.1		(GWP), HT	integrated process operation, reactor and component design		[10]
5	cradle-to-grave and cradle-to-gate	SimaPro 8.5.2.0	Ecoinvent v.3.4	(GW), (SOD), (FE), (HT), (MRS, in kg Cu eq), (FRS, in kg oil eq), (WC, in m3). (CED)	raw materials extraction to product manufacture	ReCiPe 2016 Midpoint (H) V.1.02	[39]
6	cradle to grave		Ecoinvent 2.2	GHG emissions	the impacts engendered by the by-products.	ReCiPe	[40]
7	cradle-to-grave	Gabi 8.7	Ecoinvent	(GHG)	the whole life cycle of three different BESs		[41]
8	Cradle to gate	Excel	previous literatures	(GWP) and (EP)	after anaerobic digestion		[42]

S. No	Approach	LCA Software	Database	Life Cycle Impact	Boundary	Method	Reference
					after the production of biogas		

4 LCA Methodology

Life Cycle Assessment (LCA) is a process that involves a systematic evaluation of a product or system's environmental impact throughout its entire life cycle. In this study, A cradle to gate LCA models were developed to investigate the environmental burdens associated with the operation stage of pure methane (CH_4) production via BES.

The ISO 14040 LCA standard defines four distinct stages in an LCA [15]

i. Goal and Scope Definition

ii. Inventory Analysis

iii. Impact Assessment

iv. Interpretation

4.1 Process Description

4.1.1 BES Reactor:

BES reactor consists of a two-chamber made up of polycarbonate, the microbial electrolysis cell is separated by an anion exchange membrane. At the anode oxidation reaction takes place which generates protons and electrons. The electrons travel in the external circuit, while the protons pass through the anion exchange membrane to the cathode chamber. At the cathode (biocatalyzed), the electrons and protons facilitate the microbial reduction of CO_2 to organic chemicals such as methane. This reaction is, however, non-spontaneous and requires an external input of power. In addition to the electric grid, the power required for BES (MEC) can also be harvested from renewable energy sources (solar, wind) [43].

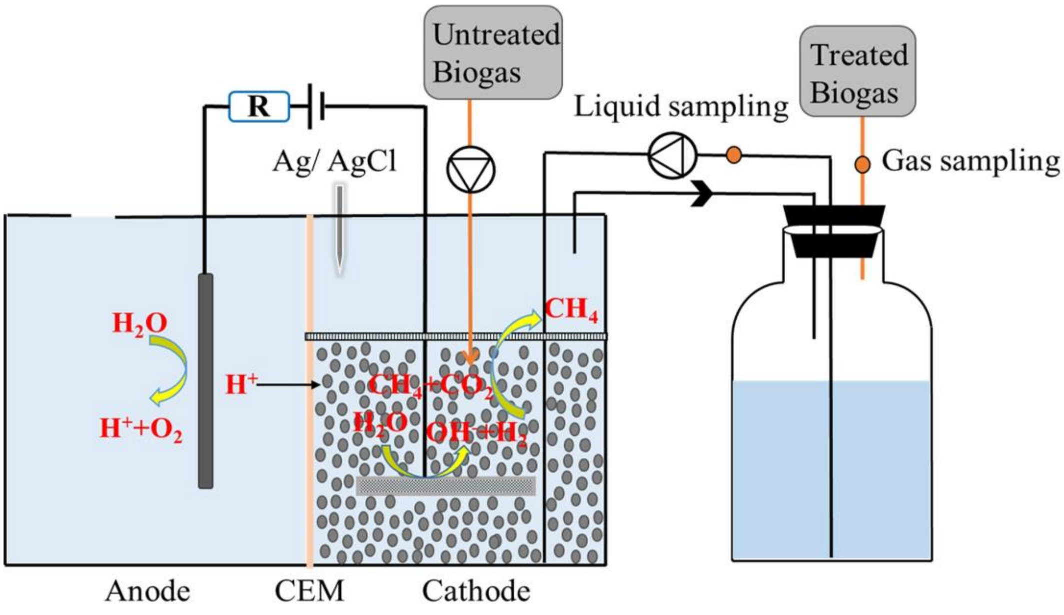


Figure 6: The schematic diagram of AGS- EM System (Source: Zhou et al; [43]

4.2 Goal and Scope

The first stage of the LCA study aims to define the objective, system borders, and assumptions. This thesis work aims to recognize the system hotspots applying the LCA and this is important to understand the overall environmental adverse effects of applying novel methods. This study is based on the experimental work by researchers [43]. It is challenging to evaluate the emission generated by the lab-scale experiment work. Therefore, in order to have a sensible amount of impact, the input quantities are scaled up.

4.2.1 System Boundary

The purpose of this study is to assess the environmental consequences of BES from the cradle to the gate including raw materials extraction, energy used during the operation, and the amount of raw biogas and sludge used for the upgradation.

Functional Unit: The functional unit is a vital part of the life cycle assessment study of any product, process, or system. The environmental impact of the BES system will be determined using a functional unit of 1 cubic meter of biogas for 1 hour and the inputs were normalized for a year.

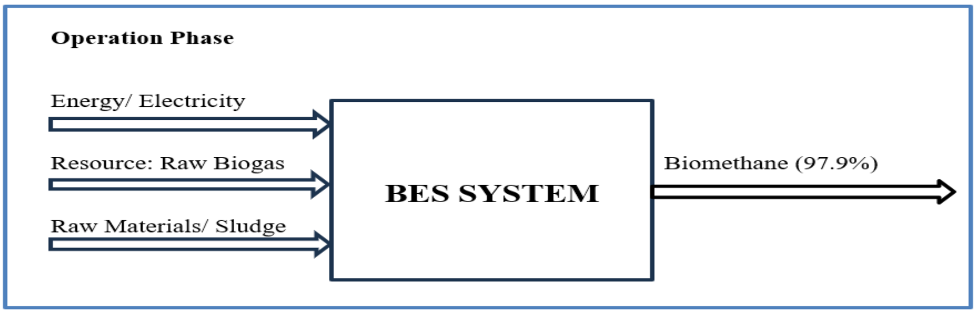
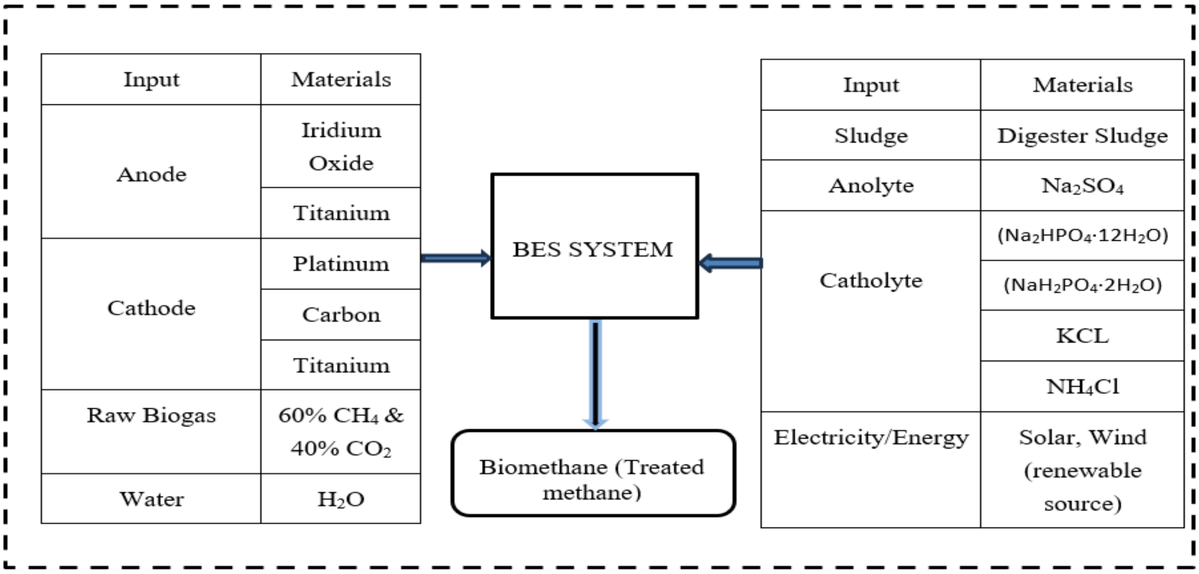


Figure 7: Operational phase of BES system for Biogas upgrading for FU 1m^3 of biogas



Input	Materials
Anode	Iridium Oxide
	Titanium
Cathode	Platinum
	Carbon
	Titanium
Raw Biogas	60% CH_4 & 40% CO_2
Water	H_2O

Input	Materials
Sludge	Digester Sludge
Anolyte	Na_2SO_4
Catholyte	($Na_2HPO_4 \cdot 12H_2O$)
	($NaH_2PO_4 \cdot 2H_2O$)
	KCL
	NH_4Cl
Electricity/Energy	Solar, Wind (renewable source)

Figure 8: System Boundary for functional unit 1 cubic meter of biogas.

4.3 Life Cycle Inventory Analysis

The Life cycle inventory describes about the primary and secondary data used during analysis. Based on primary data from the lab experiment performed, [43] the inventory used for treated methane production through Bioelectrochemical Systems is scalable to get sensible amount of environmental impact treating 1 cubic meter of biogas per hour. To conduct this study the OpenLCA software is used and the Ecoinvent database version 3.6 is also used. While the secondary data is collected from the literatures. Table number 6 shows the inventory data used in the study which includes inputs such as mateials, water, biogas, sludge, and electricity consumption etc.

Table 5: Life Cycle Inventory details for functional unit 1 cubic meter of biogas

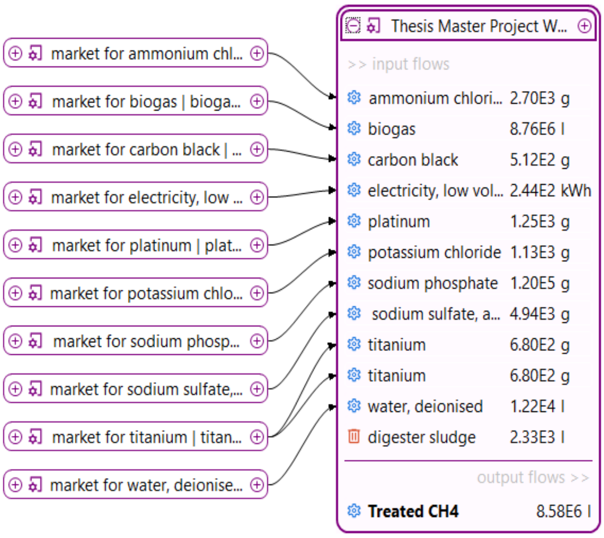
Inputs	Unit of input value	1 time used duration of the input value	Scale up input Value	Quantity required for 1 year operation	Input Value for 1 year (Operation time)
Anode					
IrO_2	g	6 months	31.2	2 pieces	62.4
Titanium	g	6 months	340.1	2 pieces	680.1
Cathode					
Platinum	g	6 months	624.3	2 pieces	1248.7
Titanium	g	6 months	340.1	2 pieces	680.1
Carbon	g	6 months	256.1	2 pieces	512.3
Anaerobic granular sludge	L	7 days	44.6		2325.6
Raw Biogas	L	1 hour	1000		8760000
Electricity/Energy	kWh	7 days	4.682		243.5
Water Consumption	L	7 days	234.1		12173.9
Anolyte (Na_2SO_4)	g	7 days	94.97		4938.4
Catholyte ($Na_2HPO_4 \cdot 12H_2O$)	g	7 days	1929.5		100333.4
Catholyte ($NaH_2PO_4 \cdot 2H_2O$)	g	7 days	379.54		19736.3
Catholyte (NH_4Cl)	g	7 days	51.83		2695.3
Catholyte (KCl)	g	7 days	21.74		1130.3
Output					
Treated Methane	L	1 hour	979.0		8576040

The above table number 6 shows the components used duing operation, and its raw materials detail. Anolyte (Na_2SO_4), catholyte (Na_2HPO_4*12 H_2O), (NaH_2PO_4*$2H_2O$), NH_4Cl, KCl, and the mass of anode (IrO_2, Ti), cathode (Titanium, Platinum, Carbon) are among the input data. The emission of one year of operation duration is identified. It is shown in the lab scale that the highest methane concentration was shown with an increment of about 94.4% to 97.9% when the applied voltage was raised from 0 to 4 V. The system has to be bigger to treat 1000 L biogas (60% CH_4 and 40% CO_2) in an hour in the scale up system. There was 7% CH_4 loss observed when the circuit was open which is not taken in the analysis.

Also, the study does not take into account vitamin solutions, trace element solutions, liquid waste (effluents), anion exchange membranes. The geography is considered as europe (RER) and the input providers are chosen as marketplaces (available in Eco-invent database).

4.3.1 Model Graph

The model graph is a useful tool in openLCA software that shows the product system visually and it also involves the supply chain plus connects to the various other procedures. The below graph figure number 10 shows how the multiple flows and their processes (providers) are deeply interconnected.



ammonium chlori...	2.70E3 g
biogas	8.76E6 l
carbon black	5.12E2 g
electricity, low vol...	2.44E2 kWh
platinum	1.25E3 g
potassium chloride	1.13E3 g
sodium phosphate	1.20E5 g
sodium sulfate, a...	4.94E3 g
titanium	6.80E2 g
titanium	6.80E2 g
water, deionised	1.22E4 l
digester sludge	2.33E3 l
Treated CH4	8.58E6 l

Figure 9: Model graph of LCA study for FU 1 m^3 of biogas

4.4 Life Cycle Impact Assessment Phase

The LCA was performed on the OpenLCA software using the CML IA baseline method developed by the Centre of Environmental Science – Leiden University, The Netherlands [44]. The CML-IA baseline method consists of various midpoint categories such as Abiotic depletion, Acidification, Eutrophication, Freshwater aquatic ecology, Global warming potential, Human toxicity, Marine aquatic ecotoxicity, Ozone layer depletion, Photo chemical oxidation, Terrestrial ecotoxicity etc. Out of which global warming potential (GW, in kg CO_2 eq,), environmental impacts are calculated in this study using OpenLCA software.

Table 6: Summary of scope definition and assumptions

Functional Unit	1 cubic meter of biogas.
System Boundary	Cradle to Gate
LCIA Method	CML-IA Baseline
Impact Categories	Acidification, eutrophication, global warming potential, Human Toxicity
Tools	OpenLCA 2.0
Database	Ecoinvent database version 3.6
Major Assumptions	i. The impacts of the transportation of raw materials, anion exchange membrane and supplementary chemicals to the pilot plant, material processes, and the wastes are not included in the analysis. ii. Scalling up lab scale inputs by 334.4 times for large plant opeation phase structure. iii. The electodes are assumed to be durable for 6 months (pesimistic value) [45] [46]. iv. The iridium oxide is used as iridium in the OpenLCA and it is listed under elementay low in eco-invent. Therefore, the impact generated by iridium is not consideed in this study. v. Catholyte $Na_2HPO_4 \cdot 12H_2O$ and $NaH_2PO_4 \cdot 2H_2O$ are assumed as Sodium phosphate in the OpenLCA software. vi. Mass of Nickel is assumed to be equal to the mass of platinum for a comparative study. vii. Carbon is considered as carbon black and Na_2SO_4 as sodium sulphate, anhydrite in the OpenLCA software viii. The pure methane is assumed 97.9% as output. ix. IrO_2 Coating Thickness = 2.5 Micron [47] x. The thickness of Ti mesh = 0.2 mm [48]and the thickness of 20 wt.% Pt/C = 136µm [49] xi. Density of Titanium = 4.54 g/cm^3 [50] [51] xii. Density of IrO_2 = 11.66 g/cm^3 [47] xiii. Density of Pt = 21.45 g/cm^3 [52] xiv. Density of C = 2.2 g.cm-^{3} [53]

4.5 Interpretation

The interpretation of the LCA study is discussed in the chapter number 5.

5 Results

This chapter presents the findings of major contributor of Global Warming (GWP100a), Human Toxicity potential and Acidification, Eutrophication environmental impacts. The highest environmental impact contributor from the input components is investigated and highlighted in this study.

5.1 Global Warming Potential

The effects of various gases on the climate may compare by using the Global Warming Potential metric. It indicates the amount of heat emissions that one ton of gas may trap over time as opposed to one ton of carbon dioxide (CO_2). Higher GWP gases warm the planet more than CO_2 does, generally over 100 years [54].

Platinum emerges as the leading contributor with 94.76 % to GWP and the majority of contribution is done by the market for the platinum group during mining and concentration operation with 90.21 %. Titanium contributes a minor portion at 00.07%. Biogas and Sodium phosphate contribute 4.79 % and 00.37 % respectively. The direct contribution of treated methane to GWP is 0.002 (kg CO_2 eq) by electricity which is negligible. The total GWP (100a) is 91,090.5 kg CO_2 equivalent.

Table 7: GWP (100a) (kg CO_2 eq) impacts of the components for FU 1 m^3 of biogas

Components	**Global Warming Potential (kg CO_2 eq)**
Platinum	86314.60
Biogas	4360.39
Sodium Phosphate	338.73
Titanium	64.10
Ammonium Chloride	4.19
Electricity/Energy	4.06
Sodium Sulphate	2.84
Carbon	0.95
Potassium Chloride	0.69
Water	0
Sludge	-0.11

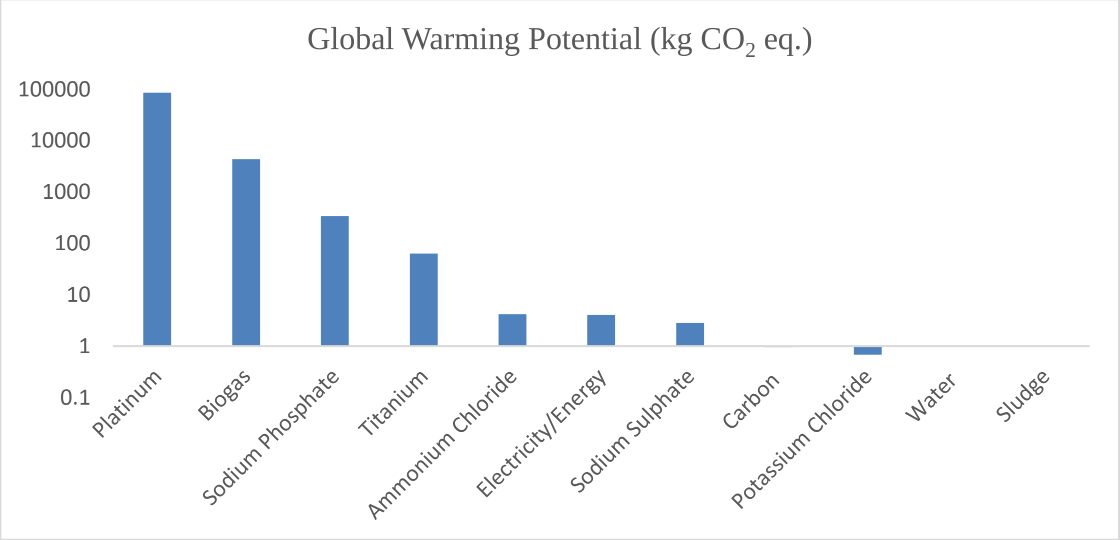


Figure 10: A graph representing the comparison of input components for Global warming potential impact (kg CO_2 equivalent)

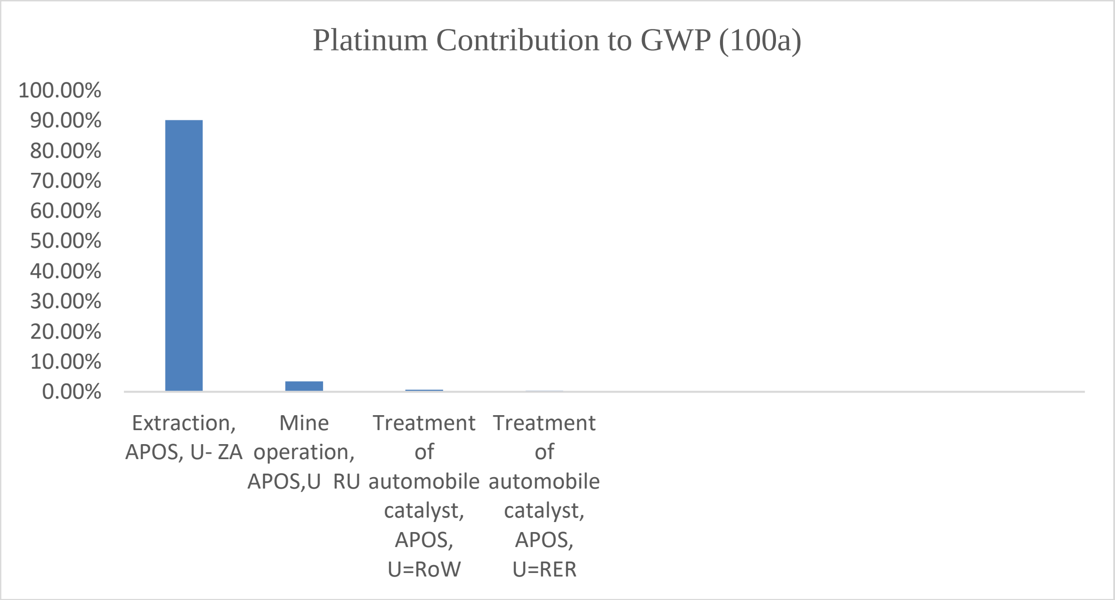


Figure 11: Graph representing Platinum contribution to GWP (100a)

5.2 Acidification

Acidification Potential measures how much precipitation and fog reduce pH, which damages ecosystems by allowing nutrients to seep out of soils and increasing the solubility of metals in the soil. Acidification potential is usually expressed in mass of sulfur dioxide equivalents and is a regional problem [55].

The major contribution to acidification is done by platinum with 99.36%. Platinum mine operation plays a vital role with 63.81% of the total contribution. The minor contribution of 00.01%, 00.07%, and 00.55% is done by titanium, sodium phosphate, and biogas respectively. The total acidification impact is 5196.16 kg SO_2 equivalent.

Table 8: Acidification (kg SO_2 eq) impacts of the components for FU 1 m^3 biogas

Components	**Acidification (kg SO_2 eq)**
Platinum	5163.14
Biogas	28.72
Sodium Phosphate	3.85
Titanium	0.35
Ammonium Chloride	0.02
Electricity/Energy	0.04
Sodium Sulphate	0.03
Carbon	0.01
Potassium Chloride	0
Water	0
Sludge	0

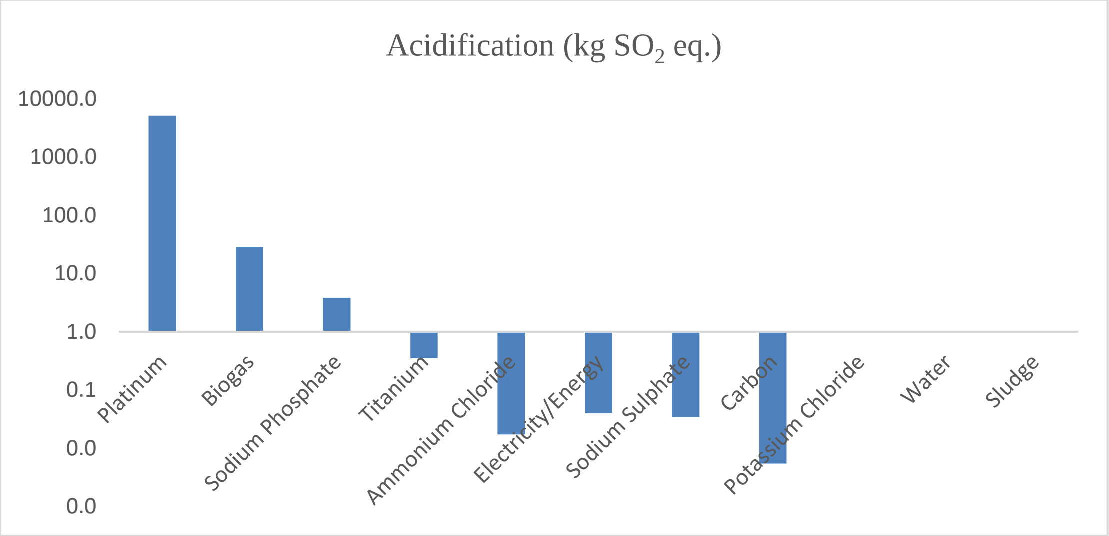


Figure 12: Comparing the input components for acidification impact (kg SO_2 eq) for FU 1 m^3 of biogas

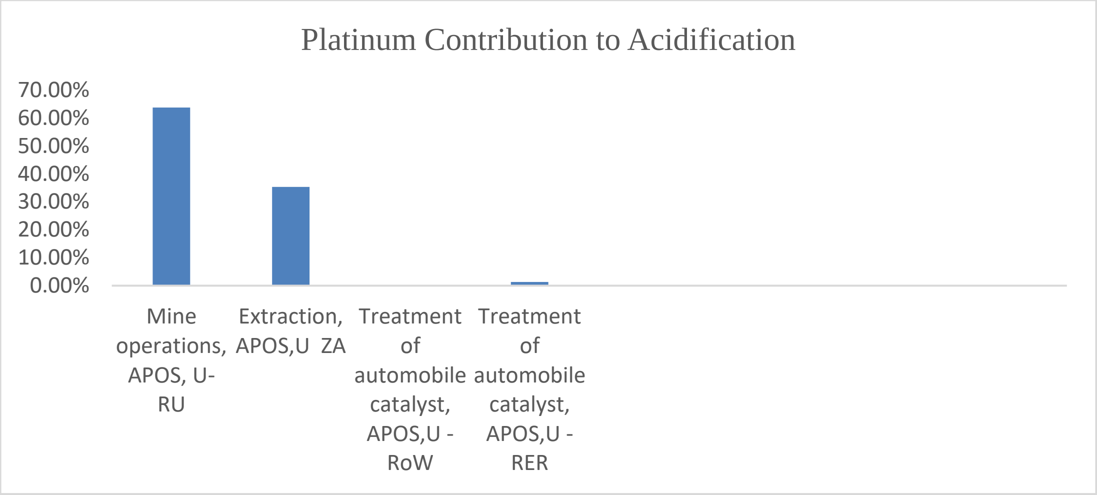


Figure 13: Graph representing the Platinum contribution to acidification (kg SO_2 eq)

5.3 Human Toxicity Potential

There may be health hazards to humans when some compounds including heavy metals are released. The assessments of toxicity are based on standards that have been set in both water and air. The reference unit of kg 1,4-dichlorobenzene (1,4-DB) equivalent is used to communicate HTPs for each dangerous chemical [56] [57].

Platinum shows the highest toxicity in humans with 98.76% of its effect and minor cause with 00.01% done by electricity. The extraction and refinery show the highest contribution for platinum with 95.02 %. Titanium, sodium phosphate, and biogas contribute 00.04%, 00.28%, and 00.90% to human toxicity potential respectively. The total human toxicity potential is 293478 kg 1,4-DB equivalents.

Table 9: HTP (kg 1,4 DB eq) impacts of the components for FU 1m^3 of biogas

Components	**Human Toxicity Potential (kg 1,4-DB eq)**
Platinum	289840
Biogas	2647.20
Sodium Phosphate	830.80
Titanium	114.46
Ammonium Chloride	4.54
Electricity/Energy	30.06
Sodium Sulphate	9.72
Carbon	0.34
Potassium Chloride	0.77
Water	0
Sludge	-0.06

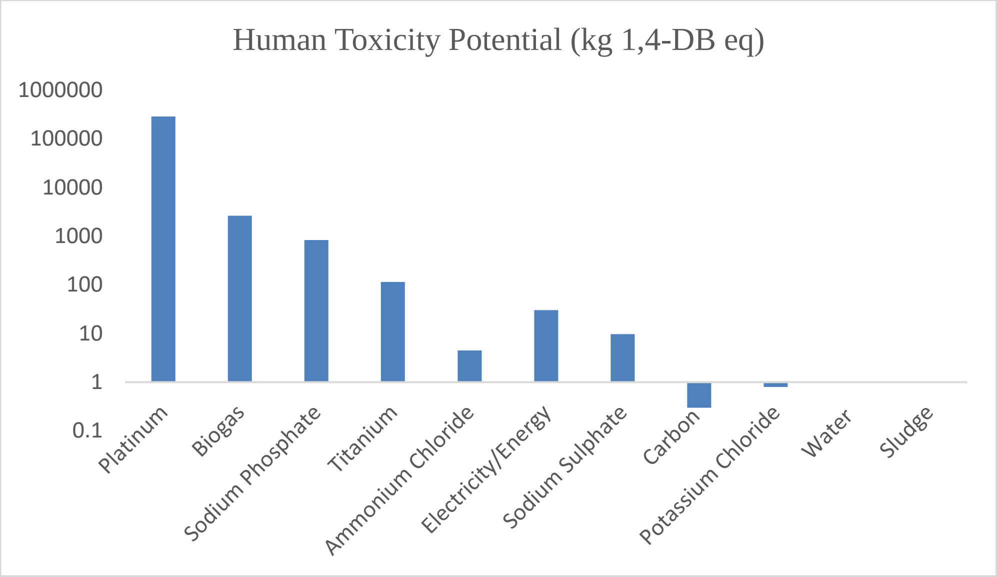


Figure 14: Comparison of input components for human toxicity potential impact (kg1,4-DB eq) for FU 1 m^3 of biogas

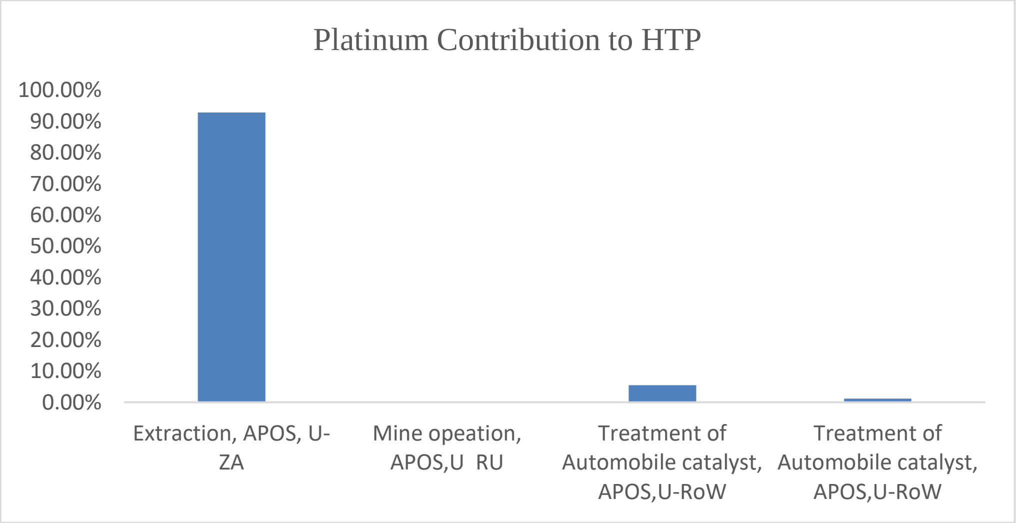


Figure 15: Graph representing process of Platinum contribution to Human Toxicity Potential

5.4 Eutrophication

The important sign of the enrichment of freshwater ecosystems with nitrogen or phosphorus compounds is eutrophication. Platinum is shown to be the main cause of eutrophication, according to 91.56% of the effect, and a minor cause with 00.02% is done by titanium. The majority of platinum contribution comes from extraction and refinery with 89.98%. The contribution from Biogas and sodium phosphate is 08.21% and 00.21%. The total eutrophication impact is 610.70 kg PO_4 equivalents.

Table 10: Eutrophication (kg PO_4 equivalents) impacts of the components for FU $1m^3$ of biogas

Components	**Eutrophication (kg PO_4 eq)**
Platinum	559.13
Biogas	50.13
Sodium Phosphate	1.26
Titanium	0.13
Ammonium Chloride	0.01
Electricity/Energy	0.02
Sodium Sulphate	0.01
Carbon	0
Potassium Chloride	0
Water	0
Sludge	0

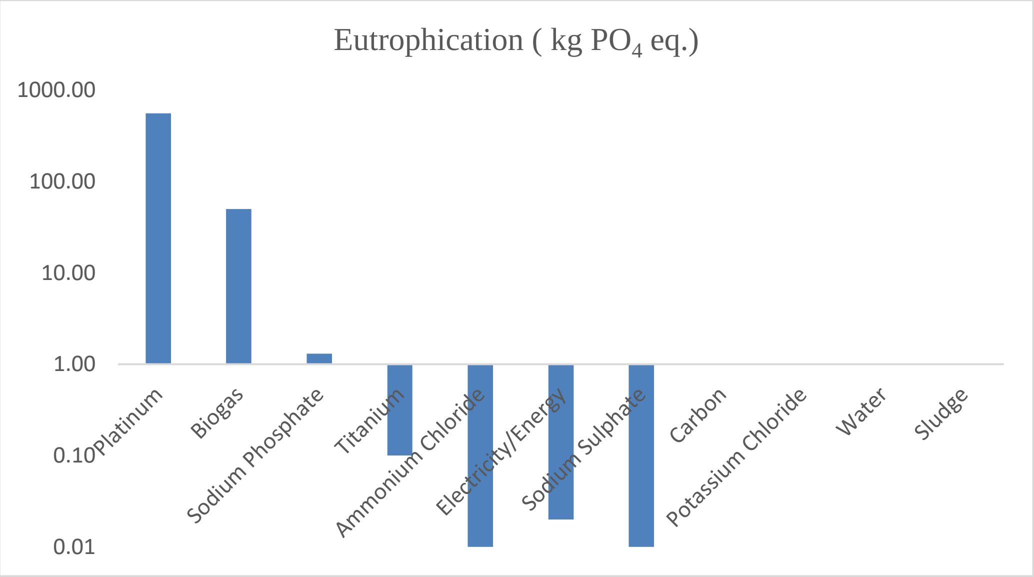


Figure 16: A graph comparing the components for eutrophication impact (kg PO_4 eq.) for FU 1 m^3 of biogas

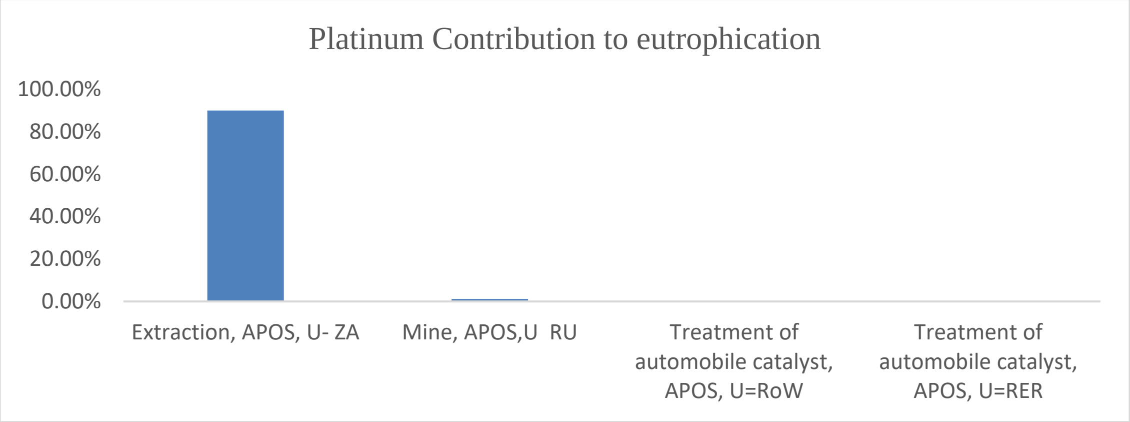
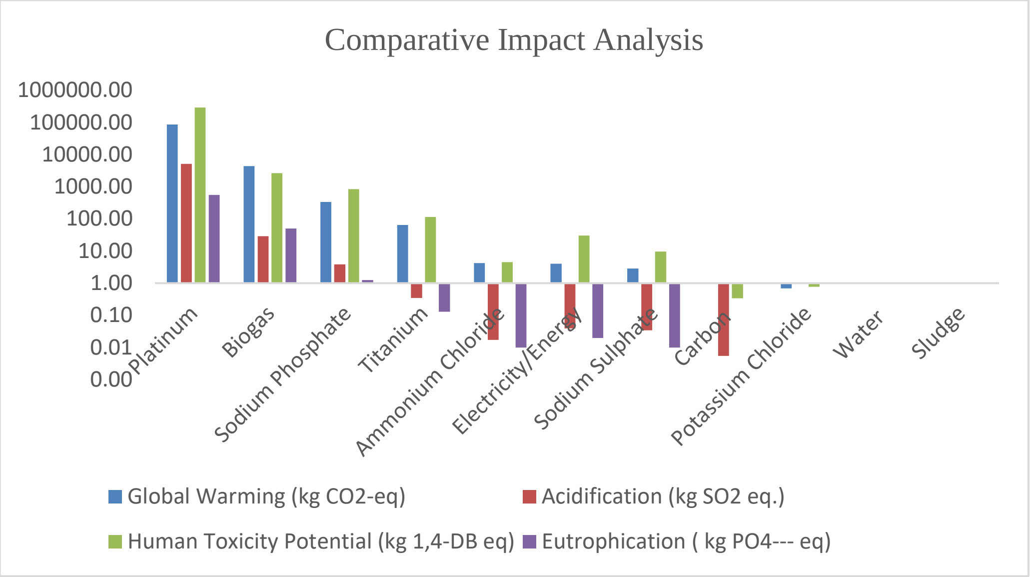


Figure 17: Graph representing Platinum contribution to Eutrophication

Table 11: Comparative analysis of impacts for functional unit 1 m^3 biogas.

Components	**Global Warming (kg CO_2-eq)**	**Acidification (kg SO_2 eq)**	**Human Toxicity Potential (kg 1,4-DB eq)**	**Eutrophication (kg PO_4 eq)**
Platinum	86314.60	5163.14	289840	559.13
Biogas	4360.39	28.72	2647.20	50.13
Sodium Phosphate	338.73	3.85	830.80	1.26
Titanium	64.10	0.35	114.46	0.13
Ammonium Chloride	4.19	0.02	4.54	0.01
Electricity/Energy	4.06	0.04	30.06	0.02
Sodium Sulphate	2.84	0.03	9.72	0.01
Carbon	0.95	0.01	0.34	0
Potassium Chloride	0.69	0	0.77	0
Water	0	0	0	0
Sludge	-0.11	0	-0.06	0



v

Figure 18: The graph represents comparison among the impacts GWP, Acidification, Eutrophication and HTP for FU 1 m^3 of biogas

The results show that platinum has the most potential to cause to global warming, acidification, human toxicity, and eutrophication, contributing 94.76 %, 99. 36%, 98.76%, and 91.56 % of these impacts respectively. The majority of platinum contribution takes place during extraction, refinery, mining and concertation operations. These results provide important information to improve the bioelectrochemical system’s environmental sustainability for biogas upgrading.

The environmental effect results across several categories were considerable according to the life cycle assessment that was completed using the CML impact assessment approach, notably the Baseline scenario. The possibility of acid rain generation was highlighted by the measurement of the acidification potential, which was 5196.16 kg SO_2 equivalent. The release of phosphates during eutrophication produced a value of 610.70 kg PO_4 equivalent, showing the possibility of nutrient over- enrichment in ecosystems. The element's major contribution impact to climate change can be seen by its considerable Global Warming Potential over a 100-year timescale, which registered at 91090.5 kg CO_2 equivalent. Also, the Human Toxicity Potential which represents the possible negative effects on human health resulting from exposure to dangerous substances was evaluated at 293478 kg 1.4 DB equivalent.

Water, Potassium chloride and sludge shows negligible environmental impact. The negative value of sludge raises the possibility of a moderating influence on impacts showing the need to take by-products into account in the environmental evaluation.

5.5 Comparative Study of Cathodes (Platinum & Nickel)

After observing the result of platinum's major impact on environmental, it is decided to find an alternative material in platinum's place. Nickel can be used as a replacement of platinum [13].

A comparative LCA study is conducted in between platinum and nickel. Nickel is used in place of platinum and rest inputs are considered same. The mass of nickel is assumed to be same as platinum and CML-IA baseline method is used to check the environmental impacts such as GWP (100a), acidification, eutrophication and HTP.

Table 12: Comparative analysis of Nickel and Platinum case study for FU 1 m^3 of biogas

Impact category	Nickel Case study	Platinum Case Study
Global warming (GWP100a) (kg CO_2 eq)	4780.7	91090.5
Acidification (kg SO_2 eq)	33.06	5196.16
Human toxicity (kg 1,4-DB eq)	3701.15	293478
Eutrophication (kg PO_4 eq)	51.61	610.70

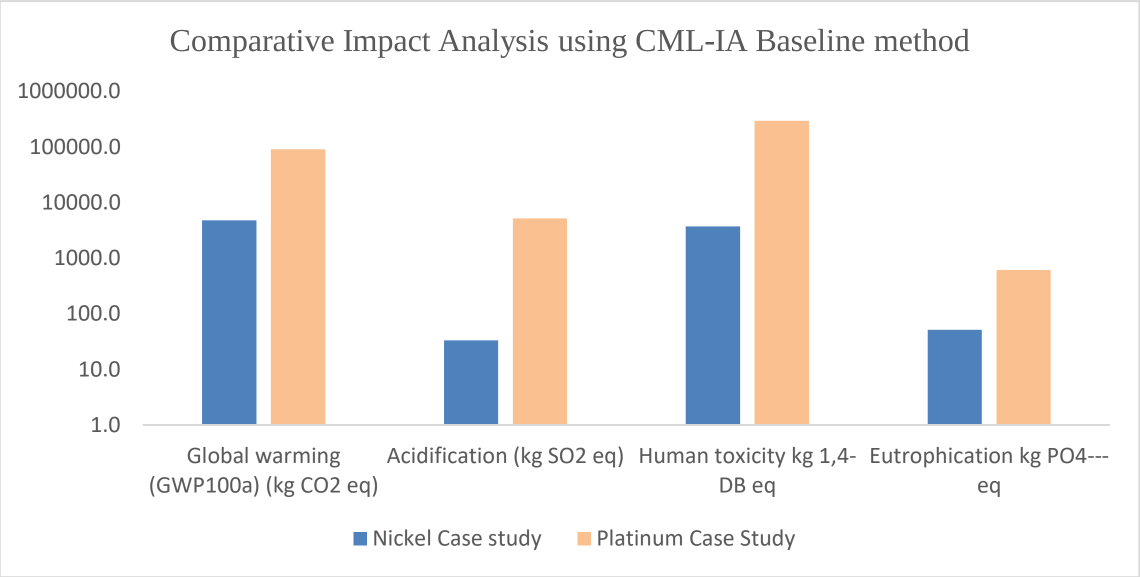


Figure 19: Graph representing comparative study of nickel and platinum study for FU 1 m^3 of biogas

The result shows that platinum contributes to GWP (100a), acidification, eutrophication and HTP comparatively more than the nickel. Table number 6 shows the platinum case study to GWP, acidification, eutrophication and HTP are 91090.5 kg CO_2 equivalent, 5196.16 kg SO_2 equivalent, 610.70 kg PO_4 equivalent, and 293478 (kg 1,4-DB equivalent) respectively. Similarly, for the nickel case study to GWP, acidification, eutrophication and HTP are 4780.7 kg CO_2 eq, 33.06 kg SO_2 eq, 51.61 kg PO_4 equivalent and 3701.15 (kg 1,4-DB equivalent). It is observed that there is a room for the further research related to the use of nickel electrode in the BES system for biogas upgrading.

6 Discussion

The life cycle assessment (LCA) of scaled-up BESs has given important new information on how it performs environmentally in a number of impact areas. This chapter discusses 5 components that has contributed to the environmental impacts. The main conclusions on acidification, eutrophication, human toxicity potential (HTP), and global warming potential (GWP) are the subject of the debate that follows.

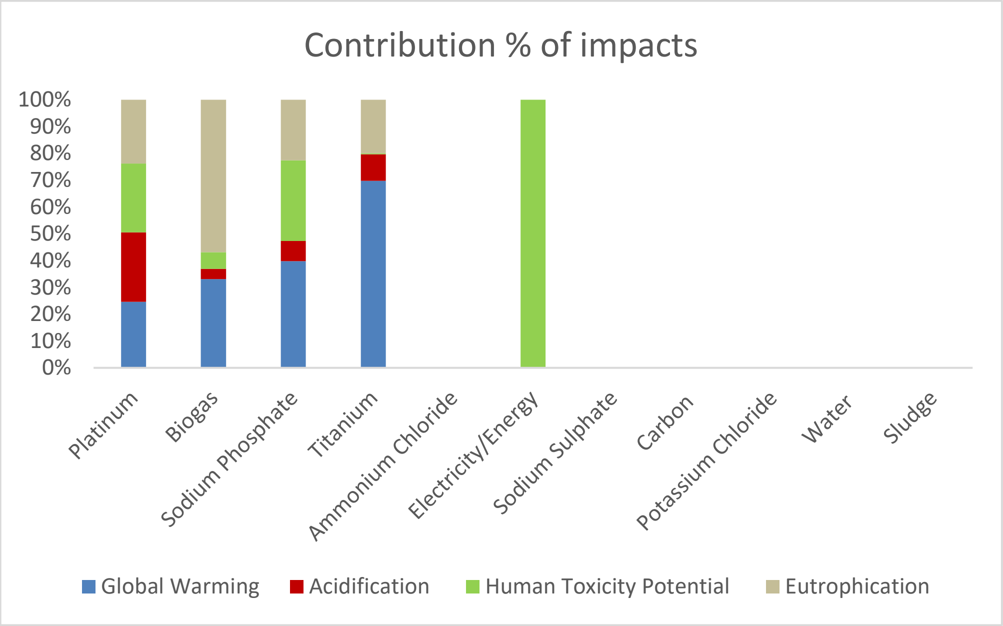


Figure 20: Contribution percentage of components to GWP, Acidification, EP and HTP for FU 1 m^3 of biogas

6.1 Platinum

The use of platinum in the expanded bioelectrochemical system increased the global warming potential (GWP) by an estimated 86314.60 kg CO_2 eq, i.e. 94.76% This implies that the system's platinum use harms the environment. Platinum's estimated value of 5163.14 kg SO_2 eq i.e. 99.36% contributed significantly to the acidification potential which indicates that platinum use has a major impact on the emergence of acid rain and its related environmental impacts. The result shows that it also has a high impact on Human Toxicity Potential (HTP) with an approximate value of 289840 kg 1,4-DB eq i.e. 98.76%. This indicates the major effect of platinum on potential health issues for people. Platinum significantly increased the eutrophication potential of the scaled-up bioelectrochemical system; its estimated value was 559.13 kg PO_4 equivalent. i.e. 91.56%. This highlights the substantial impact that platinum use has on nutrient imbalances in aquatic habitats.

The primary cause of platinum's significant GWP, eutrophication, and human toxicity contribution is its extraction process, which is mostly carried out in South Africa (U-ZA) whereas the mining and extraction processes of platinum in Russia (U-RU) and South Africa (U-ZA) are the main sources of its acidification potential. Mining also contributes to global warming, eutrophication, and human toxicity. The predominance of these two processes emphasizes how important it is to carefully assess how using platinum may affect the environment. The worldwide (RoW) and European (RER) treatment of automobile catalysts adds to GWP, human toxicity, and eutrophication.

Research [58] explains regarding its effects on people and other living things, the possible toxicity of Platinum Group Elements (PGEs) released into the environment is still up for discussion. Certain Pt chloro-compounds are strong allergens and sensitizers, although these metals are thought to be physiologically inert in their metallic state. People who are exposed to halogenated Pt salts at work are more vulnerable to the harmful effects of platinum (Pt) exposure. although these metals are thought to be physiologically inert in their metallic state. People who are exposed to halogenated Pt salts at work are more vulnerable to the harmful effects of platinum (Pt) exposure.

The world’s leading platinum group elements (PGE) producers are South Africa and Russia with over 80 % of the global PGE output. Labor, energy, and money are all needed in large quantities for the extraction of platinum group metals, or PGMs. Both open pit and underground mining affect the environment. Before high-temperature smelting, ore is subjected to blasting, crushing, milling, and concentration. PGM mining requires a significant amount of power for refrigeration, pneumatic drills, and ore hauling. 85–90% of the global warming potential is attributed to primary production's consumption of energy. Because PGM extraction requires a lot of energy, it hurts the environment, which makes the sector adopt sustainable procedures [59] [60] [61].

To use alternate metals in place of Pt or lessen the dependence on it. Promising alternatives to electrode materials include titanium (Ti), nickel (Ni), and stainless steel (SS). Excellent conductivity is exhibited by metals like iron, copper, silver, and gold, but their long-term operating stability is undermined. Large-scale systems benefit from electrodes with excellent conductivity and mechanical strength. An electrode must have strong conductivity, non-toxicity, high corrosion resistance, a large specific surface area, and excellent biocompatibility in order to operate at maximum efficiency [13].

6.2 Biogas

The scaled-up system's raw biogas added around 28.72 kg SO_2 equivalent to the acidification potential. about 4360.39 kg CO_2 equivalent to the GWP, roughly 50.13 kg PO_4 equivalent to the eutrophication potential, and roughly 2647.20 kg 1,4-DB is equivalent to the HTP. Its relative contributions to acidification, eutrophication, GWP, and human toxicity potential are 0.55%, 8.21%, 4.79%, and 0.90% respectively.

Gases such as carbon dioxide, methane, and nitrous oxide are released by livestock. Enteric fermentation, a gas generated in the stomachs of the animals, is the primary source. The management of manure also increases greenhouse gas emissions; however, these emissions may be greatly decreased by employing an anaerobic digester. By capturing volatile carbon as biogas, this technique stops the release of methane. Reducing exposure to oxygen also considerably lowers emissions of nitrous oxide from manure storage [62].

Respiratory illnesses in biomass plant workers may be related to endotoxin and fungal exposure. In biogas facilities, unintentional hydrogen sulfide leaks can have deadly or seriously harmful effects on human health [63]. Acidification, eutrophication, inorganic compounds, and respiratory organics are all greatly impacted by combined heat and power unit (CHPU) emissions [64].

6.3 Sodium Phosphate

Approximately 3.85 kg SO_2 eq more acidification potential was produced by the addition of sodium phosphate in the catholyte solution. 830.80 kg 1,4-DB eq per to the HTP. The global warming potential is 338.73 kg CO_2, while the eutrophication potential is 1.26 kg PO_4 equivalent.

The contribution to Eutrophication, GWP, HTP and acidification is done by 0.21%, 0.37%, 0.28% and 0.07% respectively.

How sodium phosphate is used and how it could affect soil and water bodies determine how it affects the environment. Although excessive discharge of sodium phosphate into water can raise phosphorus levels, which in turn promotes algae development and can result in problems like algal blooms and decreased water quality, even if sodium phosphate itself is not hazardous. Aquatic ecosystems are impacted in terms of balance. Restrictions on the usage and discharge of sodium phosphate are required in order to prevent eutrophication of water bodies. To prevent soil from becoming acidic, sodium phosphate normally undergoes adsorption, precipitation, hydrolysis, and absorption on the soil. On the other hand, it can function as a phosphate fertilizer to promote plant development. Conversely, overuse might lead to phosphorus waste, which would reduce the diversity and microbes in the soil. As such, care must be taken while handling sodium phosphate to avoid environmental problems [65] [66].

6.4 Titanium

The scaled-up system's titanium added around 0.35 kg SO_2 equivalent to the acidification potential. about 64.10 kg CO_2 equivalent to the GWP, roughly 0.13 kg PO_4 equivalent to the eutrophication potential, and roughly 114.46 kg 1,4-DB is equivalent to the HTP.

It has contributed 0.01 %, 0.02%, 0.04% and 0.07% to acidification, eutrophication, HTP and GWP respectively.

In China, the Kroll method was used in research [67] to evaluate the life cycle of titanium sponge manufacture. The results showed that the smelting of titanium slag in the Kroll process accounted for 22.4% of the overall effect, while the electrolysis of magnesium chloride accounted for 39.6%. The toxic compounds were released into the environment with heavy metals being one of the main causes of harm to humans.

6.5 Electricity

In the scaled up bioelectrochemical system, the potential for acidification linked to the consumption of electricity or energy was roughly 0.04 kg SO_2 eq; the potential for human toxicity was 30.06 kg 1,4-DB eq; the potential for eutrophication was 0.02 kg PO_4 equivalent, and the potential for global warming (100a) was 4.06 kg CO_2 equivalent. The potential for human toxicity is increased by 0.01% by the electricity.

Copper is utilized 5 times more than traditional power generating methods such as nuclear power plants and fossil fuels. The copper plays an important part in renewable energy systems.

It is a vital part of the revolution in renewable energy because of its exceptional conductivity, robustness, and resistance to corrosion. Therefore, it is used for fueling solar panels, wind turbines, energy storage devices, and also electricity transmission. Researchers learned about possible outcomes by examining how various copper manufacturing scenarios affected the ecosystem. It shows a progressive rise in human toxicity [68] [69].

6.6 Methane Loss

In the conventional method of biogas upgrading, the researcher [70] explained that the assumption is that 1% of the biogas plant's total methane production rate is lost due to gas-producing section losses (not including situations in which biogas is used and digestate storage tanks are either exposed or not sealed). It's crucial to remember that this estimate excludes establishments like biogas upgrading units that use biogas exclusively.

Loss during sampling can influence the dependability of data used to evaluate the environmental advantages of a biogas upgrading system that produces biomethane, even while it may not directly contribute to environmental impact [43].

In conclusion, Platinum has shown a major contribution to acidification, human toxicity, eutrophication, and global warming potential. It is observed that extraction methodology in South Africa and Russia is the cause of platinum's highest environmental impact.

7 Conclusion

In conclusion, a thorough life cycle assessment (LCA) of a bioelectrochemical system for biogas upgrading has been carried out in this thesis, with a focus on the environmental effects related to input components. The CML impact assessment method was used in the study with a focus on the Baseline scenario. Global Warming Potential (GWP100a), Acidification, Human Toxicity Potential (HTP), and Eutrophication are the main environmental effect categories taken into consideration.

It is observed that platinum is responsible for the large portion of envionmmental impacts i.e Acidiication 99.36%, human toxicity 98.76%, eutrophication 98.76% and GWP 94.76%. The main contributor of platinum process to the impacts are the extraction, reinery, mining, and concentration opeations. The other input components such as biogas, sodium sulphate, titatanium, electricity used has shown the minor impacts as compared to the platinum. The used sludge has shown the negative value representing that it is beneicial to the environment. It is important to improve and practice sustainable extraction, refining and mining process in the places like South Africa, ZA and Russia.

Platinum is one of the best noble metals for electrochemical systems because it is inert and has a low overpotential, However, Pt is expensive and has a negative impact on the environment upon disposal. Platinum seems to be the best catalyst however the use of such catalysts at an industrial scale is deterred by their high price. Thereore, using alternative cathode e.g Nickel in place of platinum could be a sustainable solution for the biogas upgrading in the BES plant.

Overall, Platinum has shown a great environmental impact whereas the negative effects of sludge have indicated possible improvement in some areas. The environmental factors of the BES systems used for biogas upgrading are better understood by these findings which also provide guidelines for future developments.

7.1 Future Work

There are various scopes of performing the future work for a sustainable large scale BES plant for biogas upgrading.

i. Sustainable practice must be followed for extraction, refinery and mining of platinum in the South Arica and Russia.
ii. Alternative Cathode such as Nickel should be used in place of platinum and perform a lab scale experiment to observe the efiiciency of biogas upgrading and LCA should be performed for a large scale plant.
iii. A broad LCA study should be conducted including manuauturing, construction and after prroduction stage to check the overall environmental impacts.

8 References

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9 Appendices

Appendix A Inventory List

This section includes the details of the input components used during lab scale experiment [43].

Lab Scale Input components	Units	value (quantity)
Electricity (energy) consumed	kWh	0.014
Water consumed	L	0.71
Raw Biogas used	L	2.99
Anolyte ($Na2SO4$)	g	0.284
Catholyte ($Na2HPO4·12H2O$)	g	5.77
Catholyte ($NaH2PO4·2H2O$)	g	1.135
Catholyte ($NH4Cl$)	g	0.155
Catholyte (KCl)	g	0.065
Sludge	L	0.13333
Anode ($IrO2$)	g	0.09328
Anode (Titanium)	g	1.01696
Cathode (Platinum)	g	1.871
Cathode (Carbon)	g	0.765
Cathode (Titanium)	g	1.01696

i. Calculating for Mass of Anolyte: 10 mM/L of Na_2SO_4 is used as anolyte and effective liquid volume of anolyte is given 200 mL = 0.2 L
Therefore,

Calculating Mass of anolyte	= 10 mM/L X 0.2 L = 2 mM = 2 mM X (1mol/1000mM = 2 mol/1000 of Na_2SO_4 = 2mol/1000 X 142 g/mole {(Molecular wt. of Na2SO4 = 142 g/mole)} = 0.284 g

ii. Calculating for Mass of Catholyte: 11.54 g/L of $Na_2HPO_4·12H_2O$, 2.27 g/L of $NaH_2PO_4·2H_2O$, 0.31 g/L of NH_4Cl, 0.13 g/L of KCl),
The effective liquid volume of catholyte was 500 mL = 0.5 L
Therefore,

Mass of Catholyte (Na2HPO4·12H2O)	(11.54 g/L) X (0.5 L) = 5.77 g

Mass of Catholyte ($NaH_2PO_4·2H_2O$)	2.27 g/L X 0.5 L = 1.135 g

Mass of Catholyte (Na_4Cl)	0.31 g/L X 0.5 L = 0.155 g

Mass of Catholyte (KCl)	0.13 g/L X 0.5 L = 0.065 g

iii. Calculating for Mass of Sludge: 2/3 of Cathode chamber and volume of cathode chamber = 200 mL

Mass of Sludge	2/3 of 0.2 L = 0.133 g

iv. Calculating for Mass of Anode (IrO_2):

Mass of IrO_2 IrO_2 Coating Thickness 2.5 Micron Density of IrO_2 11.66 g/cm³ Projected Surface area 16 cm^2 considering only upper and lower 2 faces of IrO2	= 0.008 X 11.66 g/cm3 = 0.09328 g

v. Calculating for Mass of Anode (Ti):

Mass of Ti thickness of Ti mesh: 0.2 mm Density of Titanium = 4.54 g/cm3 Projected Surface area 16 cm^2 (Assuming 30% open area)	= (4 cm X 4 cm X 0.02 cm) X 4.54 g/cm3 = 1.45 g X 70% = 1.0169 g

vi. Calculating for mass of Cathode (Platinum): Considering the components of the cathode electrode: the titanium (Ti) electrode mesh and the platinum/carbon (Pt/C) coating.

Mass of Pt thickness of of 20 wt.% Pt/C : 136µm Density of Pt = 21.5 g/cm^3 Projected Surface area 16 cm^2 (Considering upper and lower portion) (20 wt.% Pt/C)	0.4352 cm^3 X 21.5 g/cm^3 X 0.2 = 1.871 g

vii. Calculating for mass of Cathode (Carbon):

Mass of Carbon thickness of of 20 wt.% Pt/C : 136µm Density of C = 2.2 g/cm^3 Projected Surface area 16 cm^2 (Considering upper and lower portion (80 wt.% Pt/C)	0.4352 cm3 X 2.2 g.cm-3 X 0.8 = 0.765 g

viii. Calculating for mass of Cathode (Titanium):

Mass of Ti thickness of Ti mesh: 0.2 mm Density of Titanium = 4.54 g/cm3 Projected Surface area 16 cm^2 (Assuming 30% open area)	= (4 cm X 4 cm X 0.02 cm) X 4.54 g/cm3 = 1.45 g X 70% = 1.0169 g

Appendix B: List of providers

Name	Category	Location
market for ammonium chloride | ammonium chloride | APOS, U	C: Manufacturing/20: Manufacture of chemicals and chemical products/201: Manufacture of basic chemicals, fertilizers and nitrogen compounds, plastics/2011: Manufacture of basic chemicals	Global
market for biogas | biogas | APOS, U	E: Water supply; sewerage, waste management and remediation activities/38: Waste collection, treatment and disposal activities; materials recovery/382: Waste treatment and disposal/ 3821: Treatment and disposal of non-hazardous waste	Rest-of-World
market for carbon black | carbon black | APOS, U	C: Manufacturing/20: Manufacture of chemicals and chemical products/ 201: Manufacture of basic chemicals, fertilizers and nitrogen compounds, plastics/ 2011: Manufacture of basic chemicals	Global
market for digester sludge | digester sludge | APOS, U	E: Water supply; sewerage, waste management and remediation activities/38: Waste collection, treatment and disposal activities; materials recovery/382: Waste treatment and disposal/3821: Treatment and disposal of non-hazardous waste	Global
market for electricity, low voltage, renewable energy products | electricity, low voltage, renewable energy products | APOS, U	D: Electricity, gas, steam and air conditioning supply/35: Electricity, gas, steam and air conditioning supply/351: Electric power generation, transmission and distribution/3510: Electric power generation, transmission and distribution	Switzerland
market for platinum | platinum | APOS, U	C: Manufacturing/24: Manufacture of basic metals/242: Manufacture of basic precious and other non-ferrous metals/2420: Manufacture of basic precious and other non-ferrous metals	Global
market for potassium chloride | potassium chloride | APOS, U	C: Manufacturing/20: Manufacture of chemicals and chemical products/201: Manufacture of basic chemicals, fertilizers and nitrogen compounds, plastics/2012: Manufacture of fertilizers and nitrogen compounds	Europe

market for sodium phosphate | sodium phosphate | APOS, U	C: Manufacturing/20: Manufacture of chemicals and chemical products/201: Manufacture of basic chemicals, fertilizers and nitrogen compounds, plastics/2011: Manufacture of basic chemicals	Rest-of-World
market for sodium sulfate, anhydrite | sodium sulfate, anhydrite | APOS, U	C: Manufacturing/20: Manufacture of chemicals and chemical products/201: Manufacture of basic chemicals, fertilizers and nitrogen compounds, plastics/2011: Manufacture of basic chemicals	Rest-of-World
market for titanium | titanium | APOS, U	C: Manufacturing/24: Manufacture of basic metals/242: Manufacture of basic precious and other non-ferrous metals/2420: Manufacture of basic precious and other non-ferrous metals	Global
market for water, deionized | water, deionized | APOS, U	E: Water supply; sewerage, waste management and remediation activities/36: Water collection, treatment and supply/360: Water collection, treatment and supply/3600: Water collection, treatment and supply	Rest-of-World

Appendix C: Project Thesis Description

University of
South-Eastern Norway

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

FM4017 Project

Title: Life Cycle Assessment of Bioelectrochemical Systems for Biogas Upgradation

USN supervisor: Nabin Aryal, Zahir Barahmand

KU supervisor: Anish Ghimire, Sunil Prasad Lohani

External partner:

Task background:

Produced by the anaerobic digestion of organic waste, biogas is a sustainable energy source. It might help to promote waste management and sustainable energy generation. By minimizing the demand for fossil fuels and greenhouse gas emissions, this adaptable fuel may be utilized for a variety of tasks including transportation, heat production, and power generation. Raw biogas, however, can lose some of its value and economic feasibility due to contaminants like carbon dioxide and hydrogen sulfide.

More energy content, less environmental effects, and easier integration into current energy infrastructures are all made possible by efficient biogas upgrading. The potential of Bioelectrochemical systems (BES) to overcome the drawbacks of traditional approaches have made them stand out among the many upgrading technologies that have been investigated. By selectively removing contaminants from biogas and producing a cleaner, more valuable energy product, BES technology combines electrochemical reactions with microbiological activities.

OpenLCA software is used to conduct a life cycle assessment (LCA) utilizing the cradle-to-gate stage in the search for sustainable energy solutions. However, this LCA research solely assesses the operational performance of BES-based biogas upgradation. Within the renewable energy industry, this strategy is crucial for encouraging sustainable behaviors, improving technology design, and helping to make well-informed judgments.

Task description:

This thesis aims to conduct a comprehensive life cycle assessment (LCA) of the Bioelectrochemical System (BES) for biogas upgradation, encompassing cradle-to- gate stages, to evaluate its environmental impacts.

Student category: Exchange Student from Kathmandu University, Nepal (Rajani Neupane)

The task is suitable for students not present at the campus (e.g. online students): Yes/No

Practical arrangements:
The necessary LCA software and data will be provided at the USN university

Signatures:

Supervisor (date and signature): Nabin Aryal

Students (write clearly in all capitalized letters: RAJANI NEUPANE

(Date and Signature):

RAJANI NEUPANE

28th Aug 2023