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Master of Science in ENGINEERING AND MANAGEMENT

Thesis Title

Low cost biogas purification systems: LCA study

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Acknowledgment

In the beginning, I thank God, who guided me and eased my path.

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ABSTRACT

A significant amount of carbon products are emitted as a result of burning fossil fuels, the direct release of such products has a bad effect on the environment and has a clear contribution to raising global warming temperature. This calls for the immediate adoption of renewable energy sources to mitigate the impact of fossil fuel combustion emissions.

This study aims to apply the environmental analysis, through the life cycle assessment (LCA) methodology for a purification operation of the biogas to identify the main contributions to the impacts due to the various sub-processes in the analyzed low-cost system that use ashes as a medium to eliminate unwanted contained in the biogas.

The data of the case study was collected from the Edmund Mach Foundation of Trento's "Up-ASH" plant, where biogas is produced through the anaerobic digestion process for the organic fraction of municipal solid waste (OFMSW) and using low-cost technology to adsorb impurities from biogas using wood-chip ashes coming from a district heating plant.

This technology is meant to enhance the characteristics of biogas increasing the methane ratio and lowering carbon dioxide. This method identifies ash as a key player turning waste into a primary component of the biomethane production cycle. Moreover, this strategy has the potential of upgrading technical advancement in the field of a circular economy focusing on the re-use of all-natural resources.

To analyze the life cycle impact of the purifying system, ISO 14040 and ISO 14044 frameworks were followed. By applying these frameworks criteria the life cycle assessment of the purifying was studied defining the goal and scope of the LCA study and setting the boundaries, inventory analysis of the system, calculating the impact, and interpreting the result.

GaBi software with an educational database was used as a tool for analyzing the LCA of the system by tracking and defining all flows and processes in the system. The functional unit chosen is 1 m^3 of biogas input and the impact assessment method used is CML 2001 for the analysis.

The analysis result shows that the avoided effects associated with CO_2 capture and biomethane production benefit a significant number of the indicators studied, but the final disposal of ash into landfills leads to negative contributions on the indicators, so the plausible solution might be to dispose of the ashes in some other way which research and then politics should intervene to dispose of these materials sustainably.

Keywords: LCA,Biogas purifying,biomethane,wood ash,watse,circular economy,GaBi.

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Acronyms

AD	**Anaerobic Digestion**
ADP	Abiotic Depletion Potential
ADP F	Abiotic Depletion Potential (Fossil Fuels)
Al	Aluminium
$Al2O_3$	Aluminum Oxide
As	Arsenic
Ba	Barium
BF	Bottom Ash In a Fluidised Bed
Br	Bromine
$C_{10}H_{14}OSi$	4-(Trimethylsilyl)benzaldehyde
C_2Cl_4	Tetrachloroethene
$C_2H_2Cl_2$	1,2-Dichloroethene
$C_2H_2Cl_4$	2-Tetrachloroethane
$C_2H_3Cl_3$	1,1,2-Trichloroethane
$C_2H_4Cl_2$	1,2-Dichloroethane
C_2H_5Cl	Chloroethane
C_2H_6S	Dimethyl Sulfide
$C_3H_6Cl_2$	1,2-Dichloropropane
C_3H_6S	Thioacetone
C_3H_8S	Isopropyl Mercaptan
$C_4H_{10}S$	2-Butanethiol
$C_6H_{12}S_2$	Allyl propyl disulfide
C_6H4Cl_2	1,4-Dichlorobenzene
Ca	Calcium
CaO	Calcium oxide
CAPX	Capital Costs

CBG	Compressed Biomethane Gas
CC	Cubic Centimeter
CCl_4	Tetrachloromethane
Cd	Cadmium
CE	Circular Economy
CFC	Chloro Fluoro Carbons
CH_2Cl_2	Dichloromethane
CH4	Methane
CH_4S	Methanethiol
$CHCl_2F$	Dichlorofluoromethane
CHP	Combined Heat and Power
CIB	Consorzio Italiano Biogas
Cl	Chlorine
CML	Centre for Environmental Studies
CNG	Compressed Natural Gas
CO	Carbon Monoxide
CO2	Carbon Dioxide
COS	carbonyl Sulphide
Cr	Chromium
Cr_2O_3	chromium oxide
Cu	Copper
DB	Dichlorobenzene
DEA	Diethanolamine
DETA	Diethylenetriamine
DMEA	Di-Methyl Ethanol Amine
EOL	End-Of-Life
EP	Eutrophication Potential
FAETP	Freshwater Aquatic Ecotoxicity Potential

Fe	Iron
FEM	Fondazione Edmund Mach
Fe2O_3	Ferric Oxide
GWP	Global Warming Potential
H2	Hydrogen
H_2S	Hydrogen sulfide
HCl	Hydrogen chloride
HCN	Hydrogen cyanide
Hg	Mercury
HHV	High Heating Value
HPWS	High Pressure Water Scrubbing
HTP	Human Toxicity Potential
ILCD	International Reference Life Cycle Data System
IPCC	Intergovernmental Panel on Climate Change
IRENA	International Renewable Energy Agency
ISO	International Organization for Standardization
K	potassium
K_2O	Potassium oxide
KW	kilowatt
L_2	Iodine
LBG	liquified Biomethane Gas
LCA	Life Cycle Assessment
LCC	Life Cycle Cost
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LNG	liquified Natural Gas
MAETP	Marine Aquatic Ecotoxicity Potential
MEA	Mono ethanol amine

Mg	Magnesium
MgO	Magnesium oxide
Mn	Manganese
MnO	Manganese dioxide
Mo	Molybdenum
N_2	Nitrogen
Na	Sodium
Na_2O	Sodium oxide
NH3	Ammonia
Ni	Nickel
NMP	N-Methyl Pyrrolidone
NMVOC	Non-Methane Volatile Organic Compound
NO_X	Nitric oxide
O2	Oxygen
ODP	Ozone Depletion Potential
OFMSW	Organic Fraction of Municipal Solid Waste
P_2O_5	Phosphorus pentoxide
Pb	lead
PEG	Polyethylene Glycol Ethers
PEI	Polyethyleneimine
POCP	Photochemical Ozone Creation Potential
PSA	Pressure Swing Adsorption
PSIG	Pound Per Square Inch
Sc	Scandium
SETAC	Society of Environmental Toxicology and Chemistry
Si	Silicon
SiO_2	Silicon dioxide
Sn	Tin

Sr	Strontium
STP	Sewage Treatment Plant
TC	Technical Committee
TEPA	Tetraethylenepentamine
Ti	Titanium
TiO_2	Titanium dioxide
TRACI	Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts
TRL	Technology readiness level
UNFCCC	United Nations Framework Convention on Climate Change
UNIDO	United Nations Industrial Development Organization
USD	United States Dollar
UV	Ultraviolet
V	Vanadium
V2O5	Vanadium Oxide
VMSs	volatile methyl siloxanes
VOC	Volatile organic compounds
Zn	Zinc
ZnO	Zinc oxide
ZrO2	Zirconium dioxide

CHAPTER ONE: INTRODUCTION

Synopsis

The introductory chapter provides insights into the justification of the dissertation topic and introduces many relevant terms. After a basic introduction to many aspects of life cycle assessment, biogas production, and purification, this chapter also aims to cover this task and the structures selected here to present it.

1.1 Background

We face two major concerns heavily reliant on the energy sector in the twenty-first century: sustainable economic development and global climate change. The decarbonization of today's energy system is frequently tied to addressing them. Primary energy consumption increases at about 2% per year, but this growth relies primarily on fossil fuels. Low carbon and renewable energy solutions are required to alleviate the negative externalities associated with the fossil fuel sector. Anthropogenic greenhouse gas emissions, in particular, are rapidly increasing and are extremely likely to be already causing changes to the global climate system; without substantial mitigation strategies, emissions are expected to rise by almost 30% in the next 20 years. As a result, future energy scenarios consistent with avoiding the worst effects of climate change feature a high penetration of low-carbon technologies, including renewable energy (1).

To alleviate the immediate dangers of global warming, it is vital to reduce greenhouse gas emissions. In 1992 Several countries signed the United Nations Framework Convention on Climate Change (UNFCCC), with the major goal of reducing greenhouse gas emissions by 5% or more by 2012, compared to 1990 levels. The Kyoto Protocol, adopted in December in Kyoto, entered into force in 2005. Then in 2009, in Copenhagen (Denmark), it was intended to persuade world governments to force behavioral changes to reduce global pollution and climate change; suppose an actual effort is made to avert global climate change, and the modern renewable biomass industry is developed sensitively and responsibly. In that case, renewable biomass could play a significant role in future energy supply as a fossil fuel substitute, food security, and global warming mitigation (2).

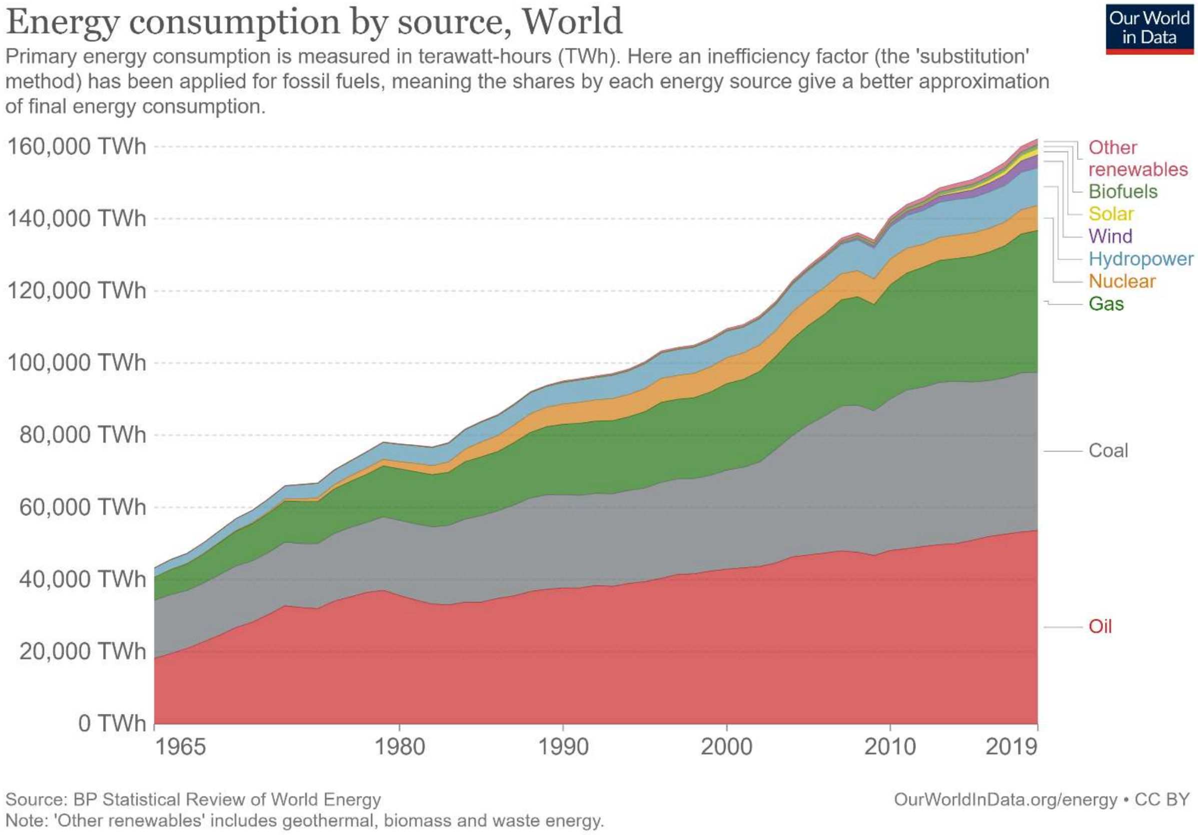


Fig (1.1): Energy Consumption by source from 1965 to 2019 (3)

Massive carbon dioxide (CO_2) emissions have raised concerns about energy sustainability and environmental protection during fossil fuel combustion. The rate of CO_2 that is presently being released at a global scale is more than 1000 kg/s. The reductions of CO_2 emissions into the atmosphere can only be achieved by either reducing the CO_2 emissions from the sources or increasing the usage of CO_2. To achieve sustainable development, energy resources with low environmental impact should be utilized(4).

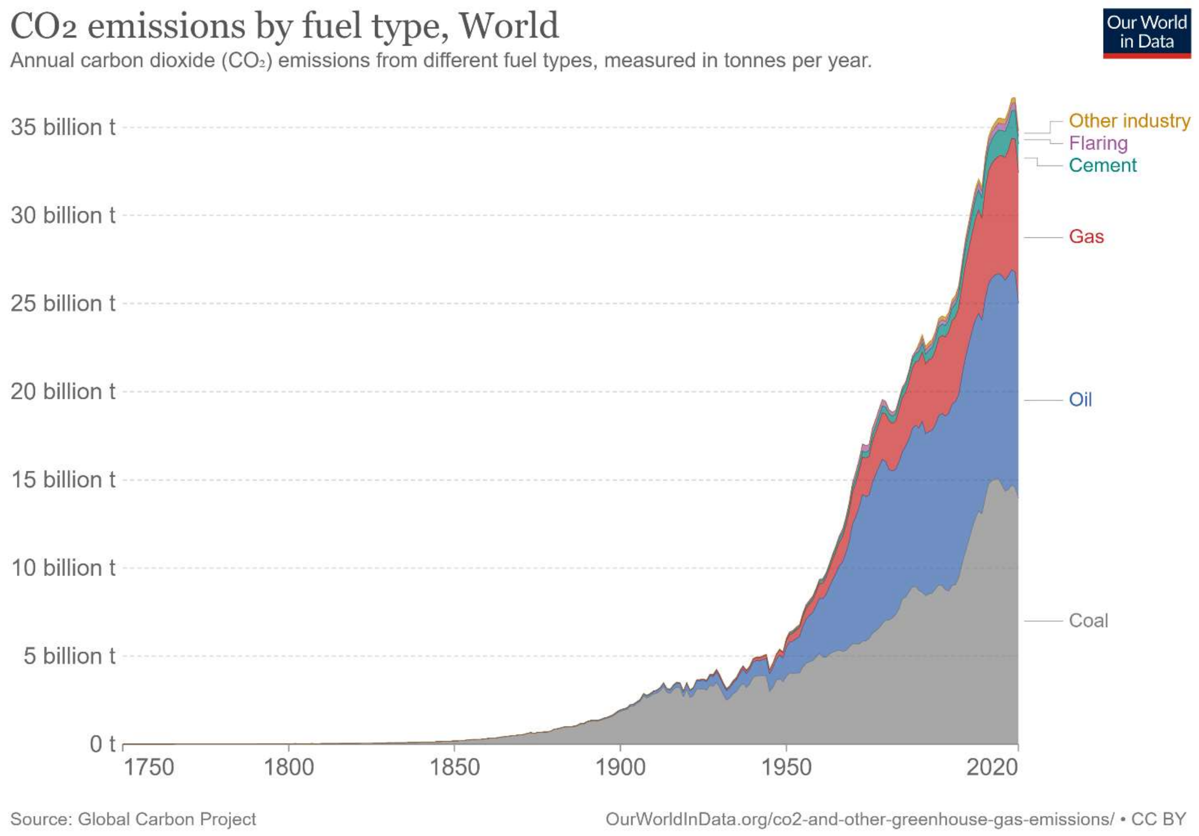


Fig (1.2): Annual carbon dioxide (CO_2) emissions from different fuel types, measured in tonnes per year (5)

Solar, hydro, wind and nuclear power are examples of energy sources with low carbon emissions; in addition to those power sources that emit a low carbon percentage, biogas is an energy source that can be used in various ways. For instance, it may be used to replace fossil fuels in heat and power generation, addressing environmental concerns and the global energy security challenge that must be handled because most conventional oil and gas deposits are located in politically unstable areas. Moreover, biogas with a high methane content (biomethane) could be used as a vehicle fuel or fed into the natural gas system; it can also be used to make chemicals and materials instead of natural gas as a feedstock (6).

Biogas implementations must meet strict quality standards. As a result, various cleaning procedures can be used to enhance the final specifications of processed gas; various technologies are placed on the market with different performances of purification and cost. In addition, these technologies have in common is the necessity to remove carbon dioxide and other polluting substances using various methods and types of equipment, resulting in methane of such high purity that it can be supplied into the grid and substitute natural gas.

There are many technologies considered a low-cost process that can be used to enhance the biogas and upgrade it into biomethane; one of these methods is using ashes as a by-product that comes from the combustion of woody biomass as an adsorbent material for biogas impurities. This technology turns wood-chip ashes from a district heating plant into the primary component of a biomethane production cycle.

1.2 Aims and Objectives

The goal of this dissertation is to apply Life Cycle Assessment(LCA) criteria based on International Organization for Standardization 14040 (ISO), to assess the environmental impact by exploring to use of ash which is considered as a low-cost system in upgrading biogas to enhance its characteristics remove unwanted components in the gas, the data for study collected from the existing system is located in Italy in the Tuscany region and using GaBi software as a tool to analyze the system.

1.3 Thesis structure

The section presents the overall design for this thesis as follows:

- **Chapter 1 (Introduction):** This chapter introduces the whole view going through the research background and aims and the thesis structure.
- **Chapter 2 (Literature review):** Presents the systematic, intensive literature review that has been done and all the information that is currently available about the topic considering scholarly writings that fulfill the thesis merit selection criteria.
- **Chapter 3 (Methodology):** This chapter will go through the research methodology used in this thesis. It will discuss the type of conducted research and the criteria used for collecting and filtering data.
- **Chapter 4 (UP-ASH Project Overview):** This chapter shows the detailed testing of innovative technology for the purification (upgrading) of biogas from (Municipal solid waste) MSW through the use of woody biomass combustion slag for a plant located in the Tuscany region in Italy.
- **Chapter 5 (Result):** The obtained results will be discussed, and an explanation of how the research and its findings help reach the objectives will be provided.

- **Chapter 6 (conclusion):** Finally, the thesis is entirely summarized, providing an active call to action. Possible recommendations for further work are also reflected and shared in this chapter.

CHAPTER TWO: Literature review

Synopsis

The literature review is a compilation of scholarly articles on the subject. All peer-reviewed publications, books, dissertations, and conference papers will be included. This chapter epitomizes the existing state of knowledge about the subject, relying on scholarly literature that satisfies the thesis merit selection criteria.

2.1 Biomass processing

Different technologies can convert biomass into valuable energy, including combustion, gasification, and anaerobic digestion. Combustion is the most basic technology, and it involves burning biomass in the steam cycle; the combusted gas is subsequently used to heat a typical boiler and drive a turbine. An alternative method to process biomass is gasification which is also called (Syngas Road). The idea of this thermochemical transformation is to handle dry or partially dry via gasification followed by phases of cleaning and conditioning, methanation, and final upgrading of the produced syngas. The latter approach is anaerobic digestion (AD), also called (Biogas Road); by this operation, wet biowaste is converted biologically with anaerobic digestion and then upgrading of resulting biogas, for the AD process, the ratio of the total solid is frequently below 30%. Syngas road is a narrower range than biogas road, with low TRL (Technology readiness level)(7,8).

Thermal systems can only be used on feeds with a low water content (less than 50%) or dewatered mechanically for a reasonable cost. This constraint is related to the energy necessary for water evaporation to reach the high temperatures required for the operation. In addition, thermal methane production technologies are likewise only cost-effective at large scales and produce a combination of gaseous products (such as hydrogen and carbon monoxide) to be converted to methane(9).

2.1.1 biogas structure and contents

Biogas is a combination of gas created anaerobically by decomposing organic matter such as energy crops, plant biomass, animal manure, agricultural wastes, wastewater treatment sludge, and other organic waste sources. Generally, biogas contains a combination of 40–60% methane gas (CH_4) and 60–40% carbon dioxide (CO_2) with traces of ammonia (NH_3), hydrogen sulfide (H_2S), H_2, nitrogen (N_2), oxygen (O_2), hydrocarbons, carbon monoxide (CO), siloxanes and volatile organic compounds

(VOC) such as ketones, alkanes, and terpenes. Using the AD technique, biogas is produced with four stages: (i) hydrolysis,(ii) acidogenesis, (iii) acetogenesis/dehydrogenation, and (iv)methanogenesis; throughout all of these actions, the different gasses generated and in the final methanogenesis step methane is produced(10).

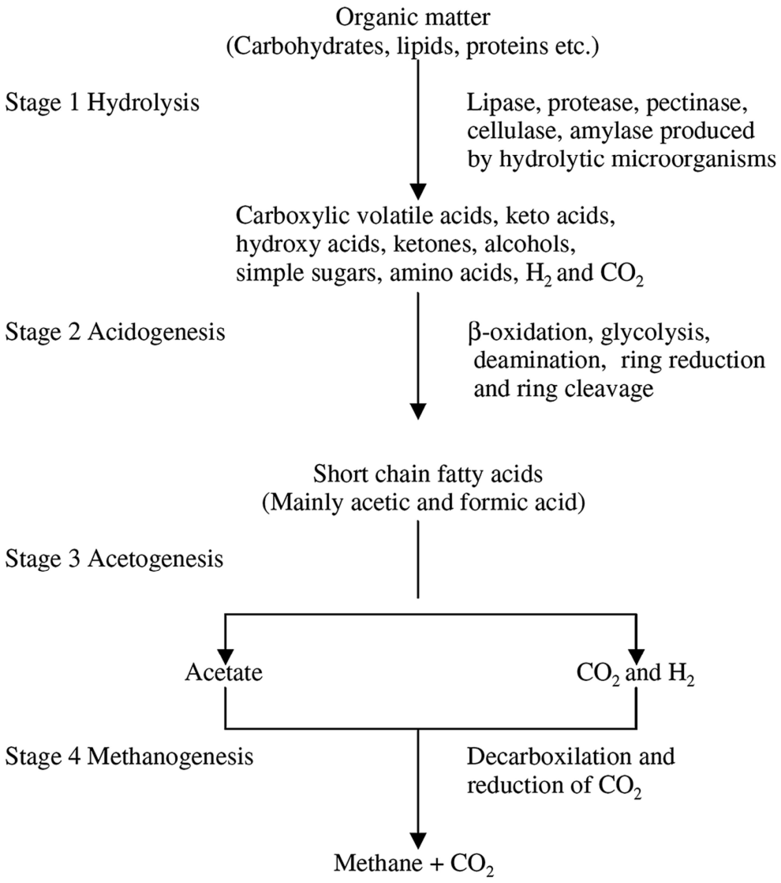


Fig (2.1): processes for biogas formation(11)

The mixture of gases formed by the anaerobic fermentation process is not stable because it depends on the raw material used, operating temperature, digester type, and retention time. Therefore, many kinds of research have focused on studying different raw materials to obtain the best texture of the produced gas. Analyzing the final generated gas through the AD process for different biomass origins is essential to know the percentage of the gas mixture.

Component	Agricultural waste	Landfills	Industrial waste
Methane CH_4	50-80	50-80	50-70
Carbon dioxide CO_2	30-50	20-50	30-50
Hydrogen sulphide H_2S	0.7	0.10	0.80
Hydrogen H_2	0-2	0-5	0-2
Nitrogen N_2	0-1	0-3	0-1
Oxygen O_2	0-1	0-1	0-1
Carbon monoxide CO	0-1	0-1	0-1
Ammonia NH_3	Traces	Traces	Traces
Siloxanes	Traces	Traces	Traces
Water H_2O	Saturation	Saturation	Saturation

Table (2.1): Typical composition (%) of biogas (11)

2.1.2 Biogas impurities during conversion and use

Several contaminants must be eliminated before use to enhance performance and reduce environmental pollution from harmful gas emissions during biogas generation (12). biogas can be used directly in different heating, cooking, and generating power applications. Still, in the case o direct use of biogas with the existence of a high percentage of CO_2, this will lead to lowering heating value and limits the economic viability of direct usage(13).

Removal of Carbon monoxide (CO) is necessary because it is poisonous to humans and several microorganisms involved in forming CH_4 in digesters, reducing biogas calorific power. H_2S must also be eliminated from biogas before combustion because it is extremely hazardous to the environment, poses a health risk, and can cause maintenance issues, particularly rusting. Chemical corrosion can occur when H_2S is burned in a boiler or an internal combustion engine. H_2S inhalation can cause loss of consciousness, coma, respiratory paralysis, seizures, and mortality in asthmatics at low concentrations (70 mg/m^3). At higher concentrations (700 mg/m^3), inhalation can cause health problems that may even lead to death. NH_3 has a strong inhibitory effect in the anaerobic digester at high concentrations, resulting in lower biogas and methane output. Furthermore, NH_3 can produce aerosols during biogas combustion, marginally increase nitrogen oxide (NO_x) emissions, and be a corrosion source. Besides that, biogas outflow from digester contains water this percentage depends on the temperature if biogas will be injected into the grid or used as a fuel for automobile, gas turbine, and combined heat and power (CHP) this percentage of water must be lowered by drying processes to use biogas properly for those applications(14,15).

Impurity	**Negative effect**
CO_2, N_2, and H_2	They are decreasing the energy content/calorific value of the biogas.
H_2O and O_2	Reaction with other compounds (e.g., siloxanes) in the combustion process forming sulfuric acid and hydrochloric acid, which contributes to corrosion; H_2O can accumulate in pipes; O_2 is corrosive and may be explosive in concentrations >6%.
NH_3	Corrosive; This Could lead to the formation of respiratory toxic compounds after biogas combustion, such as aerosols and nitrogen oxides (NO_x).
H_2S and other sulfur compounds	Extremely corrosive to heat and power units; Can be converted to toxic and environmentally hazardous and corrosive forms (SO_2, SO_3, and H_2SO_4); Sulfur compounds poisoning on nickel sites of fuel cells Deposits of elemental sulfur.
CO	Toxic to humans and some microorganisms present in the biodigester
VOCs	Some of them are corrosive; Some of them are toxic for humans and microorganisms; Unpleasant odors.
Halogenated compounds	Corrosion in equipment/engine; May form emissions of toxic by-products during combustion such as polyhalogenated dioxins and furans.
VMSs	Silicon dioxide (SiO_2) and microcrystalline quartz are formed in the combustion process and deposit in engine components, VMS emissions that may be directly or indirectly toxic to humans.

Table (2.2): Effects of biogas impurities during conversion and use(14)

2.2 Biogas purifying

Many technologies purify biogas, these technologies are different in operations and techniques, but the purpose is consolidated to reduce the percentage of undesired contents to increase the efficiency by lifting the caloric value of the gas to be processed and used in many applications in daily life besides that the cleaned gas can substitute and replace fuels such as fossil fuel which affect the environment.

High CO_2 concentrations at the point of production reduce heating value and increase compaction and transportation costs, limiting the economic viability of biogas for power generation. Other pollutants hurt the structure of downstream system equipment, such as corrosion of engines, tubes, and chimneys(16). Cleaning (removing minor unwanted components of biogas) and upgrading (reducing CO_2 content) are the two primary processes in the treatment of biogas. The ultimate result is biomethane, composed of CH_4 (95–99 percent) and CO_2 (1–5%), with no trace of H_2S. Cleaning biogas is frequently the initial stage in biogas applications, and it is an energy-intensive process. The second procedure tries to raise the low calorific value of biogas to convert it to fuel with high standards (4).

Standards provide the limit acceptance to use biogas and to be injected into natural gas streams and also those standards assuring the operation's safety and continuation; one of those documents is UNI/TR 11537:2019, which provides technical indications for the introduction of biomethane, obtained from the purification of gas produced from renewable sources, into the natural gas transmission and distribution networks, guaranteeing the conditions of safety and continuity of service, regardless of the source and method of production used. The document applies to biomethane produced for injection into the natural gas transmission and distribution network, following current legislation, and to biomethane injection plants in the natural gas transmission and distribution networks.

Paramter	Symbol	Unit of measure	Value	Sampling
High Heating Value	HHV	MJ/Sm^3	$\geq 34,95 \leq 45,28$	Continuous
Wobbe Index	WI	MJ/Sm^3	$\geq 47,31 \leq 52,33$	Continuous
Relative density	-	-	$\geq 0,555 \leq 0,7$	Continuous
Water dew point	-	-	< -5°C at 7000 kPa	Continuous
Volumic mass	ρ	%mol	kg/Sm3	Continuous
Oxygen	O_2	%mol	$\leq 0,6$	Continuous
Carbon dioxide	CO_2	mg/Sm^3	$\leq 2,5$	Continuous
Hydrogen sulphide	H_2S	mg/Sm^3	≤ 5	Continuous
Sulphur content from hydrogen sulphide (H_2S) and carbonyl sulphide (COS)	H_2S COS	mg/Sm^3	≤ 5	Discontinued
Sulphur from mercaptans	-	mg/Sm^3	≤ 6	Discontinued
Total sulphur	-	mg/Sm^3	≤ 20	Discontinued
Total volatile silicon content	SI	%mol	0,3 ÷1	Discontinued
Carbon monoxide	CO	mg/Sm^3	$\leq 0,1$	Discontinued
Ammonia	NH_3	mg/Sm^3	≤ 10	Discontinued
Amines	-	%Vol	≤ 10	Discontinued
Hydrogen	H_2	mg/Sm^3	≤ 1	Discontinued
Fluorine	F	mg/Sm^3	< 3	Discontinued
Chlorine	Cl	%mol	< 1	Discontinued
Compressor oil	-	%mol	-	Discontinued
Powders	-	mg/Sm^3	-	Discontinued

Table (2.3): biomethane limits according to UNI/TS 11537:2019(17)

2.2.1 Biogas Purifying Technologies

Different methods are applied in purifying biogas from contaminants to pave the way for using a clean and efficient energy source in various applications. These techniques are primarily used for Carbon dioxide (CO2) separation; thus, there are constraints in selecting the appropriate technology and the most significant in terms of methane losses and cost. Each technology has its strengths and weaknesses.

According to the literature, the principal techniques are Absorption (Water scrubbing, Organic scrubbing, Chemical absorption), Adsorption (Pressure swing adsorption (PSA)), Cryogenic separation, Membrane separation, and biological upgrading.

Fig (2.2) shows the share of different biogas upgrading technologies in Europe according to UNIDO in 2016.

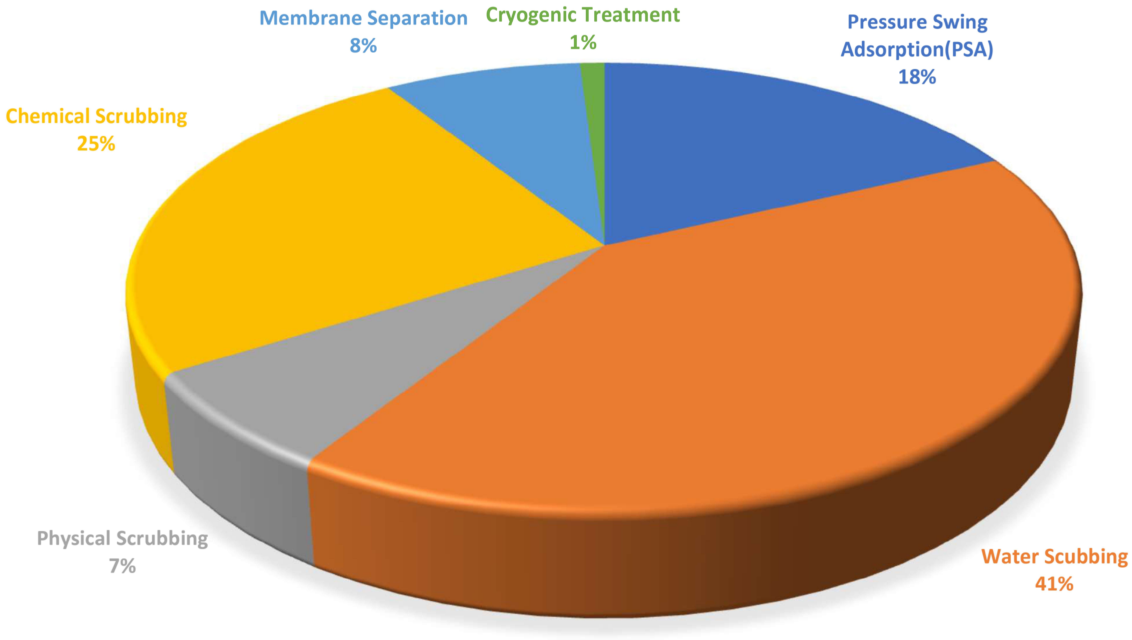


Fig (2.2): Biogas upgrading technologiesin Europe in 2016(18)

2.2.1.1 Absorption techniques

Absorption techniques can be done physically by water scrubbing and organic scrubbing or chemically. The idea of this technique is CO2 is more soluble than methane. In particular, column biogas encounters a counterflow of a liquid (liquid chemical solution, water); as a result, the liquid will have a higher concentration of CO2 when it leaves the column, whereas the enhanced gas will have a higher concentration of methane, the type of absorbents utilized in the column determine the differences in absorbent techniques (19).

2.2.1.1.1 Water scrubbing

Water scrubbing is the most widely used biogas purification method; the concept of this method is higher water absorption of CO_2 and H_2S over CH_4, enabling it to separate both CO_2 and H_2S from biogas with high efficiency(19). At 25 °C, the solubility of CH_4 is lower by 26 times than CO_2. In comparison to CO_2, H_2S has a higher solubility in water; separating the H_2S prior to CO_2 removal is recommended because the soluble H_2S is particularly corrosive(15).

The biogas is compressed to high-pressure varying from 6 to 10 bar and with a temperature up to 40 °C, then biogas is fed into the bottom of the absorption column while the water is supplied from the top and to enhance gas-liquid mass transfer, the absorption column is frequently filled with random packing material, then at the top of the scrubber biomethane is released, the water that contains CO_2 and H_2s Is channeled from the bottom into a flash vessel, and the pressure dropped to the range of 2.5 to 3.5 bar, and some residues of CH_4 dissolved in the water are retrieved to decrease the losses of biomethane of the process(20).

The challenge in the process is the availability of water to be reused in the process again, so two systems can be applied in this case, the first one is single-pass scrubbing, and this can be utilized if the source of water is sewage treatment plant (STP) which is considered as a cheap water source, the other system is called regenerative absorption, the concept here is to recycle the water to reuse it again in scrubber operation by decompression the water at atmospheric pressure in desorption column to regenerate the water to remove CO_2 and H_2S, this process is vital for high capacity systems which consume a large amount of water(20,21) For the regeneration process stripping with air is not suggested when a large amount of H_2S occurs in biogas because elemental sulfur is generated, which might cause operational issues, so instead of this Steam or an inert gas must be utilized(22).

2.2.1.1.2 Organic scrubbing

Organic scrubbing is one of the physical methods, the concept of operation is similar to water scrubbing, but the difference here is the organic solvent instead of water. Different types of solvent can be used, such as methanol (CH_3OH), polyethylene glycol ethers (PEG), and N-methyl pyrrolidone (NMP), For the same upgrading capacity, CO_2 solubility in PEG is five times higher than in water, and this will lead to reducing the volume required of the solvent and pumping capacity, In addition to the absorbing carbon dioxide solvent can absorb impurities such as H_2S, H_2O, O_2, N_2, and halogenated hydrocarbons, However(23), for this absorption process, it is advised that H2S be removed first to reduce the consumption of energy due to high solubility of H_2S; as a result, greater temperatures are required for its separation during solvent regeneration(20).

Raw biogas is compressed to 7–8 bar to be upgraded by organic solvent and then decreasing temperature to 20°C before injecting from the bottom the absorption column while the solvent is cooled before being supplied from the top; after the scrubber process is finished, an organic solvent is regenerated by heating up to 80°C and depressurizing to 1 bar into in a desorption column(21).

2.2.1.1.3 Chemical absorption

Chemical absorption operates with amine solution, or alkali solution works on the principle as water scrubbing, Mono ethanol amine (MEA) and di-methyl ethanol amine (DMEA) were the two most often used amine compounds, and for alkali Sodium, potassium, and calcium hydroxides are the most often used. Chemical scrubbing operates on the principle of a reversible chemical reaction involving absorbed gases and a chemical solvent(24).

The process occurs when the raw biogas enters from the bottom of the absorber while the amine is delivered to the top of the column to form a countercurrent flow contact. CO_2 is absorbed after reacting with an exothermic reaction with the amine solution, which raises the absorber's temperature from 20–40 to 45–65 °C. The increased temperature in amine scrubbing will increase the ability of absorption of CO_2 by amine solution. The resultant gas (CH_4) is ejected from the column's top while the liquid at the bottom of the absorber is sent to the top of the stripper column, where it is linked to the steam, and CO_2 is discharged via the heat exchanger. The amine solution is heated at 120–150 °C in the lower half of the stripper column. This reboiler heat reaction is used to regenerate the amine solution by releasing the CO_2 from the waste amine solution(23).

2.2.1.2 Pressure swing adsorption (PSA)

This approach was initially used to enhance CH_4 from biogas in 1989 when simulated biogas was purified with natural zeolite. Then the Pressure swing adsorption approach has been widely utilized for biogas cleaning. PSA functioned in a high pressure to extract desired gases by using the adsorbents variances in gas adsorption ratios; after that, the adsorbates are released at low pressure to renew the adsorbent for another adsorption loop. Adsorbents are chosen based on their low-cost rates, large specific area, pore-volume, and high thermal steadiness. The most common adsorbents used are zeolite, silica gel, activated carbon, and carbon molecular sieve(19).

Pressure swing adsorption operation occurs with four main steps: the first phase is adsorption: After removing H_2S and H_2O, biogas is delivered from the bottom at a pressure of 6–8 bar through one of the adsorbers, carbon dioxide and/or oxygen and/or nitrogen are selectively absorbed by the medium as they move through the vessel and the gas released as methane. To achieve proper functioning, biogas is transferred to another appropriate vessel that has already been regenerated before the adsorbent substance is saturated. The second phase is blow-down (Depressurization); in this step process, the adsorber vessel is gradually depressurized to atmospheric pressure and then to close vacuum conditions situation. Firstly, a pressure of 6–8 bar is decreased to roughly 3–4 bar by pressure interaction with column 4, which was initially degassed by a bit of vacuum before being dropped to atmospheric pressure. The third stage is purge (Regeneration); in this phase, after evacuating the vessel nearly to atmospheric pressure (0.1 bar), the desorbed gas primarily consists of CO_2, with some $CH_{4,}$ so the purge phase is procced to reduce the amount of CO_2 in the desorbed gas by recycling some of the purified CH_4 to displace CO_2 from the CH_4 product end, with depressurization, the off-gas contents throughout regeneration. At high pressures, the percentage of emitted CH_4 in off-gas is significant, while the bulk of CO_2 is desorbed at low pressures. To reduce CH_4 loss, off-gas from the initial decompression stage with a high proportion of CH_4 is piped back to the raw biogas intake. The CO_2-rich off-gas produced during the later stages of regeneration could be directed to the next step of adsorption in the off-gas treatment system or released to the atmosphere (if CH_4 loss is low). The exhaust gas of the CO_2 saturated column is sent to the adjacent recently regenerated adsorption column. A combination of CO_2/CH_4 with a high CH_4 content is discharged and recycled back to the PSA system's input. To complete the regeneration of the adsorbent material, the saturated column is washed with upgraded biogas. The last step is pressurization; the pressure should be increased to start the next round in this phase. The adsorber vessel is re-pressurized step by step to the final adsorption pressure before the adsorption phase resumes. The final pressure build-up is achieved with feed gas after a pressure balancing with an adsorber that has previously been in adsorption mode(21).

2.2.1.3 Cryogenic separation

The fundamental of this technology is based on the variance in liquefaction temperatures for biogas compounds by a progressive drop in gas temperature extraction of CH_4 from the other components achieved. Liquefaction is performed by gradually lowering the temperature to eliminate a single contaminant (or a subset of them) in stages; in the first step, the temperature is set up at − 25 °C, whereas products such as H_2O,

H_2S and siloxanes are captured, then the temperature is lowered to − 55 °C to partially liquefy CO_2; the last step temperature drops to − 85 °C to remove any remaining CO_2 via a solidification stage. There is another system operating with a lower temperature of between −45 and −55 °C, and gas is then dried before being compressed in stages up to 80 bar. Still, the need for cooling in multiple-stage compression is a drawback. Liquified CO_2 is considered a by-product for cryogenic separation, and it can be offered for sale to enhance the economic efficiency of this technology(25).

2.2.1.4 Membrane separation

The general concept of membrane separation was that some elements of raw biogas were carried through a membrane while others were preserved. Average working pressures ranged from 25 to 40 bars. Hollow fiber and spiral wound modules were more commonly used because of the large packing density. The procedure was widely carried out in two steps. Before entering the hollow fibers, the gas passes through a filter, which removes water, oil droplets, and aerosols that might otherwise harm the membrane's function. In addition, there are two methods for membrane separation; for both techniques, several phases may be necessary, but these resulting methane losses, the first technique is gas/gas (high-pressure gas separation), and the other one is gas/liquid adsorption. To remove H_2S and oil vapors, pressured gas ranging from 20 to 36 bar was employed initially in gas–gas separation(24).

Extensive membrane gas extraction is more effective at low gas flow and the incoming CO2 level. Besides that, many polymeric membranes are used in this separation operation; the most common materials are polysulfone, polydimethyl siloxane polycarbonate, cellulose acetate, and polyimide(23).

Gas/Gas units are designed in various arrangements, including single membrane modules and multiple membrane modules with internal permeate recirculation for CH_4 recovery. Only the penetrated gas from the last module is recirculated when numerous units are connected in sequence. For Gas/Liquid, gas molecules such as oxygen and hydrogen sulfide (H_2S) permeate through the membrane and are absorbed into the liquid on the opposite side. To prevent the liquid from flowing towards the gas side, the gas is gently compressed to near atmospheric pressure, amine solution is used for Gas/Liquid, it is efficient and with a single-stage CH_4 released with a purity of 96%, and at the end, the heating is applied for a regenerative process(21).

2.2.1.5 Biological upgrading

The biological approach may be a viable option for upgrading biogas. This biological system can effectively remove CO_2 while roughly raising the mass of CH_4. Because the chemicals employed in this procedure were minimal, it was deemed a cost-effective and environmentally beneficial process. It was generally known that chemotrophic, heterotrophic, and autotrophic bacteria might be used to improve biogas(24).

There are three groups of biological for biological processes: (1) in situ biogas: H_2 is carried through the liquid phase of the reactor of biogas and afterward reacts with the CO_2 stored within the reactor to produce CH_4. (2) ex situ biogas wherein CO_2 is supplied from external sources, and H_2 is fed into the liquid phase of a reactor containing hydrogenotrophic cultures, yielding CH_4. (3) Hybrid biogas improvement technique that combines in situ and ex situ biogas upgrading to optimize the process(23).

2.2.2 Technical comparison between different purification technologies

All biogas purification techniques have their pros and cons. To assess the performance of these technologies, the following should be taken into consideration: the percentage of impurities that have been removed, the energy required to run the process, and the need for chemicals or other consumables.

Table (2.4) shows the comparison between different technologies used for biogas purification.

Technology	Pros	Cons
Water scrubbing	• It the not a complicated process, so it is easy to use and to be scaled for different pressures and temperatures • Purity of CH_4 up to 97% • Extract $CO_{2,}$ $NH_{3,}$ and dust • Reomve H_2S When H_2S < 300 cm^3/m^3 • No chemicals needed • Possibility to regenerative • CH_4 loss is low < 2 %	• Require high amount of water for processing even In regenerative • clogging occurs in the case of bacterial growth • Foaming possibility • The presence of sulfur dioxide leads to corrosion • Input gas's flexibility is limited • The process is slow due to physical solubility • In some cases, H_2S removability is low
Organic scrubbing	• Higher solubility of CO_2 than water • CH4 purity is high >96 % for organic solvent and < 93–98 for polyethylene glycol • Low CH_4 losses	• In the case of the regenerative process, energy consumption will increase • Solvent regenerative is complex when removal of H_2S does not occur • Operating is difficult
Chemical absorption	• The efficiency of CH4 purity is 96-99 % • CH4 losses <0.1 % • H_2S, HCN, $NH_{3,}$ and H_2O is removed through this process • Operation is faster than water scrubbing, and column size is lower compared with water scrubbing • Regenerative process of chemical solvent is easy	• Operating is difficult • Heat is required to supply steam for the regenerative process • At high temperatures, corrosion can take a place • Foaming possibility • Chemicals used are expensive • Chemical water is produced
Pressure swing adsorption (PSA)	• Efficient is high (CH_4 96% –98%) • No heat or chemical is used • CO_2, N_2, and O_2 are removed • Easy to scale and compact • Installation and start-up are comparatively quick	• When a valve fails, CH_4 is lost • H_2S and water must be removed before processing • Process control is essential

Cryogenic separation	• The efficiency of CH_4 purity is 90-98 % • CO_2 is produced as a by-product and can be sold • Gas volume is reduced due to the liquid form of CH_4, and it will be easy to distribute • Low methane losses	• A large number of pieces of equipment and process is used • Pre-treatment actions are required • The energy required for cooling is high • CO_2 can rest in the CH_4
Membrane separation	• CH_4 purity is >96 % • No chemicals are used • Simple, compact, and high reliability • Simple to run and maintenance • CO_2 can be produced in its purest form • H_2O and H_2S are removed	• To achieve a high purity ratio, numerous steps must be processed • Methane losses range from moderate to high (CH_4 losses <10%), so it is not recommended for high purity needs • Membrane blocking and fouling • The need for replacing the membrane varying from 1-5 years
Biological upgrading	• Low energy consumption • Enhancement of CH_4 • CO_2 and H_2S is removed • No undesired end products	• For bacterial growth, adding nutrition is needed • In treated gas tiny quantity of O_2 and N_2 is remained

Table (2.4): comparison between different technologies used for biogas purification(15,19–22,24)

2.2.3 Economic effectiveness of biogas purifying methods

The quantity of energy required to improve raw biogas into a pure CH_4 has become a high priority because that energy consumed in these processes will affect the cost of the upgrading, which must be feasible at the end to use the technology in purifying biogas; the less energy consumed for upgrading, the much more net energy is available for usage in the end(24).

For economic assessment for upgrading technologies, some costs should be considered: capital costs (CAPX) and operating and maintenance costs (O&M).

Biogas enhancing technologies' capital and operating expenses are determined mainly by the method chosen for upgrading, the raw biogas quality, the intended output quality, and, most crucially, the plant's capacity(23).

Capital costs are linked directly with the plant's capacity; they are linked inversely proportional, which the more significant the plant, the cheaper the capital costs(26), regarding the plants with a small capacity, an approximately identical number of pipes, fittings, equipment, valves, and auxiliaries for a plant with far more capacity(23).

Operating and maintenance costs (O&M) are composed of energy consumption cost, labor cost, substances used, either water or any chemicals used in the different technologies and maintenance procedures(26).

Technology	**Cost per €/Nm^3 of biogas**	**Capital costs for different plant sizes**	
		Plant size m^3/h	**Capital costs kUSD/(m^3/h)**
PSA	0.4	250	5.5
		500	3.2
		600	2.4
		1000	2.2
high-pressure water scrubbing (HPWS)	0.13	250	1.22
		500	2.7
		660	2.78
		1000	2
Organic physical scrubbing	-	250	4.8
		500	3.8
		1000	2.4
Chemical scrubbing	0.17	100	10.5
		250	5.5
		500	3.6
		1000	2.6
Membrane separation	0.12	100	6.6
		600	2.5
		700-1400	2.2

Table (2.5): capital cost of investment for biogas purification methods (23)

To compare the maintenance cost for different technologies, the comparison should be based on a uniform size, so for a 1000 m^3/h of raw biogas, The maintenance cost for Chemical scrubbing is 59 K€/year which is the highest value among other technologies and with 91 % technical availability per year which is the lowest compared with other techniques, PSA value maintenance cost is not far away from chemical scrubbing, the yearly maintenance for PSA is 56 K€/year but the availability per year is better of compared of chemical scrubbing with 3%. Water scrubbing is categorized as the lowest maintenance cost with a yearly value of 15 K€/year and technical availability of 96%.in addition, membrane separation and organic physical scrubbing have an annual maintenance cost of 25 K€/year and 39 K€/year, respectively. Membrane separation has 98% and 96% technical availability for organic physical scrubbing per year. This comparison shows that technology availability increase with low maintenance costs and vice versa(23).

Operation energy in water scrubbing is needed for water and gas compression, the required cost of energy to raise the pressure of water with the range of 0.05–0.1 kWh/ Nm^3, while the gas compression ranges from 0.10 to 0.2 kWh/Nm^3 for the pressure range from 6 to 8 bar. For organic scrubbing, the energy is needed to compress the biogas and solvent into processes, and its cost is 0.2–0.25 kWh/ Nm^3. In technical literature, greater energy demands in the range of 0.4–0.51 kWh/ Nm^3 can be discovered. In the case of Chemical absorption techniques, the expenditures of chemicals, antifoaming substances, the chemical makeup of chemicals are minor. The energy needs for gas compression and liquid pumping range between 0.12 and 0.15 kWh/Nm^3, while the expense for amine regeneration is 0.55 kWh/Nm^3.PSA The energy required for gas compression and drying is 0.24–0.6 kWh/Nm^3.

Regarding the PSA technology, the energy required for gas compression and drying is in the range of 0.24–0.6 kWh/Nm^3. A recent review indicates that electricity is required by 0.25–0.3kWh/Nm3, including off-gas processing with catalytic oxidizers. For cryogenic separation, energy cost evaluations for this process are highly ambiguous, with values in the range between 0.42 and 1 kWh/Nm^3 (21,23,27).

2.2.4 Low-cost technique for purification of the biogas

Using commercial techniques can upgrade biogas, enhance its characteristics to be more efficient, and raise the heating value in different applications. Still, the problem with these techniques is the high cost of capital and operating, which will be a critical issue to apply technologies in upgrading because of the significant energy demand.

Modern biogas improvement systems are challenging to implement in small-scale biogas digesters(28). For small-scale plants, low-cost methods can be a benefit to be applied because the circular economy strategy can be achieved through the reuse of materials(29).

Natural and modified adsorbents such as clay, wood ash, zeolite, fly ash, and activated carbon could also be used to purify biogas. Natural adsorbents are harmless to the environment, have low operating costs, and are easily accessible. However, many of these adsorbents perform poorly in capturing biogas pollutants, necessitating further research to optimize the process(28,30).

- **Clay**

Clay is a fine-grained natural rock mainly made up of hydrous aluminum phyllosilicates used to adsorb CO_2 from biogas in one of two ways: physically or chemically. The natural clay minerals have an insufficient carbon dioxide adsorption capacity; however, activation with chemicals can augment this capacity while also increasing the textural characteristics and porosity. Different varieties of natural clay have carbon dioxide absorption capacities ranging from 0.3 to 1.48 mmol/g-clay(30).

- **Zeolite**

Aluminosilicate minerals make up the majority of zeolite, which is a microporous substance. Because the ingredients and reagents are readily available, the biogas upgrading system uses natural zeolites, which have a carbon dioxide absorption range of 0.2–4 mmol CO_2/g-adsorbent. Physical and chemical activation can boost the adsorption amount of natural zeolites. High temperatures are used for physical activation, whereas acids or bases can be used for chemical activation(31).

- **Fly ash**

Fly ash is a by-product of coal combustion caught before the flue gases enter the chimneys by electrostatic precipitators or another filtration. Fly ash contains significant levels of silicon dioxide (SiO_2) plus calcium oxide (CaO), and particles of fly ash are very tiny and low in weight with a density range of 1.97–2.89 g/cc(32). The chemical composition of the removal agent determines the efficacy of CO_2 removal through carbonation. Since metallic oxides react with carbon dioxide and water to generate carbonates, they will allow for more excellent elimination. Wet carbonation has a removal range of 1–11 mmol CO_2/g-fly ash for unmodified natural materials, indicating that it can enhance biogas(31).

- **Wood ash**

Wood ash is produced when the wood is burned in various contexts, such as large power plants or residential fireplaces, and CaO, SiO_2, Al_2O_3, Fe_2O_3, K_2O, MgO, MnO, Na_2O, P_2O_5, and TiO_2 are the primary chemical elements of wood ash. Wood ash can remove pollutants from gases by either the dry or wet adsorption methods 28). Wood ash's high CaO content leads to its strong capacity for removing carbon dioxide from biogas. When using dry ash, the removal rate of CO2 can be within the range of 0.4-4.5 mmol/g-ash. Besides that, the wet method can remove carbon dioxide with the content of 0.5–6 mmol- CO_2/g-ash; in addition, adsorption of wood ash can be enhanced through an adjustment with some chemical material such as monoethanolamine (MEA), tetraethylenepentamine (TEPA), diethylenetriamine (DETA), diethanolamine (DEA) and polyethyleneimine (PEI) (31).

Wood ash's application is governed mainly by its chemical structure. Its composition is determined by the tree species, the burned wood section, the climate the wood grew, and the combustion conditions(28).On the other hand, the amount of carbon transformed in wood-ash has a significant impact on process productivity and ash recovery because the more carbon converted, the greater the efficiency and the less ash produced (33).

Chemical Composition (%)	
SiO_2	7.80
$Al2O_3$	2.25
$Fe2O_3$	1.22
MgO	7.47
CaO	46.70
Na_2O	0.86
K_2O	9.61
TiO_2	0.11
MnO	4.51
P_2O_5	2.34
Cr_2O_3	<0.01
V2O5	<0.01
ZrO2	<0.02
ZnO	0.04
Loss on ignition	14.20
Conventional parameters	
Organic material (mg/kg)	<10
pH	13
Physical properties	
Density (kg/m^3)	2970
Specific surface (m^2/kg)	261

Table (2.6): Physical and chemical properties of wood ash(34)

2.3 Challenge of biogas composition to be injected into pipelines

Biomethane can be delivered from the processing facility to the final user via a natural gas grid, compressed biomethane gas, or liquefied biomethane gas, and delivered by truck to the filling station. If a gas grid is accessible close to the production plant (5 km), gas grid injection is the most popular and generally the most cost-effective alternative(35).

Compressed biomethane gas (CBG) has advanced in technological maturity, with millions of automobiles using natural gas compressed natural gas (CNG) worldwide. CBG can also be more cost-effective on smaller sizes than other options, which is essential because the raw material for biogas production is generally distributed in lower volumes over a broader region. However, the usage of liquified natural gas (LNG) in heavy-duty vehicles and transportation is expanding, allowing for the production and use of LBG(36).

To maximize the benefits of biogas, it is suggested that significant improvements in biogas injection infrastructure are required. Biogas sales incentives are also needed to sell this sustainable energy at a competitive rate as natural gas. Upgraded biogas will be compressed to the necessary pressure depending on the type of user. Compressed biomethane might be pumped into the natural gas grid via city gate stations (260 PSIG), district stations (50 PSIG), or service stations(37).

The produced gas must still meet impurity criteria for natural gas grid injection. The injection of biomethane inside the natural gas network is covered under the recently issued European Standard EN 16723. Total sulfur in biomethane shall not exceed 5 mg/m^3, and total volatile silicon must not exceed 0.3 mg/m^3. The quantities of O_2 and N_2 in biomethane, on the other hand, must be kept low to inject the biomethane into the infrastructure of natural gas(38).

2.4 Life Cycle Assessment

2.4.1 promoting of circular economy (CE) through Life Cycle Assessment (LCA)

Consumer products' environmental effects have a long history dating back to the 1960s and 1970s, focusing on comparisons between the products. It has long been realized that a significant portion of the environmental effect of many of these products occurs during their production, shipping, or disposal, rather than during their use. In the 1980s and 1990s, the importance of addressing a product's life cycle, or the life cycle of numerous alternative products, progressively became a problem, which the concept of life cycle assessment (LCA) sprang from this(39).

In the 1980s, the concept "sustainable development" was introduced to emphasize the linkage between development and environmental protection, which is defined as development that meets the current generation's needs without affecting future generations' ability to meet their own, so functions of sustainable development, environmental quality, and economic development became integrated(40).

The circular economy (CE) is a paradigm that was established in response to the need for a practical solution to sustainable development, which circular economy is defined as “an economic framework that replaces the ‘end-of-life’ notion with reducing, alternatively reusing, recycling, and recovering materials in production/distribution and consumption processes”(41).In addition, Pearce and Turner defined CE as: “an economy where the wastes are recycled to resources, either through a technological feedback technicality or through a natural ecosystem feedback technicality, so that the stock of resources is steady or increasing over time”(42). LCA is presented as a suitable tool to evaluate the environmental performance of the circular economy (CE) efforts(43).

Life cycle assessment could help evaluate and compare the most promising CE approaches and alternatives for optimizing the environmental performance of society’s consumption and production patterns(42).LCA is a methodology for evaluating and measuring the potential environmental consequences of the entire product life cycle(41). By assessing possible upstream and downstream repercussions and all relevant resources and impact categories, LCA may be used to develop more consistent and rigorous CE plans. Furthermore, if used comprehensively, LCA can provide a holistic insight into decision-making, encompassing both the economic and social spheres(42). Also, some literature defined the life-cycle assessment (LCA) as a method for calculating a product's, processes, or service's environmental impact; it is used for learning (improvement possibilities, environmental key metrics), communication (eco-labels, environmental product statements, benchmarking), and decision - making process (design and production of technologies and processes, purchasing, advancement of policies and rules)(43).

2.4.2 International Organization for Standardization (ISO): Standardisation of LCA

Between 1970-1990 can be known as the conceptual period for LCA; there was a distinct shortage of worldwide scientific platforms for LCA discussion and sharing with significantly divergent techniques, terminologies, and outcomes. On the other hand, between 1990-2000 was a period of standardization in which global expansion of scientific and coordinating efforts, many workshops, handbooks, and guides was issued by SETAC (Society of Environmental Toxicology and Chemistry) and ISO (International Organization for Standardization). SETAC functional areas concentrated on method development and harmonization, while ISO took on the formal mission of methodology and procedure standardization(39).

Since the 1990s, ISO Technical Committee (TC) 207 (Environmental Management) has been developing global norms for LCA as part of the ISO 14,000 series of environmental management standards, and the development of the ISO standardization process was as follows:(44)

- ISO 14040 (1997) = Principles and framework
- ISO 14041 (1998) = Goal and scope definition, inventory
- ISO 14042 (2000) = Impact assessment
- ISO 14043 (2000) = Interpretation (formerly ‘Improvement’)
- ISO 14040 and ISO 14044 (2006)

ISO 14040 and ISO 14044 (2006) have become the commonly accepted rules for LCA. They are the ‘core standards’: ISO 14040: Environmental Management—Life Cycle Assessment—Principles and Framework, ISO 14044: Environmental Management—Life Cycle Assessment Requirements and Guidelines(44).

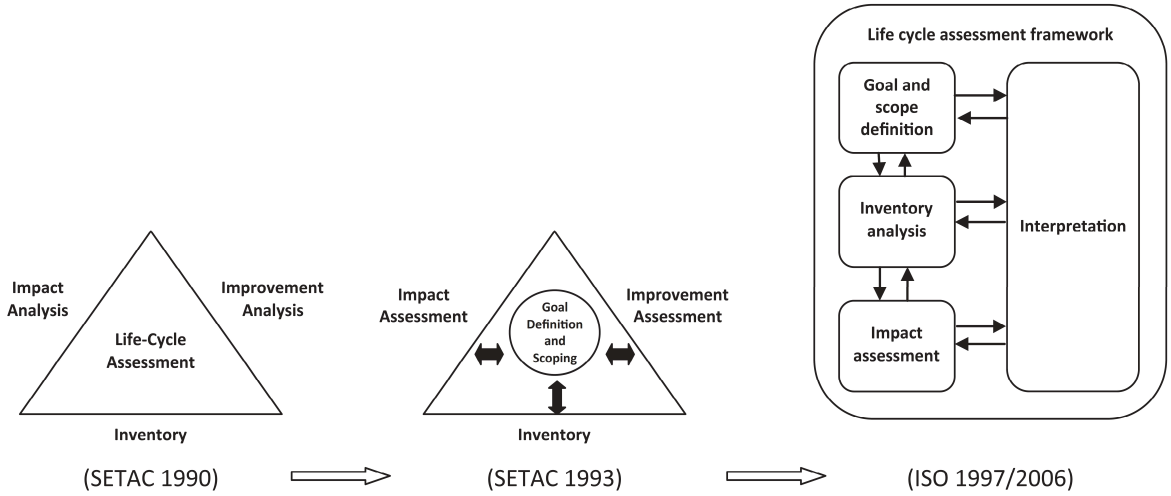


Fig (2.3): Evolution of Life cycle assessment(44)

2.4.3 Analysis of life cycle assessment

LCA has four components, according to ISO 14040/14044: aim and scope definition, life cycle inventory analysis, life cycle impact assessment, and interpretation of the result. Any adjustment in these four factors can result in varied environmental impact assessment outcomes(45).

With (cradle to grave) or (cradle to cradle), the full LCA is computed, beside the linear part of the life cycle (generation of raw materials and energy, product manufacture, all transport routes, use stage, and disposal of the product or other end-of-life procedure) cradle to cradle process analysis covers (recycling, reuse, or remanufacturing), while considering the notion of circular economy, cradle to cradle coverage is essential. In another hand (Cradle to the gate) and (cradle to customer) computations are partial LCAs that examine the product's life cycle just until it is manufactured (cradle to gate) or until it is carried to the consumer (cradle to customer), but not the usage phase or end-of-life stages(46).

2.4.3.1 Goal and Scope Definition

The study's purpose and scope are defined in this first step. The principal application (e.g., for analysis, design, or information), the study's motivations, and the audience are all part of the LCA's aim (e.g., within the company, the public). A greater understanding of a current framework, understanding the critical environmental problems in the product or process life cycle, trying to identify possibilities for enhancing the present system, making comparisons systems and their possible effects, and selecting options prospectively are some of the goals that could be pursued. On the other hand, the scope defines the product system or process to be investigated, as well as the system's functions, the functional unit, system boundaries, allocation procedures, impact categories, data requirements, assumptions constraints, and the final report's type and format(47).

Due to unforeseen restrictions, constraints, or further knowledge, the study's purpose and scope may be amended in some situations. Such changes, as well as the reasons for them, should be documented(48), and the following is an explanation of some expressions(47–49):

2.4.3.1.1 Product system

A product system is defined not by the result but by its function. A product system comprises a collection of unit operations connected by intermediate products or wastes flows. These flows include utilizing resources and discharges into the air, water, and land. Identifying the product system's inputs and outputs are aided by dividing the product system into its component unit operations.

2.4.3.1.2 Function and functional unit

The functions (performance characteristics) of the system being investigated must be explicitly specified in the scope of an LCA. The functional unit must align with the study's goal and scope. One of the key functions of a functional unit is to serve as a point of reference for normalizing input and output data (in a mathematical sense). As a result, the functional unit must be precisely defined and quantifiable.

System comparisons must be based on the same functions, measured by the same functional system, consisting of their reference flows. The reference flow must be defined after the functional unit has been chosen. If any of the systems' additional functions are not considered when comparing functional units, these deficiencies must be explained and documented.

2.4.3.1.3 System boundaries

The system boundary must be specified following the LCA's objectives. The available resources, the temporal framing, and the availability of the essential data must all be considered. The intensity and scale of the balance and the chronological, spatial, factual, and technical recording areas must be specified in detail. The system boundary marks the contact between the environment and the product system. They also identify which processes are included in the survey and which are not. Before data collection, the scale, kind (specific, average), and required data quality must be defined.

2.4.3.1.4 Types and sources of data

The study's purpose and scope determine the data used in an LCA. Such information can be gathered or estimated from other sources or collected from the production locations connected with the unit processes within the system boundary. In practice, all data may be a mix of measured, calculated, and estimated information.

2.4.3.1.5 Allocation procedure

If coupled productions arise in the product system under investigation, allocations must be made. Coupling productions are those that, in addition to the targeted product output, produce additional products that can be utilized in other processes. The environmental consequences of such a process must be proportionately applied to all the products of the process using a specific approach (49).

2.4.3.2 Life Cycle Inventory Analysis

Data gathering and calculations are used in life cycle inventory analysis (LCI) to quantify the inputs and outputs of materials and energy connected with a product system under investigation. In this scenario, all inputs and outputs of a unit process and a product system are linked respectively to the unit process's main output and the product system's end product (50).

Once the data have been gathered, users may determine to refocus the study on the most important aspects by narrowing the scope and possibly even modifying the study's goal. This iterative process can reduce the size of the study to a more manageable level, but it runs the risk of missing some impacts (47).

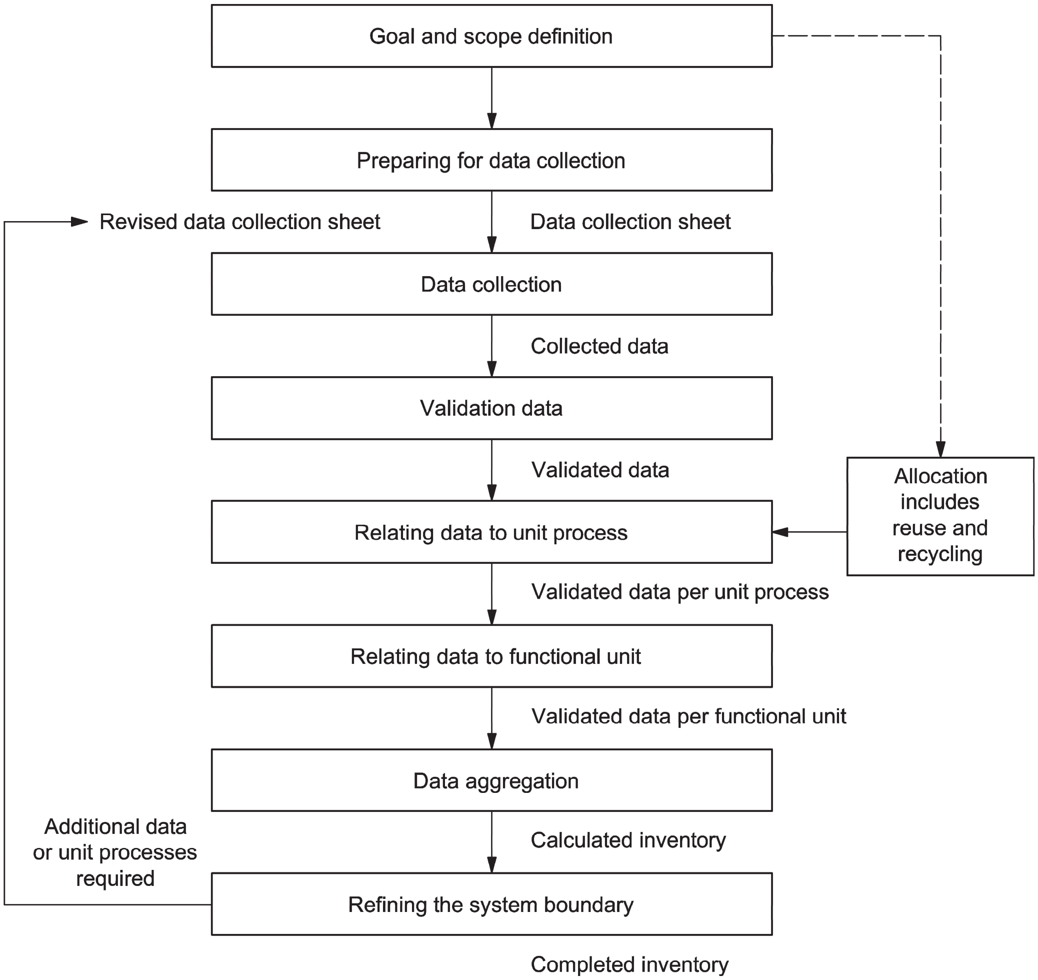


Fig (2.4): Life cycle inventory operational procedures (48)

2.4.3.3 Life Cycle Impact Assessment

The impact assessment's step is to assess the material and energy flows identified in the inventory analysis in terms of particular environmental implications. As a result, the impact assessment supports the recognition, summary, and quantification of the analyzed systems' possible environmental consequences, as well as providing critical data for the analysis(49).

According to ISO (14044:2006), Life Cycle Impact Assessment consists of the following steps(46):

1- Classification

Categorizes the LCI results into one or more effect categories, such as CO_2 influencing global warming and SO2 affecting human health and acidification.

2- Characterization

transforms LCI data into standard units and groups them into impact categories.

3- Normalization

determines the magnitude of category indicator outcomes compared to some datasets, which should be appropriate given the study's different temporal and spatial scales.

4- Grouping

the impact categories are classified and ranked by grouping, which can be done in two ways: by sorting the effect categories on a nominal basis (inputs and outputs) or by ranking the impact categories in a hierarchy (high, medium, and low priority).

5- Weighting

this step of impact assessment is optional uses numerical factors based on value decisions to convert an aggregate indicator data across effect categories; in addition, value-choice repercussions can be assessed via sensitivity analysis.

2.4.3.4 Life Cycle Interpretation

The analysis of the outcomes, as well as the clarification of the significance and constraints, are the tasks of the interpretation stage. The essential facts must be identified and validated for completeness, sensitivity, and consistency based on the inventory analysis and impact assessment outcome. The assumptions made during the goal and scope definition process must be considered (49).

CHAPTER THREE: UP-ASH project overview

Synopsis

This chapter explains an existing plant for anaerobic digestion (AD) that used ashes to enhance the characterizations of the produced biogas. This plant will be used as a case study to analyze the LCA of utilizing the ash technique to purify biogas, plant arrangement, and the experimentations to analyze the effectiveness of the ash technique illustrated in this chapter.

3.1 Project overview

Anaerobic digester pilot plant is located at Foundation Edmund Mach Institute (San Michele a/A, Trento, Italy), project "Up-ash" is referred to as “Upgrading Through Ash” and it commissioned by the Edmund Mach Foundation in participation with the University of Florence and the Polytechnic of Turin has used both generic wood chip ashes coming from a district heating plant located in Trentino and ashes coming from the Mach Foundation, which were shipped to Florence on purpose, then the ashes were processed in a reactor owned by the Region of Tuscany, the reactor can contain 700 lit of ashes, with a diameter of 80 cm and a length of 1.4 m. Another aim of this work was to ensure that the chemical structure of the produced biomethane was within the UNI TR 11537 limit composition for feeding into the network(29,51).

Another factor of the ashes that were investigated during this time was their water content: this information allows us to estimate the amount of water that should be added to each load to achieve the optimum amount of moisture for CO_2 uptake, which is estimated to be around 25-30% of the total weight. It should be noted that the timing of the tests was inextricably influenced by the characteristics of the pilot in use; specifically, the discontinuity of the anaerobic process: with each load of waste into the reactor, the days of maximum biogas production are limited to two/three weeks, after which it is necessary to empty the reactor, load a new quantity of (Organic Fraction of Municipal Solid Waste) OFMSW, and then reactivate the anaerobic process through the inoculation of bacteria(51).

Fig (3.1): Pilot plant at FEM (upgrading and compression section)(52)

Fig (3.2): FEM AD plant (53)

3.2 Laboratory tests

Biogas was simulated as a combination of CO_2 and N_2 from cylinders, through a specific mixer, in laboratory studies. The substitution of CH_4 with N_2 was required for safety reasons, but it has no impact on the results of the studies because neither N_2 nor CH_4 react with the ashes(51).

The two completed tests, which were conducted under more controlled conditions, allowed for the collection of more quantitative data and the estimation of a maximum possible Uptake value of about 200 g of CO_2 per kg of dry ash, using a flow rate of about 4 Nmc/(h.t_{ash}) of simulated gas (40-45% CO_2) and a test duration of about 35-38 hours. The tests were conducted by imposing a predetermined composition for the incoming gas flow: N_2 60% by volume and CO_2 40% by volume. For each test, the gas was pumped through the reactor containing the ashes until the CO_2 concentration in the outgoing flow reached roughly 4% by volume (i.e., CH_4 remains above 96 percent by volume in a CH_4/CO_2 mixture). Two ash moisture conditions were evaluated (20 and 30% by mass). To maintain a specified flow rate of 4 $Nm^3/(h.t_{ash})$, the inlet flow rate for each test is set at 24 Nl/h, with a quantity of ash in the reactor of 6 kg(51).

Fig (3.3): Equipment in the Florence laboratories (51)

Test	Gas composition		Ashes [kg]	Humidity [% mass]	flow [Nl/h]
	CO_2 [% v/v]	N_2 [% v/v]			
WA_m20_i **WA_m20_ii**	40	60	6	20	24
WA_m30_i **WA_m30_ii**	40	60	6	30	24

Table (3.1): Conditions imposed in experimental laboratory tests(51)

According to the data, experiments conducted at increased humidity resulted in somewhat higher absorption values, up to around 200 g per kg dry ash. After a flow of about 350 Nl CO_2, which equates to about 58 Nl CO_2 per kilogram ash, an absorption value of around 200 g CO_2 per kg ash was achieved.

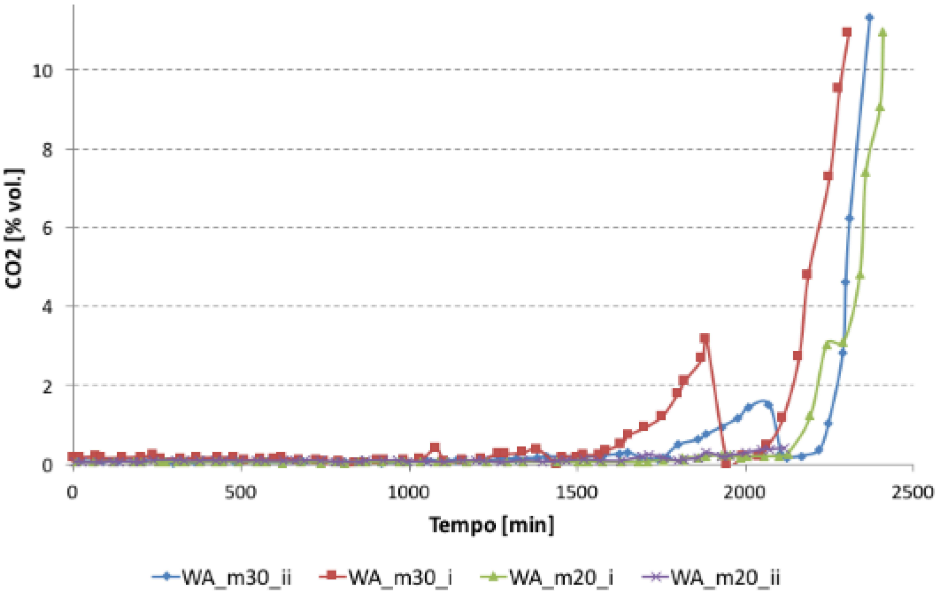


Fig (3.4): Volumetric percentage of CO2 in the gas leaving the reactor over time (51)

3.3 The FEM pilot plant

All the tests at the FEM (Fondazione Edmund Mach) pilot plant were conducted for safety reasons (to avoid the risk of an explosion): before beginning the tests, it was important to wait a few hours for the cleanup of the atmospheric air previously present in the reactor and in the interstices of the ash particles, which was accomplished through nitrogen flushing, until values of O_2 at the exit were close to zero. Furthermore, nitrogen flushing is required before opening the reactor and removing the filter bed at the end of each test to lower the proportion of methane present along the line.

Some tests were conducted in different wights of ashes and various moistures; pH and moisture ratios were measured at the start and end of each test. The efficiency of ash for CO_2 capture was also demonstrated in testing at the pilot plan. The laboratory testing was more effective than the full-scale process. In the laboratory, uptake values of around 58 Nl fluxed CO_2 per kg $_{\text{dry ash}}$ were close to 200 $g_{CO2}/Kg_{\text{dry ash}}$. The absorption value following such a carbon dioxide flow in the pilot plant, on the other hand, is roughly 115 g_{CO2}/dry $_{\text{kg ash}}$.

The decline in efficiency seen could be caused by changes in external temperature, the discontinuity of the flow rate generated by the anaerobic batch plant, the high number of discontinuity sites along the line, and the development of preferential routes inside the reactor.

3.4 Purification tests for biomethane injection into the grid

The test with a higher ash load (200 kg t.q.) was conducted to confirm the ash's opportunity to collect the main pollutant compounds for which particular limits have been set by the regulatory apparatus that was recently issued to define the properties of biomethane for it to be introduced into the natural gas network. The reference standards to inject biomethane into the network are UNI/TR 11537:2016 - Introduction of biomethane into the natural gas transmission and distribution networks and CEN-EN 16726-1 - natural gas and biomethane for use in transport and biomethane for injection in the natural gas network - part 1: specifications for biomethane for injection in the natural gas network.

Many instruments were used to measure the flow of inlet and outlet gasses; the identification of VOCs in biogas produced by anaerobic digestion of MSW was carried out using the GCMS-SPME technique and PTR-MS Q500. A portable MRU analyzer measured the macro components present in the biogas. The measuring principle for carbon dioxide and methane is the NDIR (infrared sensor).

The monitoring campaign lasted approximately 95 h, after which time most of the compounds present reached a concentration close to the limits indicated by UNI TR 11537. Therefore, the output values are Cmax ≡ T95h. The following table (3.2) shows the minimum, average, and maximum concentrations of the volatile organic compounds of interest before and after the cleaning section.

	Before ash reactor (Biogas) – (ppm(v))				After ash reactor (Biomethane) – (ppm(v))			
	C. M.	C. avg.	C. m.	C. M. (mg/m^3)	C. M.	C. avg.	C. m.	C. M. (mg/m^3)
NH_3	339 +/-2.1	15 +/-0.2	38 +/-0.3	236.1	13 +/-0.1	2.8 +/-0.1	0.001 +/-0.0001	9.1
CO	164 +/-1.1	33 +/-0.1	0.001 +/-0.0001	**187.6**	73 +/-0.1	5.0 +/-0.1	0.001 +/-0.0001	**83.1**
H_2S	126 +/-2.2	3 +/-0.1	0.009 +/-0.00001	**175.4**	3 +/-0.1	0.1 +/-0.01	0.01 +/-0.001	**3.75**
CH_4S	667 +/-2.4	23 +/-0.1	0.003 +/-0.0001	**1309.8**	1 +/-0.01	0.106 +/-0.01	0.003 +/-0.0001	**2.1**
C_2H_6S	5 +/-0.1	0.3 +/-0.01	0.0004 +/-0.00001	**13.0**	1.4 +/-2.1	0.177 +/-0.01	0.0004 +/-0.00001	**3.6**
C_3H_6S	0.5 +/-0.01	0.04 +/-0.002	0.0002 +/-0.00001	**1.5**	0.1 +/-2.1	0.011 +/-0.001	0.0002 +/-0.00001	**0.4**
C_3H_8S	22 +/-0.1	2 +/-0.01	0.008 +/-0.0001	**67.3**	1.2 +/-2.1	0.007 +/-0.0001	0.002 +/-0.0001	**3.7**
$C_4H_{10}S$	19 +/-0.2	1 +/-0.01	0.003 +/-0.0001	**69.7**	1.1 +/-2.1	0.213 +/-0.01	0.003 +/-0.0001	**3.9**
Total Mercaptans	713	26	0.014	**1461**	5	1	0	**13.7**
$C_6H_{12}S_2$	0.2 +/-0.01	0.007 +/-0.0001	0.000	**1.1**	0.006 +/-0.0001	0.0005 +/-0.0001	0	**0.01**
Total Sulphurs	839.8	29.4	0.023	**1638.0**	7.8	0.6	0.0	**17.46**
HCl	0.74 +/-0.01	0.09 +/-0.001	0.0002 +/-0.00001	**1.1**	0.09 +/-0.001	0.0531 +/-0.001	0.0002 +/-0.00001	**0.1**
C_2H_5Cl	0.80 +/-0.01	0.08 +/-0.0001	0.0010 +/-0.0001	**2.1**	0.01 +/-0.001	0.0064 +/-0.0001	0.0010 +/-0.0001	**0.03**
CH_2Cl_2	0.10 +/-0.02	0.003 +/-0.0001	0.0000	**0.3**	0.04 +/-0.001	0.0022 +/-0.0001	0.0003 +/-0.00001	**0.11**
$C_2H_2Cl_2$	3.69 +/-0.1	0.12 +/-2.1	0.0000	**14.5**	0.01 +/-0.001	0.0007 +/-0.00001	0.0000	**0.03**
$C_2H_4Cl_2$	0.33 +/-0.05	0.012 +/-0.0001	0.0001 +/-0.00001	**1.3**	0.06 +/-0.001	0.0023 +/-0.0002	0.0001 +/-0.00001	**0.2**
$C_3H_6Cl_2$	0.04 +/-0.001	0.002 +/-0.0002	0.0000	**0.2**	0.03 +/-0.001	0.0009 +/-0.00001	0.0000	**0.1**
$C_2H_3Cl_3$	0.01 +/-0.001	0.00	0.0000	**0.1**	0.01 +/-0.001	0.0009 +/-0.00001	0.0000	**0.06**
$C_6H_4Cl_2$	0.01 +/-0.001	0.000	0.0000	**0.0**	0.01 +/-0.001	0.0001 +/-0.00001	0.0000	**0.03**
CCl_4	0.03 +/-0.001	0.001 +/-0.0001	0.0023 +/-0.0001	**0.2**	0.03 +/-0.0002	0.0013 +/-0.0001	0.0023 +/-0.0002	**0.16**
C_2Cl_4	0.01 +/-0.001	0.000	0.0000	**0.0**	0.01 +/-0.002	0.0002 +/-0.00001	0.0000	**0.04**
$C_2H_2Cl_4$	0.22 +/-0.01	0.004 +/-0.0001	0.0000	**1.5**	0.02 +/-0.002	0.0005 +/-0.00001	0.0000	**0.12**
Total Chlorines	6.0	0.3	0.00	**21.3**	0.3	0.1	0.0	**0.98**
$CHCl_2F$	0.75 +/-0.01	0.055 +/-0.001	0.0002 +/-0.00001	**3.1**	0.4 +/-0.02	0.04 +/-0.001	3.7E-05 +/-0.0000001	**1.8**
Total Fluorines	0.75	0.05	0.0002	**3.14**	0.4	0.04	3.7E-05	**1.8**
L2	0.1 +/-0.001	0.0021 +/-0.0001	0.0000	**0.7**	0.111 +/-0.01	0.0027 +/-0.0001	0.0000	**0.7**
$C_{10}H_{14}OSi$	0.022 +/-0.001	0.0008 +/-0.00002	0.0015	**0.2**	0.0147 +/-0.003	0.0006 +/-0.00002	0.0015 +/-0.0001	**0.1**
D3	0.003 +/-0.0001	0.0001 +/-0.00001	0.0000	**0.03**	0.0005 +/-0.00001	0.0000	0.0003 +/-0.00001	**0.005**
L3	0.02 +/-0.01	0.0004 +/-0.00001	0.0000	**0.21**	0.00016 +/-0.00001	0.0000	0.0000	**0.002**
D4	0.003 +/-0.0001	0.0001 +/-0.00001	0.0000	**0.033**	0.0019 +/-0.0001	0.0001 +/-0.00001	0.0000	**0.023**
Total Si	0.2	0.004	0.001	**1.2**	0.1	0.0	0.0	**0.9**

Table (3.2): Trace compounds concentration - Biogas and Biomethane (29)

CHAPTER FOUR: METHODOLOGY

Synopsis

This chapter describes how life cycle assessment has been applied to analyze a purifying biogas plant by using ash by taking the UP-ASH project as a case study; It will discuss how data will be processed by using GaBi software to analyze the LCA to realize the result.

4.1 Life cycle assessment modeling tool: GaBi software

The GaBi software system is an industry leader in life cycle engineering, life cycle modeling, and life cycle balances. It's also a modular system comprised of plans, processes, and flows. As a result, the GaBi system's structure is evident and transparent(54).

GaBi Education License for version 9.2.1.68 had been obtained to take advantage of features of the educational version and to implement the practical side of this thesis.

4.1.1 GaBi overview

GaBi combines modeling and reporting application that enables users to evaluate the potential environmental impacts of a product or service in its manufacture, use, and disposal. It facilitates every stage of an LCA, from data collection and organization through a presentation of results and stakeholder interaction (end of life)(55).

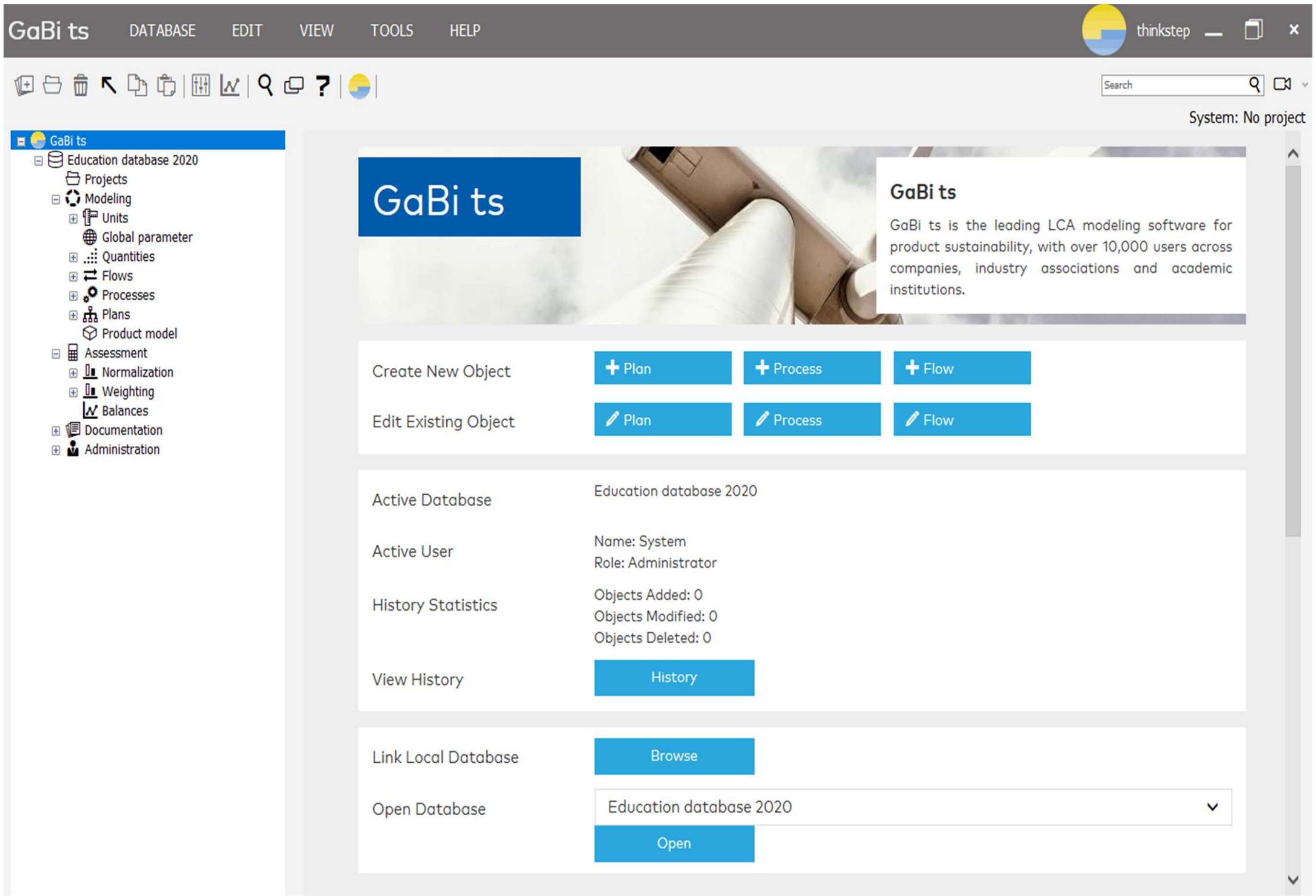
GaBi keeps track of all material, energy, and emissions flows, as well as defined monetary values, working time, and social issues, and provides real-time performance reporting in dozens of environmental impact categories. In addition, GaBi software comes with the most up-to-date and comprehensive Life Cycle Inventory database available. With over tens of thousands of Life Cycle Inventory datasets based on primary data collected during collaboration with corporations, groups, and public bodies, the databases cover virtually every industry(55).

4.1.2 Databases

The GaBi databases are essential data sources for numerous stakeholders. They comprise datasets that have been examined internally and externally by specialists, with quality assurance systems and review procedures built-in. Access to raw data sources allows for development and delivery that is within scope, on time, and of high quality, as well as help on data selection. Furthermore, the master Database contains around 20,000 plan systems, each with one or more unit processes and numerous sub-systems, the core data knowledge memory.

As a result, the GaBi Datasets are the most internally consistent and high-quality LCA databases accessible(56).

Metals (steel, aluminum, and non-ferrous metals), organic and inorganic intermediate products, plastics, mineral materials, energy supply (power grid mixes, steam, thermal energy), end-of-life, coatings, manufacturing and electronics, construction materials, renewable materials, and textile processing are among the many industries covered by many data sets(56).



GaBi ts

GaBi ts is the leading LCA modeling software for product sustainability, with over 10,000 users across companies, industry associations and academic institutions.

Active Database: Education database 2020

Active User: Name: System
Role: Administrator

History Statistics: Objects Added: 0
Objects Modified: 0
Objects Deleted: 0

Open Database: Education database 2020

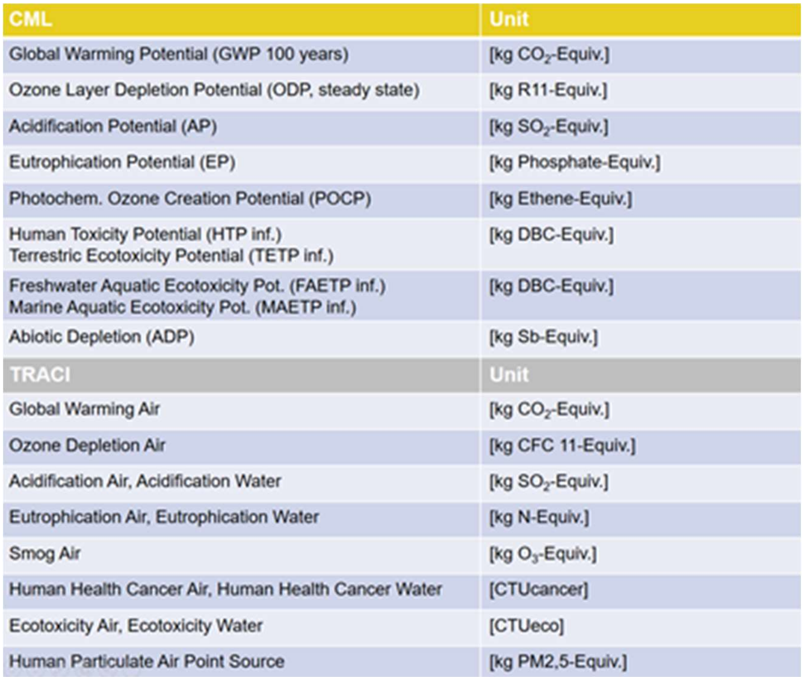
Fig (4.1): A screenshot of accessing educational database 2020

4.1.3 Impact Assessment Methods

There are several ways for performing a Life Cycle Impact Assessment, including TRACI and CML. These two approaches are used to classify and characterize over a thousand compounds based on how much they contribute to a list of environmental impact categories(57).

The Institute of Environmental Sciences at Leiden University in the Netherlands created CML 2001; furthermore, to reduce uncertainty, CML 2001 is an impact assessment method that limits quantitative modeling to early stages in the cause-effect chain. The results are categorized into middle groups based on shared mechanisms (for example, climate change) or widely acknowledged groupings (e.g., ecotoxicity)(58).

Another method is the Tool for the Reduction and Assessment of Chemical and other Environmental Impacts, called TRACI, developed by the U.S. Environmental Protection Agency. Within the TRACI methodology, the impact categories were characterized at the midpoint level, including a higher level of societal agreement concerning the certainties of modeling at this point in the cause-effect chain(59).



CML	Unit
Global Warming Potential (GWP 100 years)	[kg CO_2-Equiv.]
Ozone Layer Depletion Potential (ODP, steady state)	[kg R11-Equiv.]
Acidification Potential (AP)	[kg SO_2-Equiv.]
Eutrophication Potential (EP)	[kg Phosphate-Equiv.]
Photochem. Ozone Creation Potential (POCP)	[kg Ethene-Equiv.]
Human Toxicity Potential (HTP inf.) Terrestric Ecotoxicity Potential (TETP inf.)	[kg DBC-Equiv.]
Freshwater Aquatic Ecotoxicity Pot. (FAETP inf.) Marine Aquatic Ecotoxicity Pot. (MAETP inf.)	[kg DBC-Equiv.]
Abiotic Depletion (ADP)	[kg Sb-Equiv.]
TRACI	**Unit**
Global Warming Air	[kg CO_2-Equiv.]
Ozone Depletion Air	[kg CFC 11-Equiv.]
Acidification Air, Acidification Water	[kg SO_2-Equiv.]
Eutrophication Air, Eutrophication Water	[kg N-Equiv.]
Smog Air	[kg O_3-Equiv.]
Human Health Cancer Air, Human Health Cancer Water	[CTUcancer]
Ecotoxicity Air, Ecotoxicity Water	[CTUeco]
Human Particulate Air Point Source	[kg PM2,5-Equiv.]

Table (4.1): Comparison between TRACI and CML Methods(55)

4.1.4 GaBi procedure

for conducting an LCA in GaBi, first of all, is to connect a database to the software, where it enables to use of GaBi after accessing the dataset to construct the desired model to be evaluated, GaBi uses plans to calculate the probable environmental consequences and other critical quantities of a product system, The transmission of obtained data into the GaBi software platform is the first step in system modeling. GaBi is divided into sections. Modular elements are created from plans, processes, and flows, as well as their functions; after modeling the framework, the balance shall be constructed to analyze the environmental impacts and generate the result.

4.1.4.1 Plan in GaBi software

A plan represents the system's boundaries. The system under investigation comprises processes that represent the actual processes in progress. On the other hand, Flows reflect all of the material and energy flows that pass between the processes and to and from the system. They define the system's input/output flows(55).

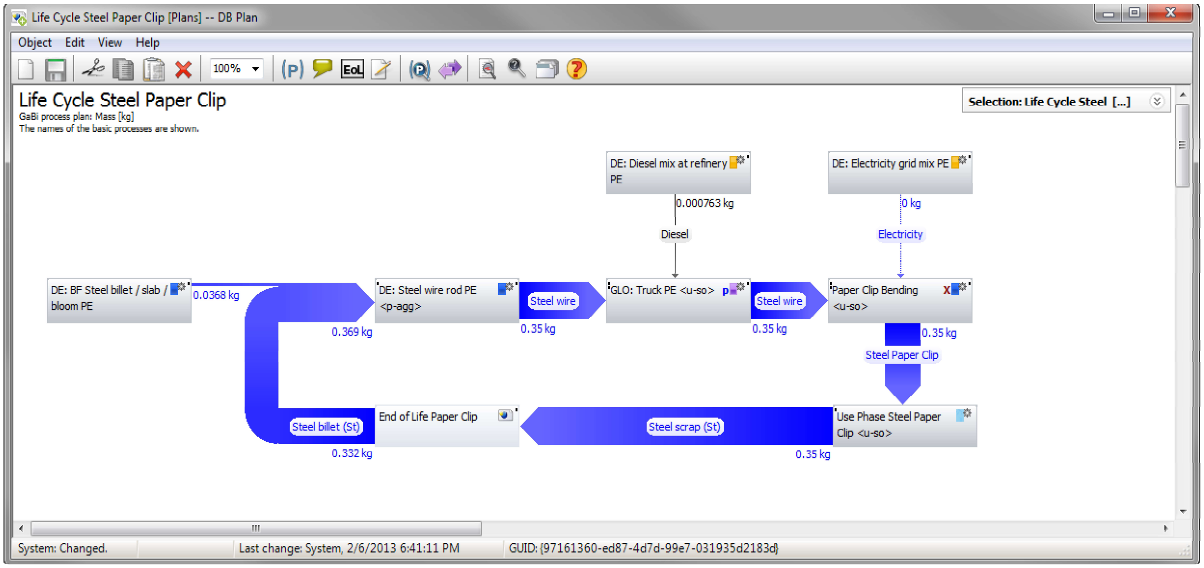


Fig (4.2): Example of GaBi Plan(55)

4.1.4.2 Flows and their types in GaBi

The object type flow is the foundation of modeling with GaBi. A GaBi flow is a model of an actual product, intermediate, material, energy, resource, or emission flow(56). Flows provide data that shows GaBi how much each unit of this flow contributes to various environmental effect categories; in addition, quantities are the attributes of a flow. The standard reference quantity for a flow is mass (kg); other quantities include the number of particles, length, and volume, among others(55).

To calculate a system's potential environmental impact, each flow must be classified as either elementary or non-elementary.

Flows that enter the technosphere directly from nature (flows in resource folder) and flow that exit the technosphere directly to nature(flows in the Emissions to air, water, and soil folders) are considered elementary flows(54,55).

In addition, Flows that exclusively travel within the technosphere are non-elementary. They don't access the technosphere directly from the natural world, and they don't leave the technosphere directly into the natural world, so it is used to link between processes in a life cycle system. Non-elementary is classified into two categories; the first one is track flow: which include valuable substance and energy flows that can be used in another process, the other flows are waste flows which are flows that require extra processing, either within or beyond the existing system, but remain within the technosphere(54–56).

4.1.4.3 Processes types in GaBi

According to the ILCD system of the European Union, GaBi has five categories of processes.

1- Unit Process Single Operation (u-so)

A gate-to-gate process is also known as a unit process. This process only has data for a single process step and no LCI (life cycle inventory) information(55).

2- Unit Process Black Box (u-bb)

A multifunctional process or process chain at the plant level is called u-bb. Rather than a single process step, this sort of process may represent a series of processes(55).

3- Aggregated Process (agg)

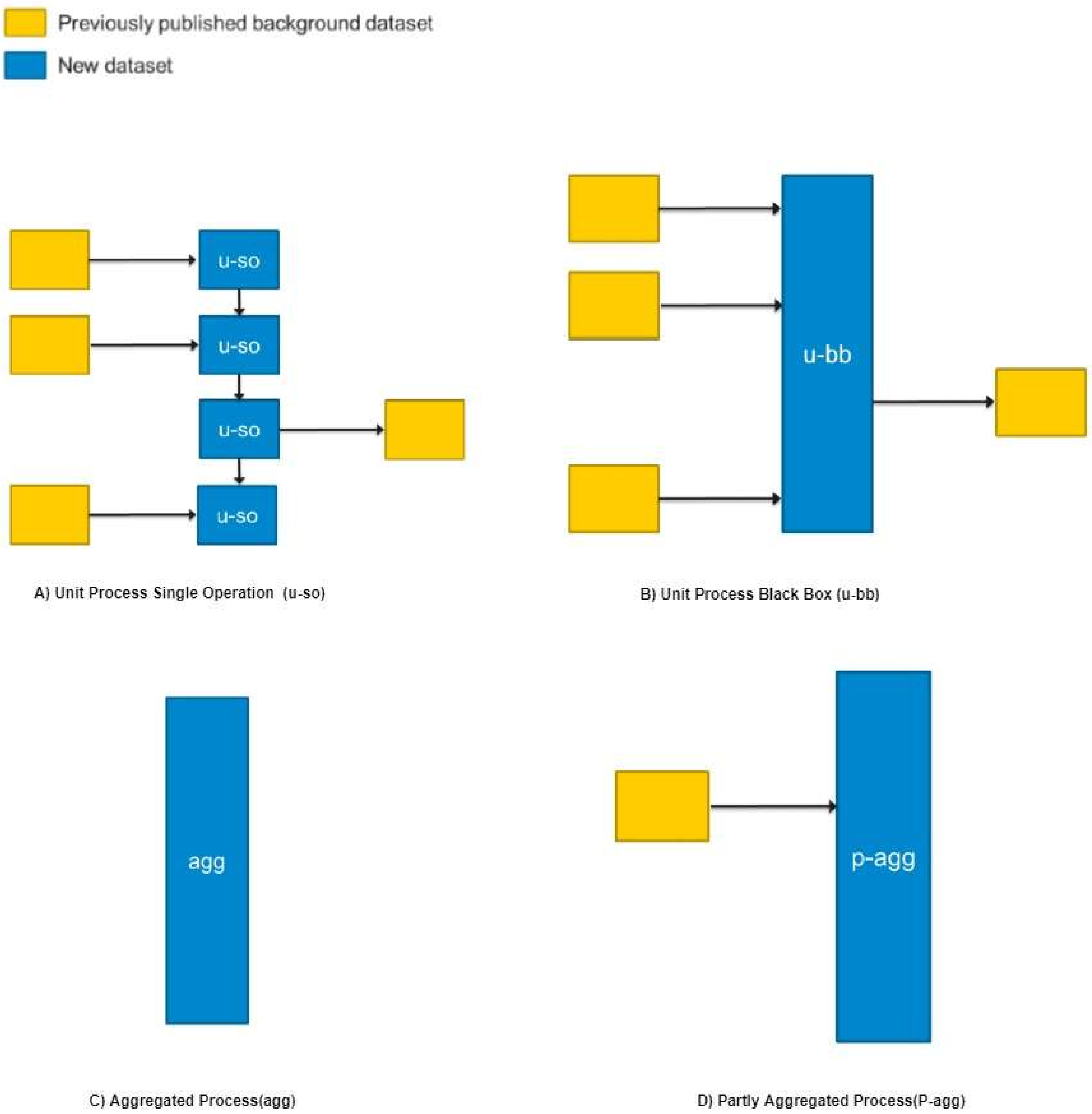
The whole life cycle data for part of or the whole life cycle of a product system is contained in an LCI Result. A cradle to gate or system process is a term used to describe this type of dataset(55).

4- Partly Aggregated Process (p-agg)

Except for one or more product flows that call extra modeling, p-agg provides all LCI data for the process(55).

5- Avoided Product System (aps)

All input and output flow for u-bb are set to negative values, or all inputs are turned to outputs or vice versa. This type of dataset is commonly used while modeling allocation and indicates how the product system under consideration avoids the usage of particular materials and energies(55).



A) Unit Process Single Operation (u-so)

B) Unit Process Black Box (u-bb)

C) Aggregated Process(agg)

D) Partly Aggregated Process(P-agg)

Fig (4.3): GaBi processes type(56)

4.1.4.4 Generating balance

After modeling the product's life cycle, a model balance must be developed to analyze the model's environmental implications. GaBi balance is a file that contains all the calculated findings for the modeled system, including both LCI and LCIA values(57).

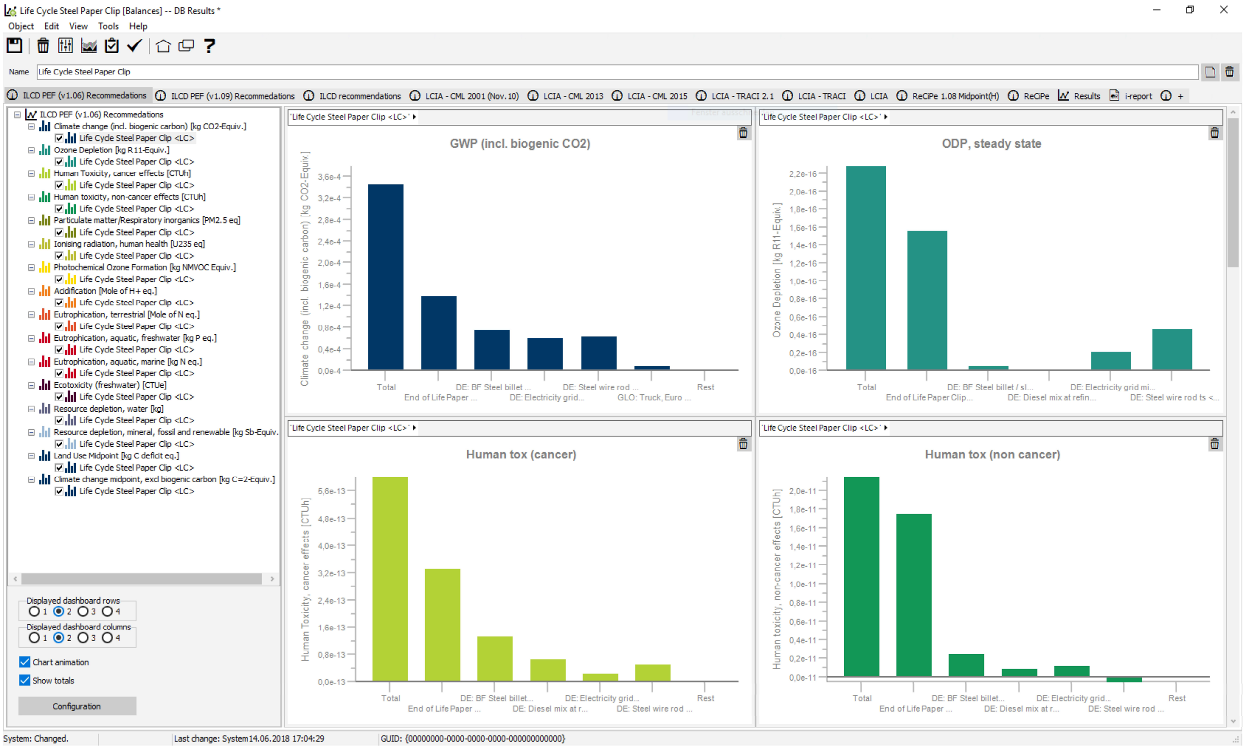


Fig (4.4): GaBi dashboard (55)

4.2 Life cycle assessment of the case study

The FEM pilot plant, which is explained in chapter 3, has been taken as a case study; the goal is to apply life cycle assessment into the reactor that uses ash as a byproduct from woody biomasses in district heating plants to capture CO_2 and other impurities that appear in biogas, by determining and data collecting of all inputs and outgoing outputs for the system GaBi software will be used for analyzing and evaluating.

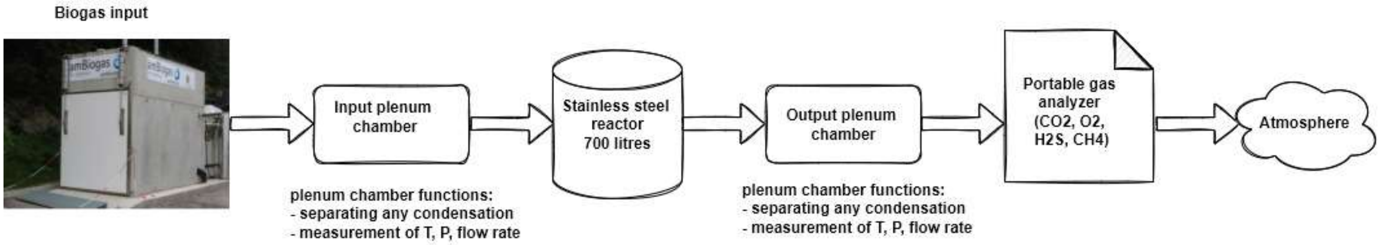


Fig (4.5): layout of the upgrading line at FEM

4.2.1 Goal and scope definition

Biogas is generated from the Organic Fraction of Municipal Solid Waste (OFMSW) in the FEM pilot plant and continues with the production of biomethane that meets the quality parameters for grid injection. The goal is to determine which sub-processes in the investigated system contribute the most to the impacts.

The eco-profile so constructed is the gate-to-gate, eco-which is a partial method that analyzes the life cycle of the reactor by exploring from the point before biogas entering the reactor by considering all inputs and their quantities and another point when biogas exit the reactor weighing various quantities of outputs.

The values for the flows getting in and exiting the system were acquired from the extraction and development of the input and output data using the GaBi database. The upgrading systems inputs and outflows have been classified into different categories of origin; these constitute a new system of analysis that includes input and output flow that must be deconstructed until they reach the origin of the flow chain within the study's constraints.

One cubic meter of biogas entering the upgrading system appears to be the functional unit chosen for the LCA analysis. All inputs and outputs considered for upgrading the reactor are shown in fig (4.6) below.

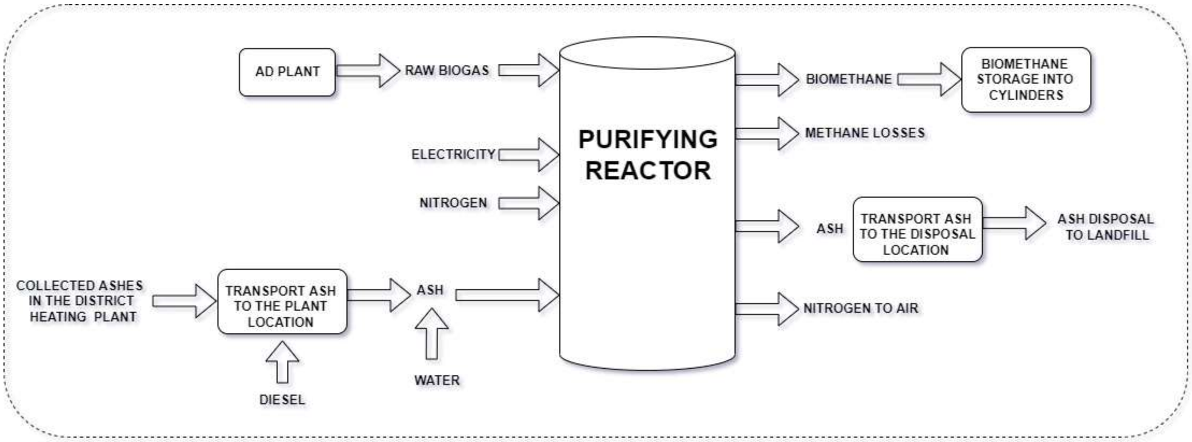


Fig (4.6): A schematic of the system Boundaries covered by the LCA

4.2.2 Life cycle inventory analysis

The inventory analysis was carried out by analyzing all the primary inflows and outflows from the FEM experimental upgrading system

Considering an input gas of 1 m^3 of biogas produced from an anaerobic digestion plant, the process can be applied to obtain an output of 1 m^3 of biomethane consisting of 96% CH_4 by volume.

From the experimental results, it can be estimated that about 7 kg of ash is needed to treat 1 Nm^3 of biogas. In addition, the ashes have a low moisture content (almost zero); it is necessary to humidify ashes at a rate of 20-30% by weight. So, by taking an average of this ratio of 25%, every 7 kg of ash needs 1.75 liters of water to moisturize the ash.

Nitrogen is needed to flush up to record values close to zero of O_2 at the outlet for safety reasons (exclusion of the risk of explosiveness) and to reduce the percentage of methane present along the line, so it is necessary to wait a few hours for the atmospheric air previously present in the reactor and the interstices of the ash particles. In the location of the case study plant, the amount of used nitrogen is not measured by the operation team and shutting off the nitrogen gas supply depends on the lack of oxygen at the outlet, so the quantity of gas is derived indirectly by considering the density of the ash at pressure and temperature were atmospheric to assume that the volume of N_2 equal to the voids in the ash pile, from the past study that shows the physical and chemical characteristics of wood ash the medium value of the density is 820 kg/m^3 (60), and the percentage of the void into ash pile is estimated 5% of the total volume of ash, this will lead to approximately a nitrogen quantity of 0.427 L for flushing the reactor for 7 kg of ash used.

After loading the ash inside the reactor and injecting biogas, purifying is started by adsorbing the impurities into biogas by ash due to its properties, which the ash as the experimental. The simulation of the concentration of biogas before the reactor and biomethane leaving the reactor is shown in table (4.2).

For the electrical power consumption, the Up-Ash project did not use the blower because the pressure at the outlet of the digester was sufficient. Still, the plant provided instruments valves used to control and measure reading the flow and analysis of methane and other impurities in the output and the consumption of 200 We.

There are very slight methane losses into the plan that can be estimated with 1% for 1 m^3 of biogas due to the fittings, connections, and valves used to control the indicators into the system.

Regarding transportation, the ash is transferred from the incinerator to the plant's location with a truck (Euro 3 type) that uses diesel for the distance estimated at 1.02 Km. After the ashes are processed, they become concentrated and saturated with carbon dioxide. It is transmitted to the landfill to be disposed of. It is sent to the landfill for the location estimated at 22.8 km with a diesel truck.

The life cycle inventory records for woody ash disposal was carried from a study conducted for environmental assessment for biomass woody ash to be used as a construction material; the inventory data in this study is for 1 ton of bottom wood ash, so in our case study, all inputs and outputs were modified for 1 kg for BF ash which is similar to the one that in this study, after that these data entered manually into the GaBi software. The adjusted data for landfilling of 1 kg of wood ash is shown in table (4.3).

Table (4.4) shows summarized inputs quantities and their source, and Table (4.5) shows the direction and amounts of the output for the purifying system.

	Before ash reactor (Biogas) (mg/m$_3$)	**After ash reactor (Biomethane) (mg/m$_3$)**
NH_3	236.1	9.1
CO	187.6	83.1
H_2S	175.4	3.75
CH_4S	1309.8	2.1
C_2H_6S	13.0	3.6
C_3H_6S	1.5	0.4
C_3H_8S	67.3	3.7
$C_4H_{10}S$	69.7	3.9
$C_6H_{12}S_2$	1.1	0.01
HCl	1.1	0.1
C_2H_5Cl	2.1	0.03
CH_2Cl_2	0.3	0.11
$C_2H_2Cl_2$	14.5	0.03
$C_2H_4Cl_2$	1.3	0.2

$C_3H_6Cl_2$	0.2	0.1
$C_2H_3Cl_3$	0.1	0.06
C_6H4Cl_2	0.0	0.03
CCl_4	0.2	0.16
C_2Cl_4	0.0	0.04
$C_2H_2Cl_4$	1.5	0.12
$CHCl_2F$	3.1	1.8
L_2	0.7	0.7
$C_{10}H_{14}OSi$	0.2	0.1
D_3	0.03	0.005
L_3	0.21	0.002
D_4	0.033	0.023

Table (4.2): Trace compounds concentration - Biogas and Biomethane(29)

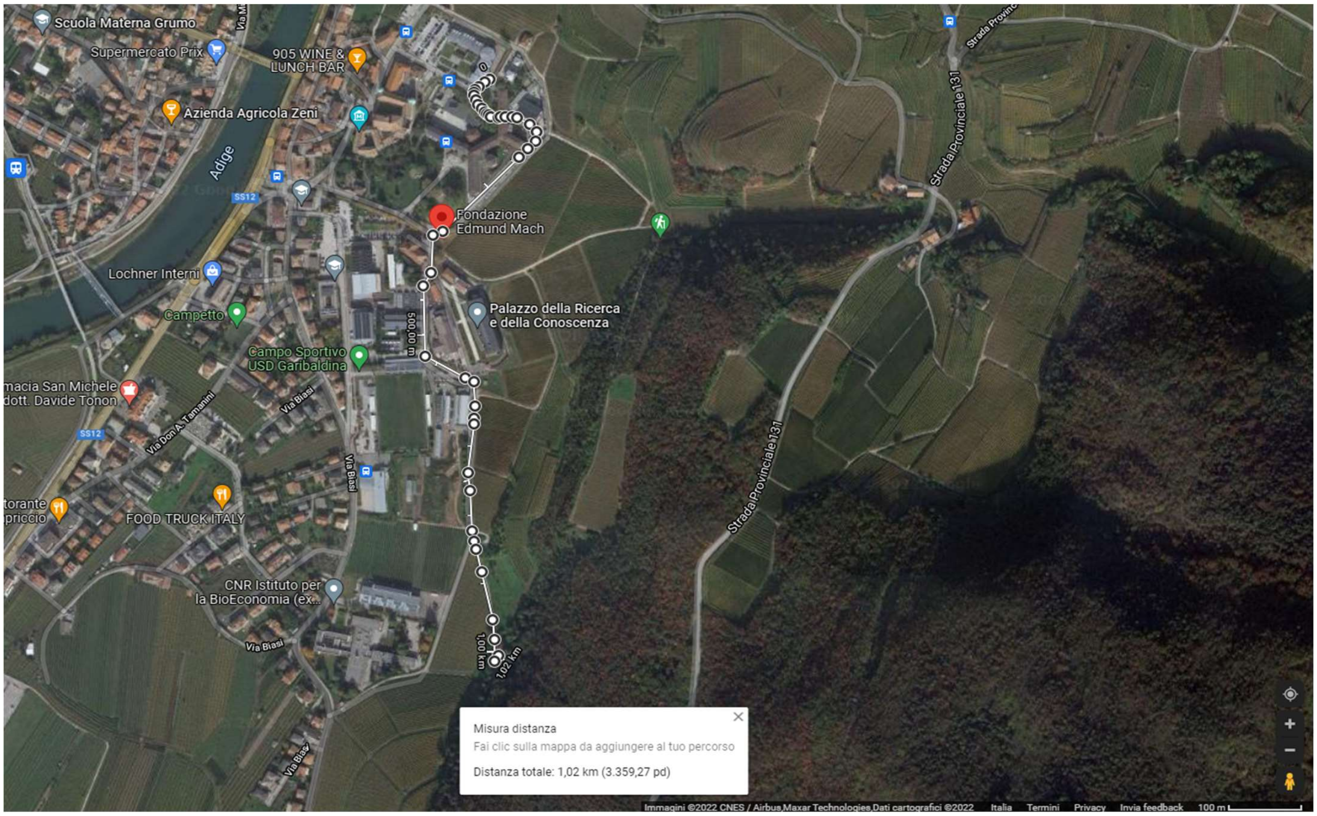
Inputs	Unit	Quantity
Sanitary landfill		
Electricity	kWh	1.77E-05
Light fuel oil	kg	3.77E-05
Diesel	kg	0.00109
Lubricating oil	kg	0.000024
Wastewater treatment		
Electricity	kWh	0.000927
Light fuel oil	kg	2.57E-05
Iron sulphate	kg	0.000031
Aluminium sulphate	kg	8.38E-06
Iron chloride	kg	4.26E-05
Sodium hydroxide	g	1.04E-05
Quicklime	mg	0.00189
Hydrochloric acid	mg	0.001
Municipal waste		
incineration		
Electricity	kWh	3.42E-07
Natural gas	m^3	3.15E-06
Ammonia	g	0.00143
Chromium	mg	0.000836
Titanium dioxide	g	4.08E-05
Water	L	0.00284

Slag compartment		
Electricity	kWh	2.14E-08
Light fuel oil	kg	4.54E-05
Diesel	kg	0.00115
Lubricating oil	kg	2.52E-05
Residual material		
landfill		
Electricity	kWh	1.17E-08
Light fuel oil	g	2.49E-05
Diesel	g	0.000111
Lubricating oil	mg	0.00244
Cement	kg	7.04E-05
Outputs		
Water emissions (after leachate treatment)		
Al	g	0.00408
As	g	0.000103
Ba	g	0.000723
Br	g	0.000504
Cd	g	1.56E-05
Ca	kg	0.000549
Cl	kg	0.000154
Cr, ion	mg	3.95E-05
Cr, VI	g	1.32E-05

Cu	mg	0.00417
Fe	g	0.00312
Hg	mg	3.25E-05
K	Kg	0.000666
Mg	Kg	0.000201
Mn	g	0.0276
Mo	mg	0.00312
Na	kg	0.00124
Ni	g	3.01E-05
Phosphate	g	0.00706
Pb	mg	0.000708
Sulphate	kg	8.36E-05
Sc	g	1.21E-05
Sn	mg	0.000493
Si	g	0.0498
Sr	g	0.00014
Ti	g	0.00211
V	g	3.35E-05
Zn	g	9.65E-05
Air emissions (sludge incineration)		
CO	g	0.000632
CH4	g	1.81E-05
NH3	g	0.000022

NOx	g	0.000902
NMVOC	g	0.000177
PM2.5	g	1.69E-05
PM10	mg	8.51E-05
Al	g	0.000102
As	mg	3.29E-05
Ba	g	1.13E-05
Ca	g	0.0001
Fe	mg	0.000969
Mg	g	3.01E-05
Mo	mg	5.19E-06
P	g	4.15E-06
Sc	mg	5.55E-06
Sn	mg	9.09E-07
Si	mg	0.00181
Sr	mg	1.36E-05
Ti	mg	0.00205
V	mg	3.25E-06

Table (4.3): Inventory data for the landfilling of 1 kg of woody biomass ash(61)



Misura distanza

Fai clic sulla mappa da aggiungere al tuo percorso

Distanza totale: 1,02 km (3.359,27 pd)

Fig (4.7): Distance from the incinerator to FEM plant to transport ash in

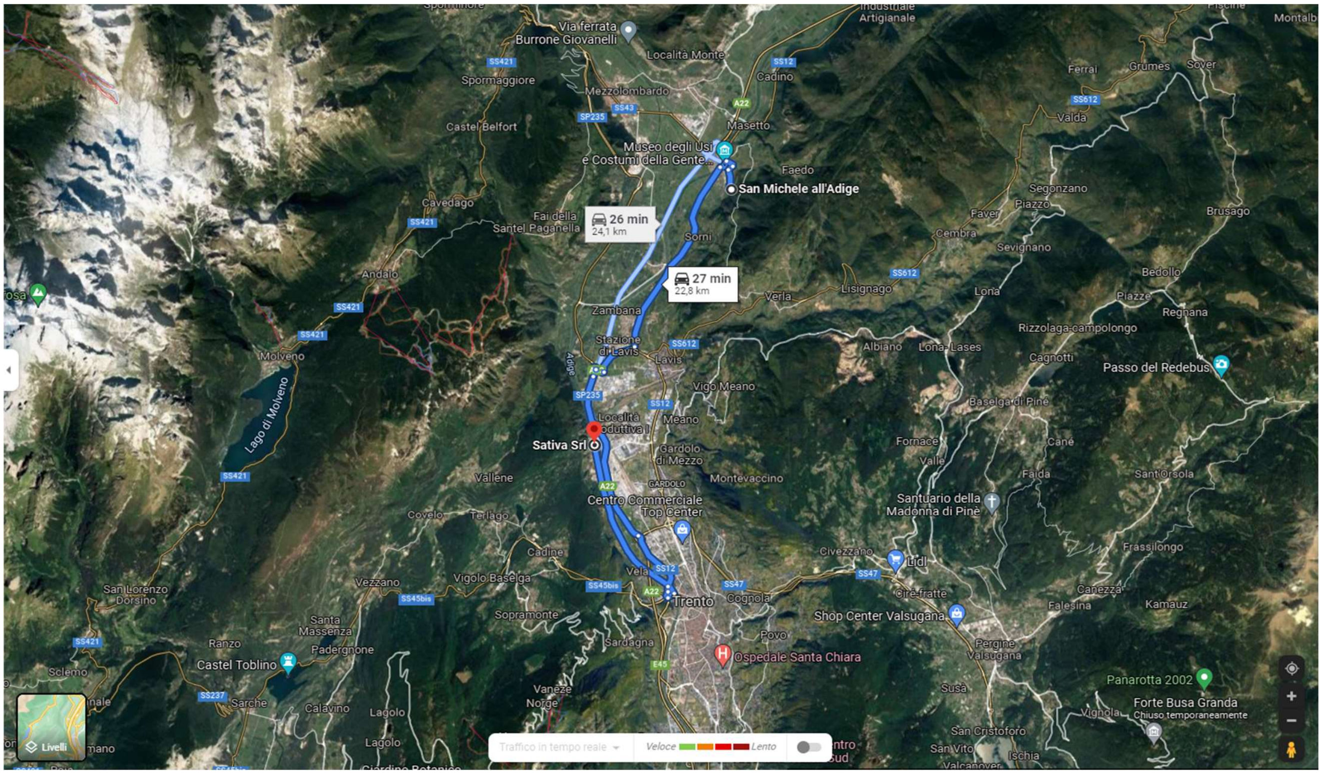


Fig (4.8): Distance from the FEM plant to transport ash out to landfill point

Input name	Quantity	Unit	Source of input
Raw biogas	1	m^3	From anaerobic digestion of OFMSW
Wood ashes	7	Kg	From district heating plant
water	1.75	liter	From groundwater
Nitrogen gas	0.427	liter	From gas cylinders
Electricity	0.2	KWh	From the public source of electricity
Transport Ash-in to the plant site	1.02	Km	From wood incineration

Table (4.4): Aggregated inputs from Up-Ash plan

Output name	Quantity	Unit	The direction of the output
Biomethane (96% % CH_4 by volume)	1	m^3	Biomethane to be used
Wood ashes	7	Kg	To be disposed into a landfill
Nitrogen	0.427	liter	Emission to air
Methane losses	0.01	m^3	Emission to air
Transport Ash-out from the plant site	22.8	Km	Landfill

Table (4.5): Aggregated outputs from Up-Ash plant

4.2.3 Life cycle impact assessment method

The CML methodology has been chosen to evaluate the Life Cycle Assessment of the innovative technique for enhancing biogas to biomethane utilizing biomass ash. The Institute of Environmental Sciences at Leiden University in the Netherlands devised this method of study, which has since become one of the most well-known and thorough in science. The method may generate characterization factors for over 1700 streams in this approach.

Table (4.2) shows the main impact categories reported in the method, and the impact categories, along with their abbreviations and units of measurement, are shown in the table (4.3) below.

CML Method	
Impact category group	**Name of the impact category in the method**
Acidification	Acidification potential - European average
Climate change	climate change GWP100
Reduce of abiotic resources	Reduction of abiotic resources - elements, last reserves
	Reduction of abiotic resources - fossil fuels
Ecotoxicity	freshwater ecotoxicity
	Marine ecotoxicity
	Terrestrial ecotoxicity
Eutrophication	Generic Eutrophication
Human toxicity	Human toxicity
Depletion of atmospheric ozone	Depletion of atmospheric ozone
Photochemical oxidation	Generic Photochemical oxidation

Table (4.6): Main impact categories in CML method

Category	Abbreviations	Unit
Abiotic Depletion Potential	ADP E	kg Sb eq/Nm^3_{biogas}
Abiotic Depletion Potential (fossil fuels)	ADP F	MJ/Nm^3_{biogas}
Global Warming Potential (GWP100a)	GWP	kg CO_2 eq/Nm^3_{biogas}
Ozone Depletion Potential	ODP	kg CFC-11 eq/Nm^3_{biogas}
Human Toxicity Potential	HTP	kg 1,4-DB eq/Nm^3_{biogas}
Freshwater Aquatic Ecotoxicity Potential	FAETP	kg 1,4-DB eq/Nm^3_{biogas}
Marine Aquatic Ecotoxicity Potential	MAETP	kg 1,4-DB eq/Nm^3_{biogas}
Terrestrial Ecotoxicity Potential	TETP	kg 1,4-DB eq/Nm^3_{biogas}
Photochemical Ozone Creation Potential	POCP	kg C_2H_4 eq/Nm^3_{biogas}
Acidification Potential	AP	kg SO_2 eq/ Nm^3_{biogas}
Eutrophication Potential	EP	kg PO_4^{3-} eq/ Nm^3_{biogas}

Table (4.7): Environmental impact indicators included in the CML method

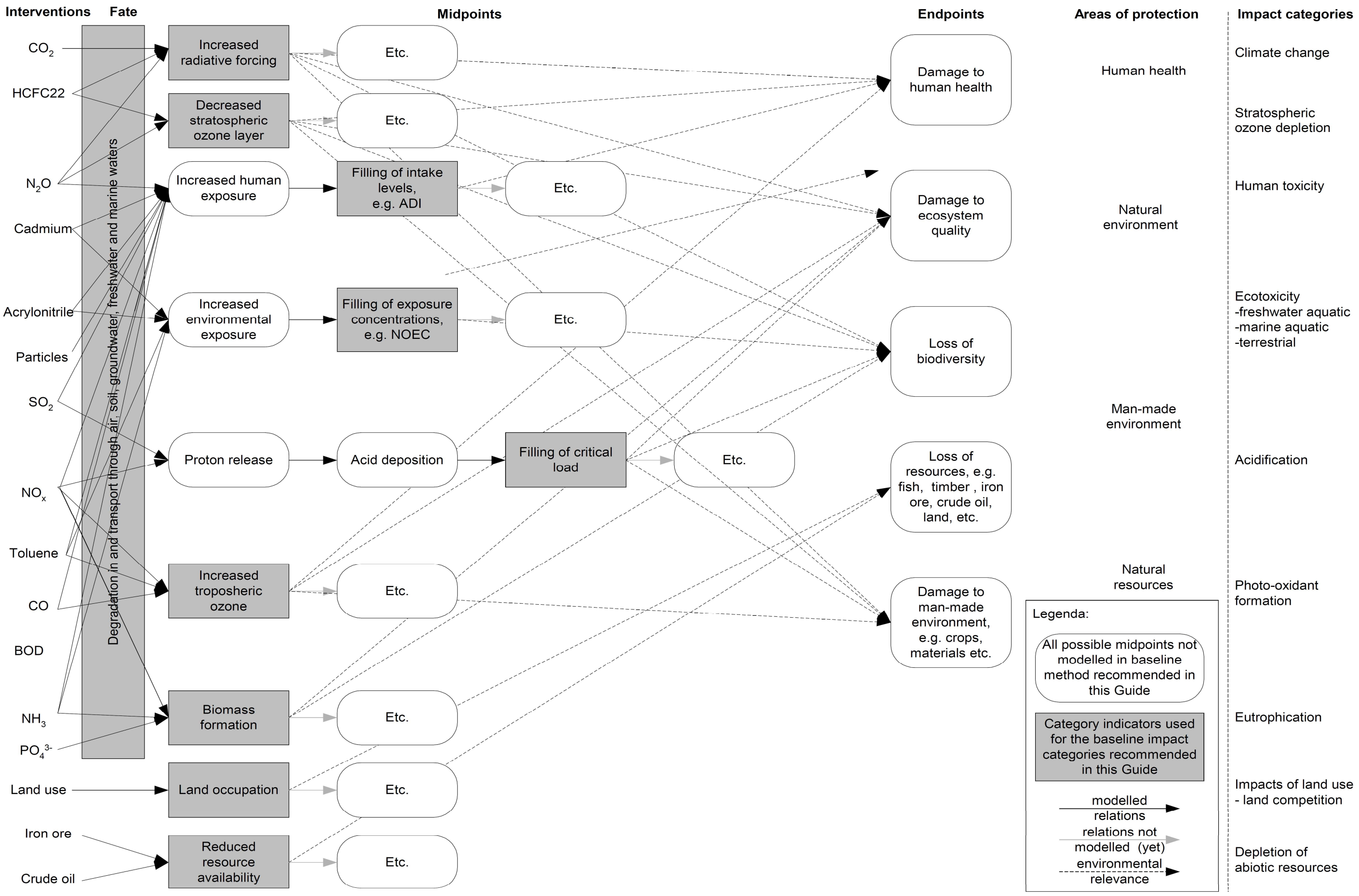


Fig (4.9): Impact categories and pathways covered by the CML methodology (62)

4.2.3.1 Abiotic depletion

Renewable resources, such as wood and groundwater, and nonrenewable resources, such as fossil fuels and minerals, are divided into input materials (natural resources) used in different production sectors. The exhaustion of nonrenewable resources and the resulting environmental consequences are referred to as abiotic depletion(63).

4.2.3.2 Global Warming Potential

Global warming is an expression that refers to the Earth's average surface temperature rising because of rising greenhouse gas emissions. CO_2 is the standard ingredient for GWP. Rising sea levels create changes in terrestrial and aquatic ecosystems and coasts as a result of global warming(63).

4.2.3.3 Ozone Depletion Potential

Ozone depletion is the phenomenon of decreased ozone density because human pollution lowers the stratospheric ozone layer (15–30 km height). As a result, human skin is exposed to more UV radiation, potentially increasing the risk of melanoma. CFCs are the standard material for ODP(63).

4.2.3.4 Toxicity

It is indicated by indices showing the potential harm that a chemical spread in the environment and individuals could cause. There are many different sorts of computations that consider many other variables, but they all start with the compound's intrinsic toxicity and its potential toxicity. Carcinogenic benzene and non-carcinogenic toluene are examples of equivalence chemicals. Models that represent the fate, exposure and consequences of dangerous chemicals for various time patterns are used to determine potentiality. One kilogram of 1,4-dichlorobenzene equivalent is the hazardous reference material for this computation. Because toxic compounds have such a wide range of impacts on different ecosystems, they must be classified into subcategories of impact, such as ecotoxicity and human toxicity.

4.2.3.5 Human toxicity

Chemicals have a high toxin content that reaches humans through the environment, creating human toxicity. Humans exposed to these emissions through the soil, water, and atmosphere may suffer health consequences, depending on the degree of toxicity inherent in the emissions' composition (64). A margin-of-exposure ratio is used in the Human Toxicity Potential (HTP) to describe the potential for health damage from exposure to toxic chemicals, including carcinogens and non-carcinogens (65). The reference toxic substance for this calculation is one kg of 1,4-dichlorobenzene equivalent.

4.2.3.6 Ecotoxicity

Hazardous material can have two types of toxicity on ecosystems: acute toxicity and temporally dispersed toxicity. Immediate toxicity occurs when a substance's concentration in the environment causes obvious and serious damage within a short period after exposure and can be lethal to the subject. Chronic effects that are not instantaneous but spread out over time are referred to as temporally dispersed toxicity. These compounds accumulate in living tissue and have poor biodegradability, and they are mostly found on a local and regional level. The assessment of ecotoxicity is not always quick since it is crucial to know the chemicals and the mechanisms that interact between the various systems, as well as chemical and ecotoxicological information about the material, to make an accurate assessment.

Ecotoxicity tests, persistence tests on living tissue, and the computation of the octanol/water partition coefficient are the elements that describe the classification of a substance's ecotoxicity (accumulation indicator on adipose tissues).

Ecotoxicity is divided into three categories based on the substance's environmental impact: Fresh Water Aquatic Ecotoxicity, Marine Aquatic Ecotoxicity, and Terrestrial Ecotoxicity.

In the computation of aquatic toxicity, certain harmful compounds are transferred from soil to water. In contrast, emissions to air are reported as precipitation in the calculations of water and land toxicity.

4.2.3.7 Photochemical Ozone Creation Potential

Ozone is protective in the stratosphere, but it is hazardous to ground-level people at significant concentrations. The interaction of volatile organic molecules with nitrogen oxides in the presence of heat and sunlight produces photochemical ozone, often known as "ground-level ozone." The amount of carbon monoxide (CO), sulfur dioxide (SO_2), nitrogen oxide (NO), ammonium, and NMVOC determines the impact category (non-methane volatile organic compounds)(66). Respiratory issues, eye discomfort, and tree and crop damage are all possible side effects of the photochemical oxidation process, and for POCP, ethylene is employed as the standard substance(63).

4.2.3.8 Acidification Potential

Acidification is an environmental issue caused by acidified rivers/streams and soil due to anthropogenic air pollutants such as SO_2, NH_3, and NO_x. Acidification enhances heavy metal mobilization and leaching in soil, causing harm to aquatic and terrestrial animals and plants by disrupting the food web. SO_2 is the standard chemical for AP testing(63).

4.2.3.9 Eutrophication Potential

Eutrophication occurs when a concentration of chemical nutrients builds up in an ecosystem, resulting in abnormal productivity. Excessive plant growth, such as algae, occurs in rivers, resulting in dramatic losses in water quality and animal populations. Eutrophication is influenced by ammonia, nitrates, nitrogen oxides, and phosphorus emissions into the air or water(66).

The strategy takes into account both direct and indirect fertilizer effects. The direct impacts are calculated using the IPCC approach to estimate emissions to water that cause eutrophication. In contrast, the indirect impacts are computed using the IPCC (Intergovernmental Panel on Climate Change) method to estimate emissions to water that cause eutrophication; in addition, eutrophication is expressed using the reference unit $PO_4{}^{3-}$(66).

4.3 Modeling inputs in GaBi software to analyze the case study

After defining all the inputs and outputs and defining the goal and scope of the study, the model was constructed into GaBi software by inserting all processes that contain a different quantity of flows, and these flows have an amount of environmental impact related to CML 2001.

To start the analysis using Gabi software, it was required from the properties of the software to open a new project and activate it to begin modeling the processes and flow into a database plan page to model the life cycle assessment of the study.

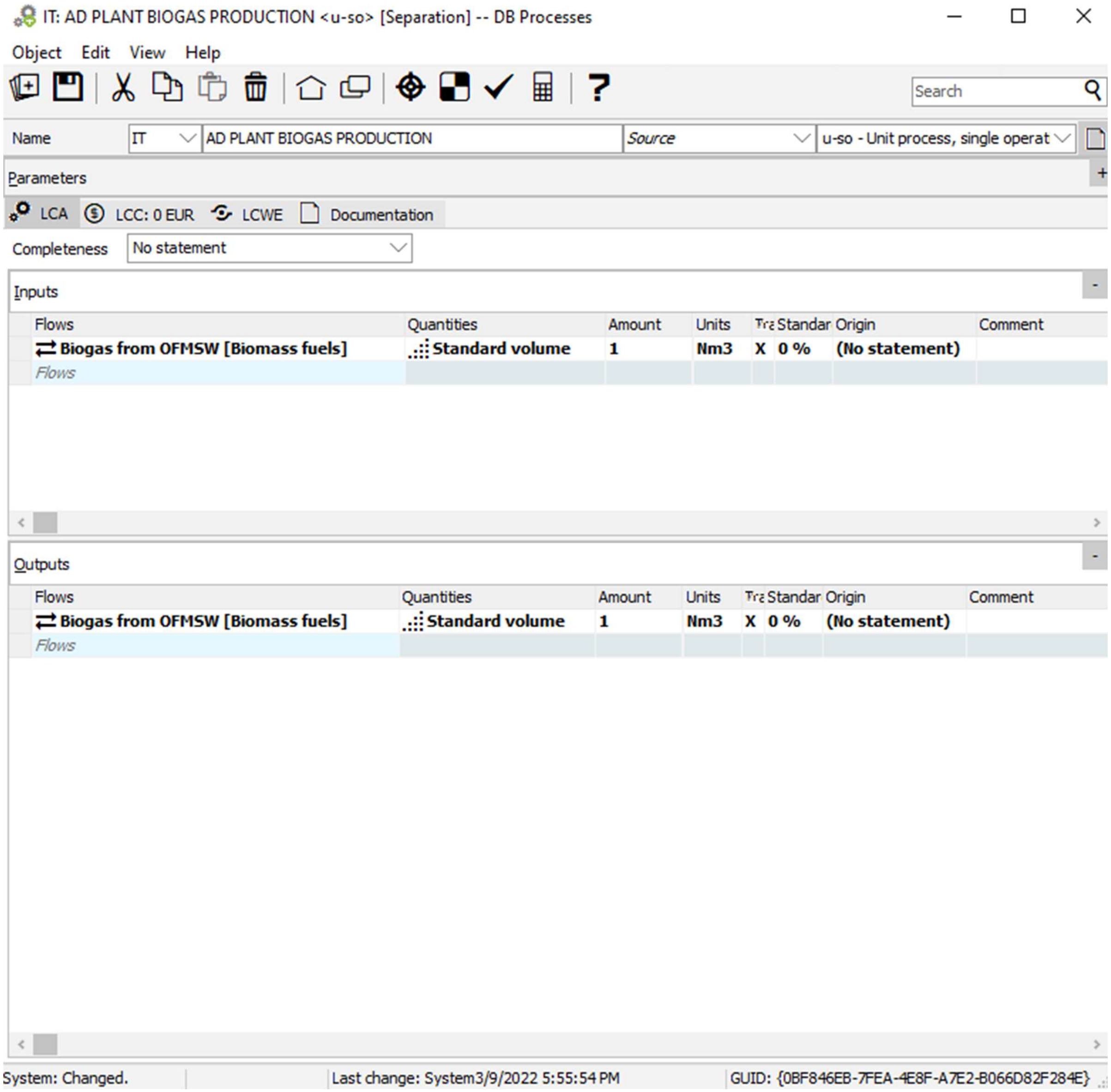
4.3.1 Initiate new processes not existing in the database

Some processes were not located in the GaBi database, so new processes were initiated to record its flows. The defined inputs and outputs of flows into these processes were selected according to their correct object group that is appeared in the parent folder.

The new processes defined in Gabi software are:

1- Anaerobic Digestion (AD) plant biogas production

This process defined biogas coming from the anaerobic digestion (AD) plant. The reference quantity for this process is 1 m^3 of biogas.



IT: AD PLANT BIOGAS PRODUCTION <u-so> [Separation] -- DB Processes

Name: IT | AD PLANT BIOGAS PRODUCTION | Source | u-so - Unit process, single operat

Completeness: No statement

Inputs

Flows	Quantities	Amount	Units	Tra	Standar	Origin	Comment
Biogas from OFMSW [Biomass fuels]	**Standard volume**	**1**	**Nm3**	**X**	**0 %**	**(No statement)**	
Flows							

Outputs

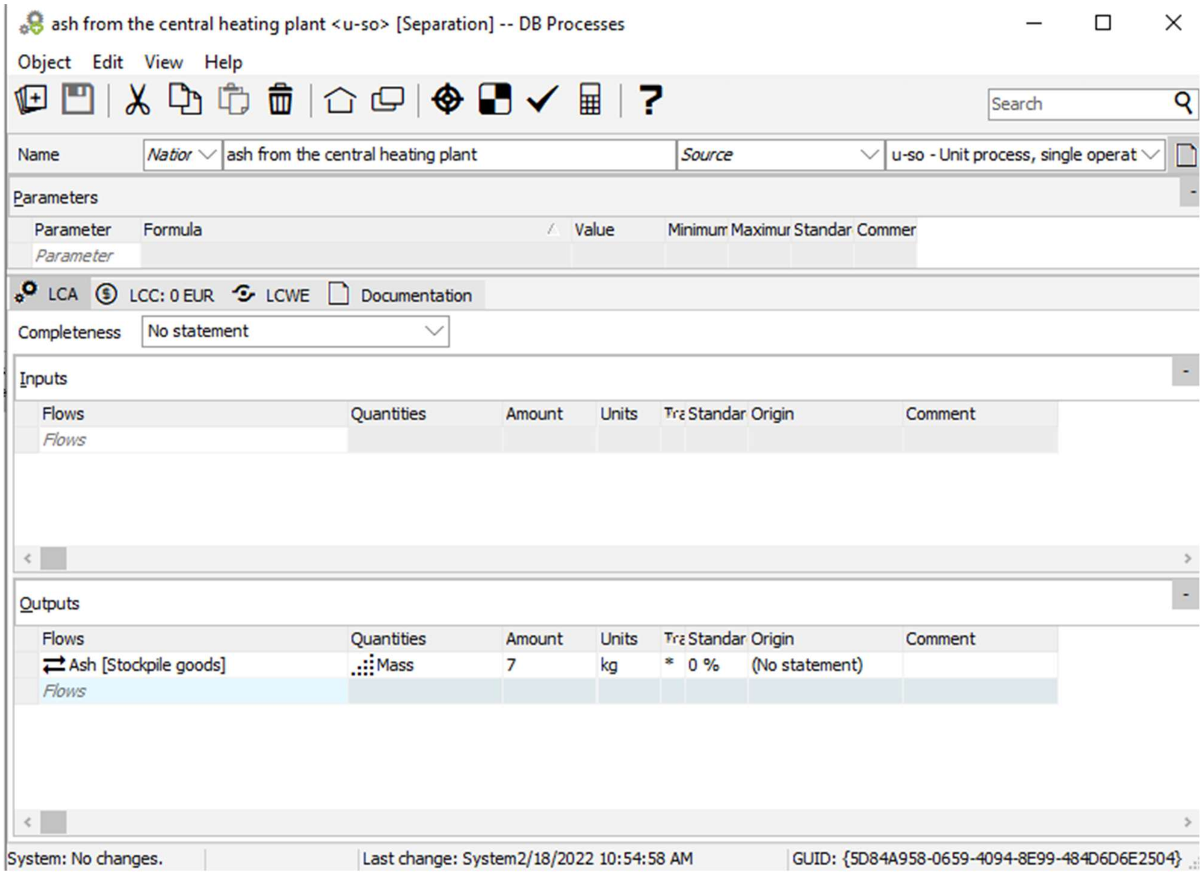
Flows	Quantities	Amount	Units	Tra	Standar	Origin	Comment
Biogas from OFMSW [Biomass fuels]	**Standard volume**	**1**	**Nm3**	**X**	**0 %**	**(No statement)**	
Flows							

System: Changed. | Last change: System3/9/2022 5:55:54 PM | GUID: {0BF846EB-7FEA-4E8F-A7E2-B066D82F284E}

Fig (4.10): Anaerobic Digestion (AD) plant biogas production Process

2- Ash from the central heating plant

This process stated the amount of ash that arrived from the wood incineration, as the amount required of ash to purify 1 m^3 of biogas is 7 kg as per lab experiments.



ash from the central heating plant <u-so> [Separation] -- DB Processes

Name: Natior | ash from the central heating plant | Source | u-so - Unit process, single operat

Parameters

Parameter	Formula	Value	Minimum	Maximu	Standar	Commer
Parameter						

Completeness: No statement

Inputs

Flows	Quantities	Amount	Units	Tra	Standar	Origin	Comment
Flows							

Outputs

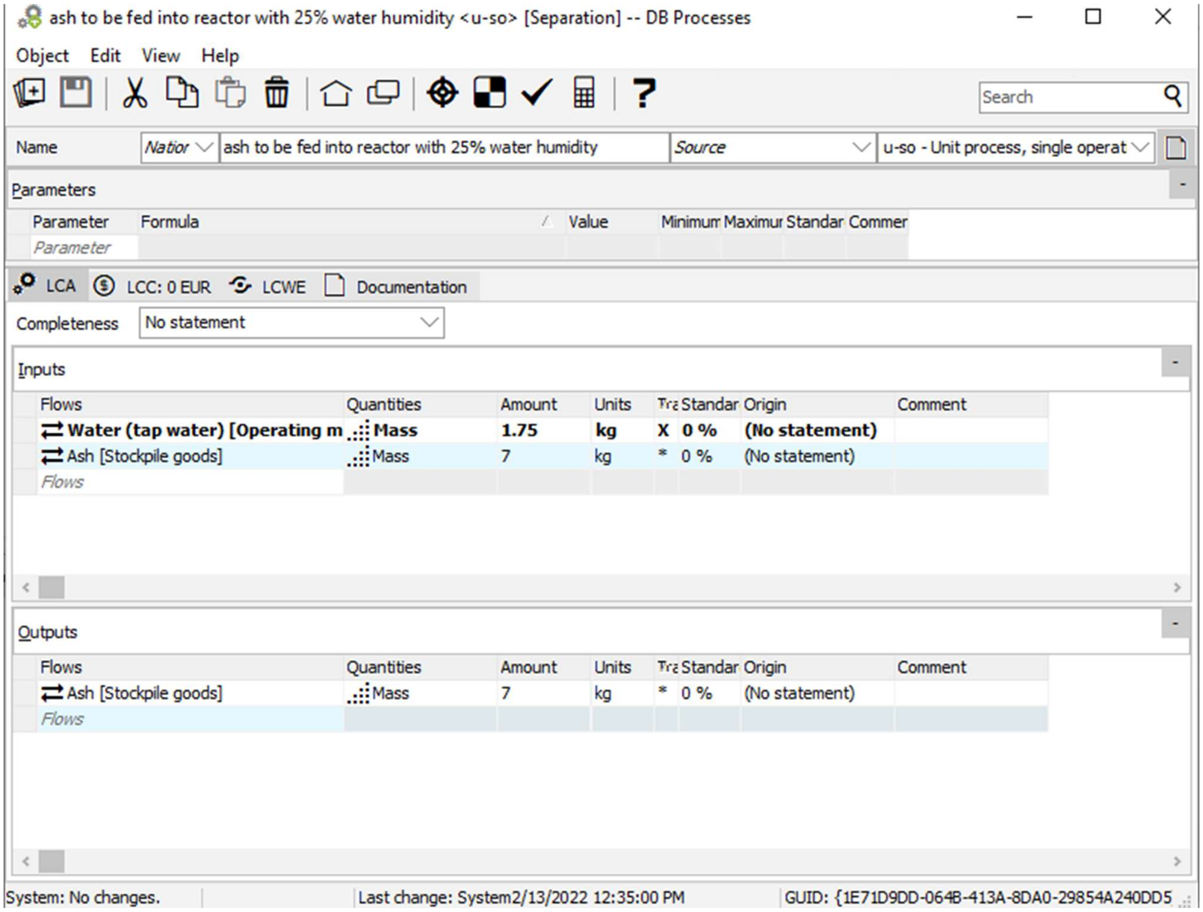
Flows	Quantities	Amount	Units	Tra	Standar	Origin	Comment
Ash [Stockpile goods]	Mass	7	kg	*	0 %	(No statement)	
Flows							

System: No changes. | Last change: System2/18/2022 10:54:58 AM | GUID: {5D84A958-0659-4094-8E99-484D6D6E2504}

Fig (4.11): Ash from the central heating plant process

3- Ash to be fed into reactor with 25% water humidity

This process shows the amount of ash added to the reactor with 25% humidity (1.75 liters of water of every 7 kg of ashes).



ash to be fed into reactor with 25% water humidity <u-so> [Separation] -- DB Processes

Name: Natior | ash to be fed into reactor with 25% water humidity | Source | u-so - Unit process, single operat

Parameters

Parameter	Formula	Value	Minimum	Maximur	Standar	Commer
Parameter						

Completeness: No statement

Inputs

Flows	Quantities	Amount	Units	Tra	Standar	Origin	Comment
Water (tap water) [Operating m	**Mass**	**1.75**	**kg**	**X**	**0 %**	**(No statement)**	
Ash [Stockpile goods]	Mass	7	kg	*	0 %	(No statement)	
Flows							

Outputs

Flows	Quantities	Amount	Units	Tra	Standar	Origin	Comment
Ash [Stockpile goods]	Mass	7	kg	*	0 %	(No statement)	
Flows							

System: No changes.

Last change: System2/13/2022 12:35:00 PM

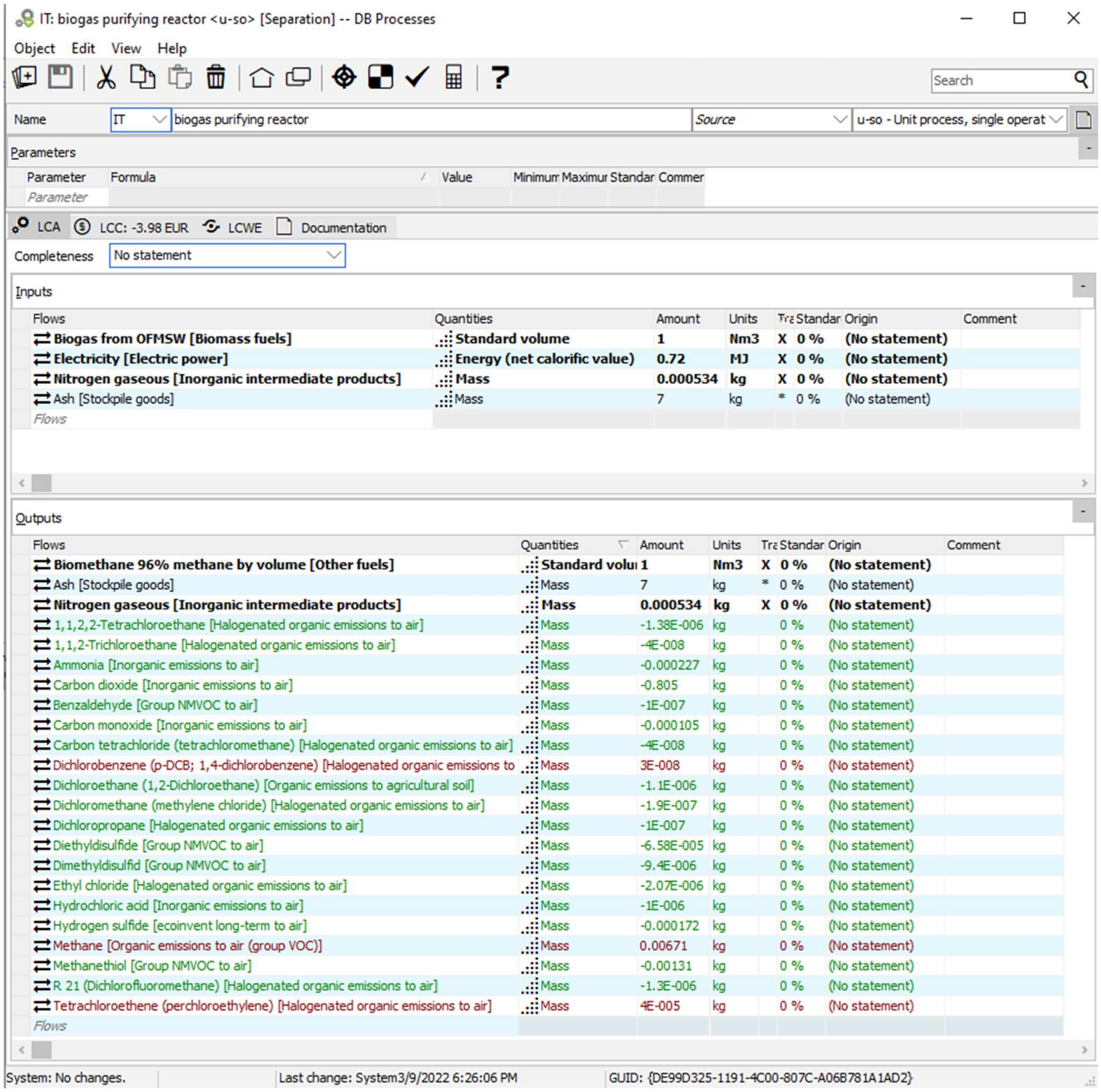
GUID: {1E71D9DD-064B-413A-8DA0-29854A240DD5

Fig (4.12): Ash to be fed into reactor with 25% water humidity process

4- Biogas purifying reactor

This process defined and aggregated all inputs to the reactor that are used to purify and enhance the structure of biogas to produce at the end a biomethane with a high ratio of methane CH_4; this process is a central process for this life cycle assessment study because it combines all inputs we have in gate-gate analysis.

In the output, methane losses are defined in this process as an emission to the air. The amount of carbon dioxide is illustrated with a negative value because it is captured through ash and absorbed the data for capturing impurities from the table (4.2), which calculated the difference between these impurities in biogas and biomethane also defined as negative values in this process.



IT: biogas purifying reactor <u-so> [Separation] -- DB Processes

Name: IT | biogas purifying reactor | Source | u-so - Unit process, single operat

Parameters

Parameter	Formula	Value	Minimum	Maximur	Standar	Commer
Parameter						

LCC: -3.98 EUR

Completeness: No statement

Inputs

Flows	Quantities	Amount	Units	Tra	Standar	Origin	Comment
Biogas from OFMSW [Biomass fuels]	**Standard volume**	**1**	**Nm3**	**X**	**0 %**	**(No statement)**	
Electricity [Electric power]	**Energy (net calorific value)**	**0.72**	**MJ**	**X**	**0 %**	**(No statement)**	
Nitrogen gaseous [Inorganic intermediate products]	**Mass**	**0.000534**	**kg**	**X**	**0 %**	**(No statement)**	
Ash [Stockpile goods]	Mass	7	kg	*	0 %	(No statement)	
Flows							

Outputs

Flows	Quantities	Amount	Units	Tra	Standar	Origin	Comment
Biomethane 96% methane by volume [Other fuels]	**Standard volu**	**1**	**Nm3**	**X**	**0 %**	**(No statement)**	
Ash [Stockpile goods]	Mass	7	kg	*	0 %	(No statement)	
Nitrogen gaseous [Inorganic intermediate products]	**Mass**	**0.000534**	**kg**	**X**	**0 %**	**(No statement)**	
1,1,2,2-Tetrachloroethane [Halogenated organic emissions to air]	Mass	-1.38E-006	kg		0 %	(No statement)	
1,1,2-Trichloroethane [Halogenated organic emissions to air]	Mass	-4E-008	kg		0 %	(No statement)	
Ammonia [Inorganic emissions to air]	Mass	-0.000227	kg		0 %	(No statement)	
Carbon dioxide [Inorganic emissions to air]	Mass	-0.805	kg		0 %	(No statement)	
Benzaldehyde [Group NMVOC to air]	Mass	-1E-007	kg		0 %	(No statement)	
Carbon monoxide [Inorganic emissions to air]	Mass	-0.000105	kg		0 %	(No statement)	
Carbon tetrachloride (tetrachloromethane) [Halogenated organic emissions to air]	Mass	-4E-008	kg		0 %	(No statement)	
Dichlorobenzene (p-DCB; 1,4-dichlorobenzene) [Halogenated organic emissions to	Mass	3E-008	kg		0 %	(No statement)	
Dichloroethane (1,2-Dichloroethane) [Organic emissions to agricultural soil]	Mass	-1.1E-006	kg		0 %	(No statement)	
Dichloromethane (methylene chloride) [Halogenated organic emissions to air]	Mass	-1.9E-007	kg		0 %	(No statement)	
Dichloropropane [Halogenated organic emissions to air]	Mass	-1E-007	kg		0 %	(No statement)	
Diethyldisulfide [Group NMVOC to air]	Mass	-6.58E-005	kg		0 %	(No statement)	
Dimethyldisulfid [Group NMVOC to air]	Mass	-9.4E-006	kg		0 %	(No statement)	
Ethyl chloride [Halogenated organic emissions to air]	Mass	-2.07E-006	kg		0 %	(No statement)	
Hydrochloric acid [Inorganic emissions to air]	Mass	-1E-006	kg		0 %	(No statement)	
Hydrogen sulfide [ecoinvent long-term to air]	Mass	-0.000172	kg		0 %	(No statement)	
Methane [Organic emissions to air (group VOC)]	Mass	0.00671	kg		0 %	(No statement)	
Methanethiol [Group NMVOC to air]	Mass	-0.00131	kg		0 %	(No statement)	
R 21 (Dichlorofluoromethane) [Halogenated organic emissions to air]	Mass	-1.3E-006	kg		0 %	(No statement)	
Tetrachloroethene (perchloroethylene) [Halogenated organic emissions to air]	Mass	4E-005	kg		0 %	(No statement)	
Flows							

System: No changes.

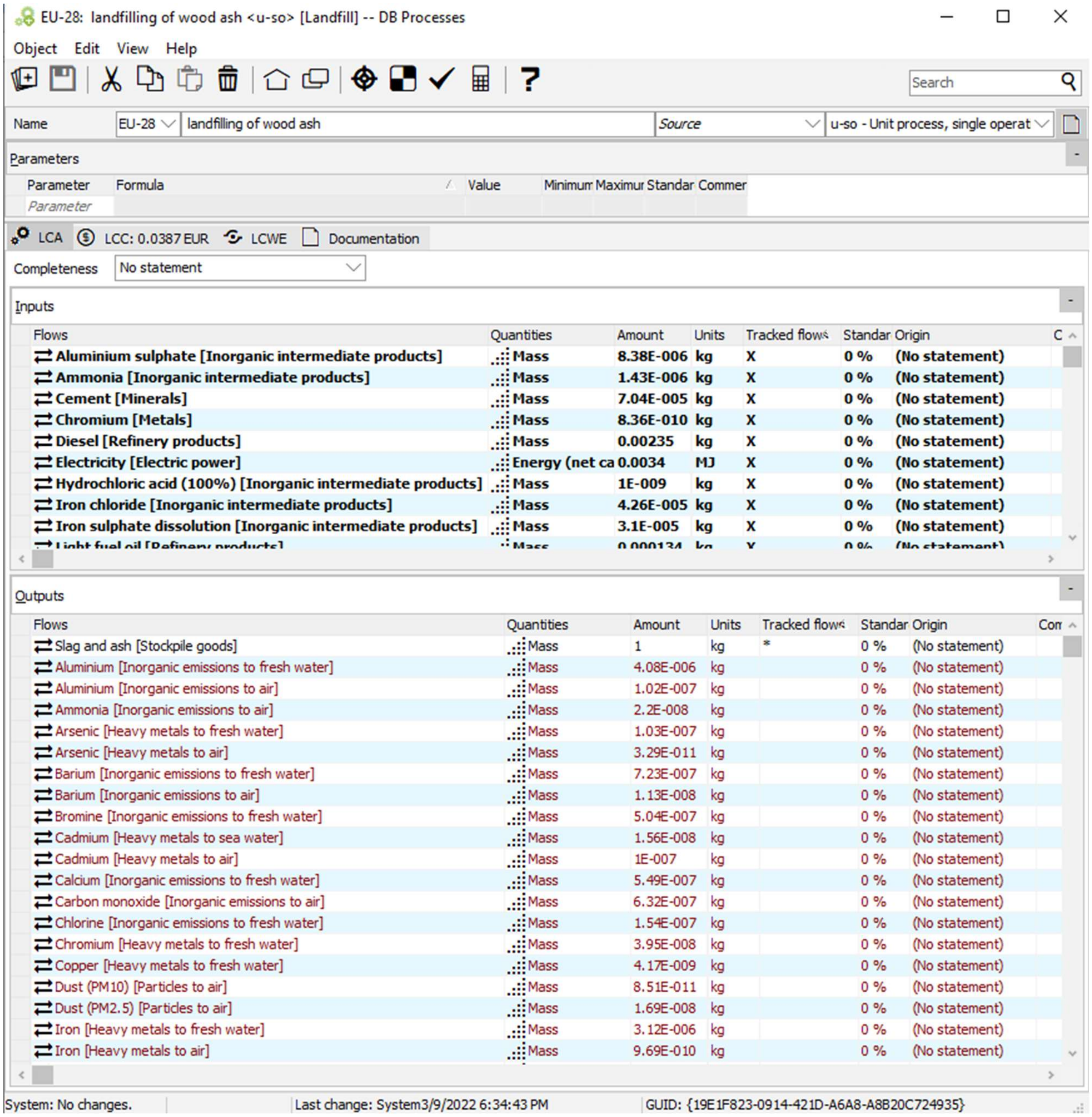
Last change: System3/9/2022 6:26:06 PM

GUID: {DE99D325-1191-4C00-807C-A06B781A1AD2}

Fig (4.13): Biogas purifying reactor process

5- landfilling of wood ash

This process presents the ash disposing of in the landfill site after processing the biogas to biomethane in the plant and transporting it to the landfill location. The inventory data of this process had taken from data in table (4.3).



EU-28: landfilling of wood ash <u-so> [Landfill] -- DB Processes

Name: EU-28 | landfilling of wood ash | Source | u-so - Unit process, single operat

LCC: 0.0387 EUR

Completeness: No statement

Inputs

Flows	Quantities	Amount	Units	Tracked flows	Standar	Origin
Aluminium sulphate [Inorganic intermediate products]	**Mass**	**8.38E-006**	**kg**	**X**	**0 %**	**(No statement)**
Ammonia [Inorganic intermediate products]	**Mass**	**1.43E-006**	**kg**	**X**	**0 %**	**(No statement)**
Cement [Minerals]	**Mass**	**7.04E-005**	**kg**	**X**	**0 %**	**(No statement)**
Chromium [Metals]	**Mass**	**8.36E-010**	**kg**	**X**	**0 %**	**(No statement)**
Diesel [Refinery products]	**Mass**	**0.00235**	**kg**	**X**	**0 %**	**(No statement)**
Electricity [Electric power]	**Energy (net ca**	**0.0034**	**MJ**	**X**	**0 %**	**(No statement)**
Hydrochloric acid (100%) [Inorganic intermediate products]	**Mass**	**1E-009**	**kg**	**X**	**0 %**	**(No statement)**
Iron chloride [Inorganic intermediate products]	**Mass**	**4.26E-005**	**kg**	**X**	**0 %**	**(No statement)**
Iron sulphate dissolution [Inorganic intermediate products]	**Mass**	**3.1E-005**	**kg**	**X**	**0 %**	**(No statement)**
Light fuel oil [Refinery products]	**Mass**	**0.000134**	**kg**	**X**	**0 %**	**(No statement)**

Outputs

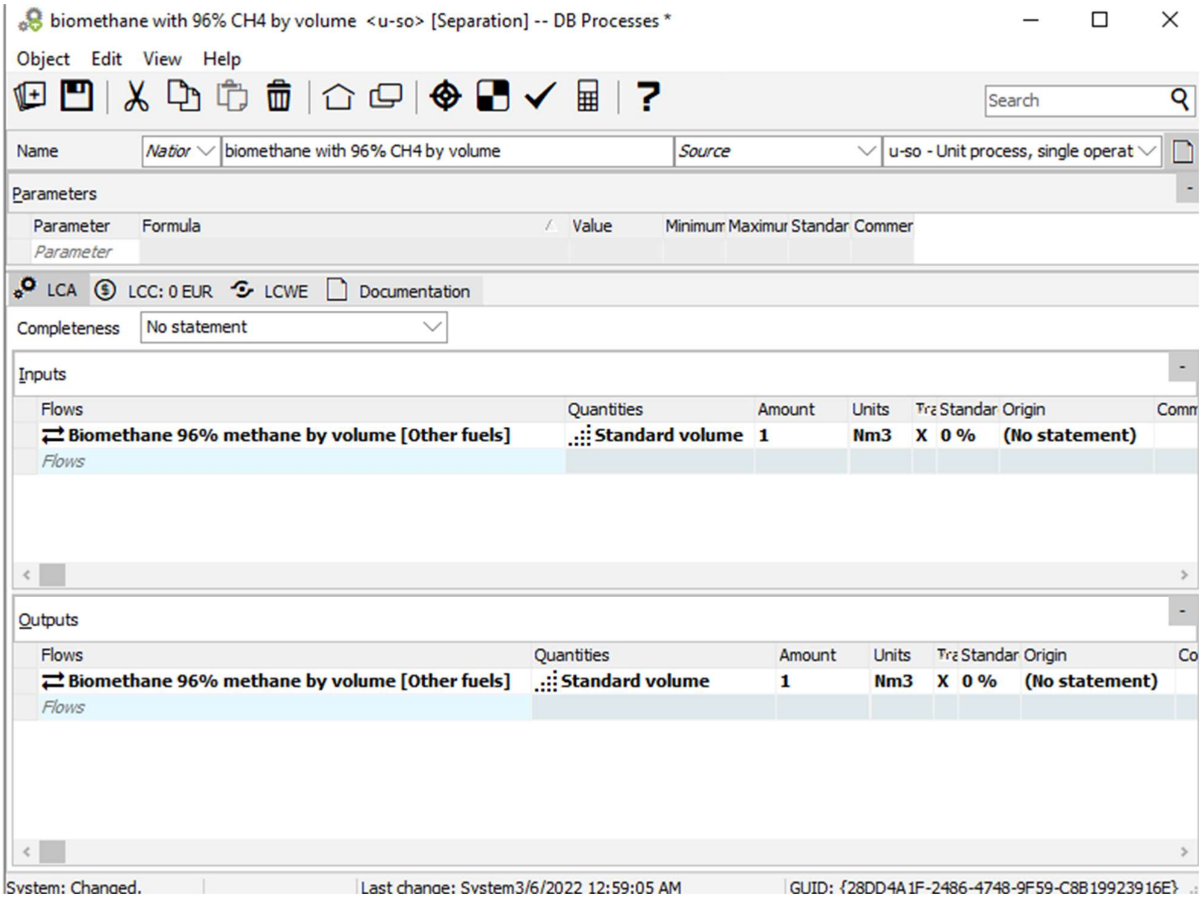
Flows	Quantities	Amount	Units	Tracked flows	Standar	Origin
Slag and ash [Stockpile goods]	Mass	1	kg	*	0 %	(No statement)
Aluminium [Inorganic emissions to fresh water]	Mass	4.08E-006	kg		0 %	(No statement)
Aluminium [Inorganic emissions to air]	Mass	1.02E-007	kg		0 %	(No statement)
Ammonia [Inorganic emissions to air]	Mass	2.2E-008	kg		0 %	(No statement)
Arsenic [Heavy metals to fresh water]	Mass	1.03E-007	kg		0 %	(No statement)
Arsenic [Heavy metals to air]	Mass	3.29E-011	kg		0 %	(No statement)
Barium [Inorganic emissions to fresh water]	Mass	7.23E-007	kg		0 %	(No statement)
Barium [Inorganic emissions to air]	Mass	1.13E-008	kg		0 %	(No statement)
Bromine [Inorganic emissions to fresh water]	Mass	5.04E-007	kg		0 %	(No statement)
Cadmium [Heavy metals to sea water]	Mass	1.56E-008	kg		0 %	(No statement)
Cadmium [Heavy metals to air]	Mass	1E-007	kg		0 %	(No statement)
Calcium [Inorganic emissions to fresh water]	Mass	5.49E-007	kg		0 %	(No statement)
Carbon monoxide [Inorganic emissions to air]	Mass	6.32E-007	kg		0 %	(No statement)
Chlorine [Inorganic emissions to fresh water]	Mass	1.54E-007	kg		0 %	(No statement)
Chromium [Heavy metals to fresh water]	Mass	3.95E-008	kg		0 %	(No statement)
Copper [Heavy metals to fresh water]	Mass	4.17E-009	kg		0 %	(No statement)
Dust (PM10) [Particles to air]	Mass	8.51E-011	kg		0 %	(No statement)
Dust (PM2.5) [Particles to air]	Mass	1.69E-008	kg		0 %	(No statement)
Iron [Heavy metals to fresh water]	Mass	3.12E-006	kg		0 %	(No statement)
Iron [Heavy metals to air]	Mass	9.69E-010	kg		0 %	(No statement)

System: No changes. Last change: System3/9/2022 6:34:43 PM GUID: {19E1F823-0914-421D-A6A8-A8B20C724935}

Fig (4.14): landfilling of wood ash

6- Biomethane with 96% CH_4 by volume

This process clarifies the amount of biomethane that leaves the reactor after the purification process; the amount of biomethane contains 96% by volume of methane.



biomethane with 96% CH4 by volume <u-so> [Separation] -- DB Processes *

Name: Natior | biomethane with 96% CH4 by volume | Source | u-so - Unit process, single operat

Completeness: No statement

Inputs

Flows	Quantities	Amount	Units	Tra	Standar	Origin	Comm
Biomethane 96% methane by volume [Other fuels]	**Standard volume**	**1**	**Nm3**	**X**	**0 %**	**(No statement)**	

Outputs

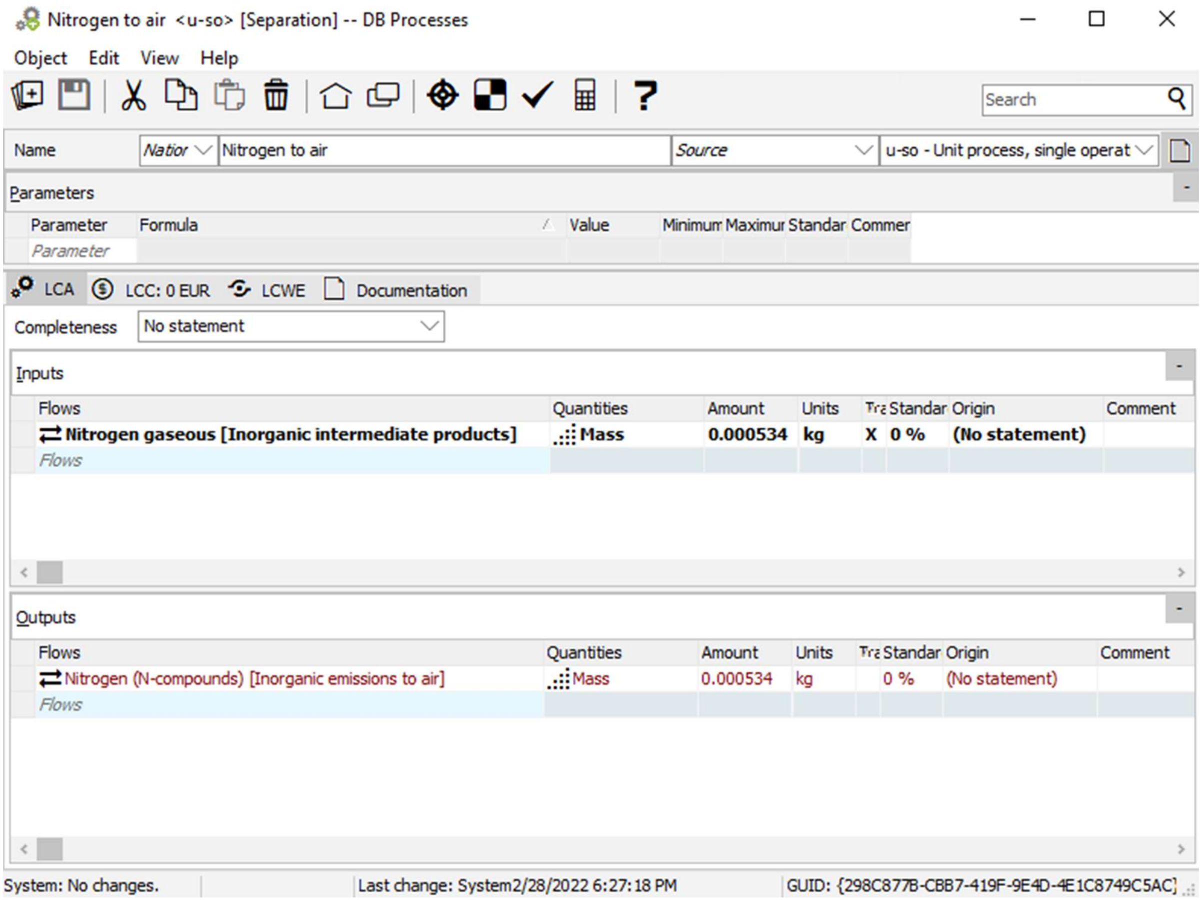
Flows	Quantities	Amount	Units	Tra	Standar	Origin	Co
Biomethane 96% methane by volume [Other fuels]	**Standard volume**	**1**	**Nm3**	**X**	**0 %**	**(No statement)**	

System: Changed. | Last change: System3/6/2022 12:59:05 AM | GUID: {28DD4A1F-2486-4748-9F59-C8B19923916E}

Fig (4.15): Biomethane with 96% CH4 by volume process

7- Nitrogen to air

This process illustrates the quantity of nitrogen leaving the reactor to the air after flushing it before starting the process and feeding biogas into the reactor; the amount of nitrogen released into the atmosphere is defined as an emission to air.



Name: Natior | Nitrogen to air | Source | u-so - Unit process, single operat

Parameters

Parameter	Formula	Value	Minimum	Maximur	Standar	Commer
Parameter						

Completeness: No statement

Inputs

Flows	Quantities	Amount	Units	Tra	Standar	Origin	Comment
Nitrogen gaseous [Inorganic intermediate products]	**Mass**	**0.000534**	**kg**	**X**	**0 %**	**(No statement)**	
Flows							

Outputs

Flows	Quantities	Amount	Units	Tra	Standar	Origin	Comment
Nitrogen (N-compounds) [Inorganic emissions to air]	Mass	0.000534	kg		0 %	(No statement)	
Flows							

System: No changes. | Last change: System2/28/2022 6:27:18 PM | GUID: {298C877B-CBB7-419F-9E4D-4E1C8749C5AC}

Fig (4.16): Nitrogen to air process

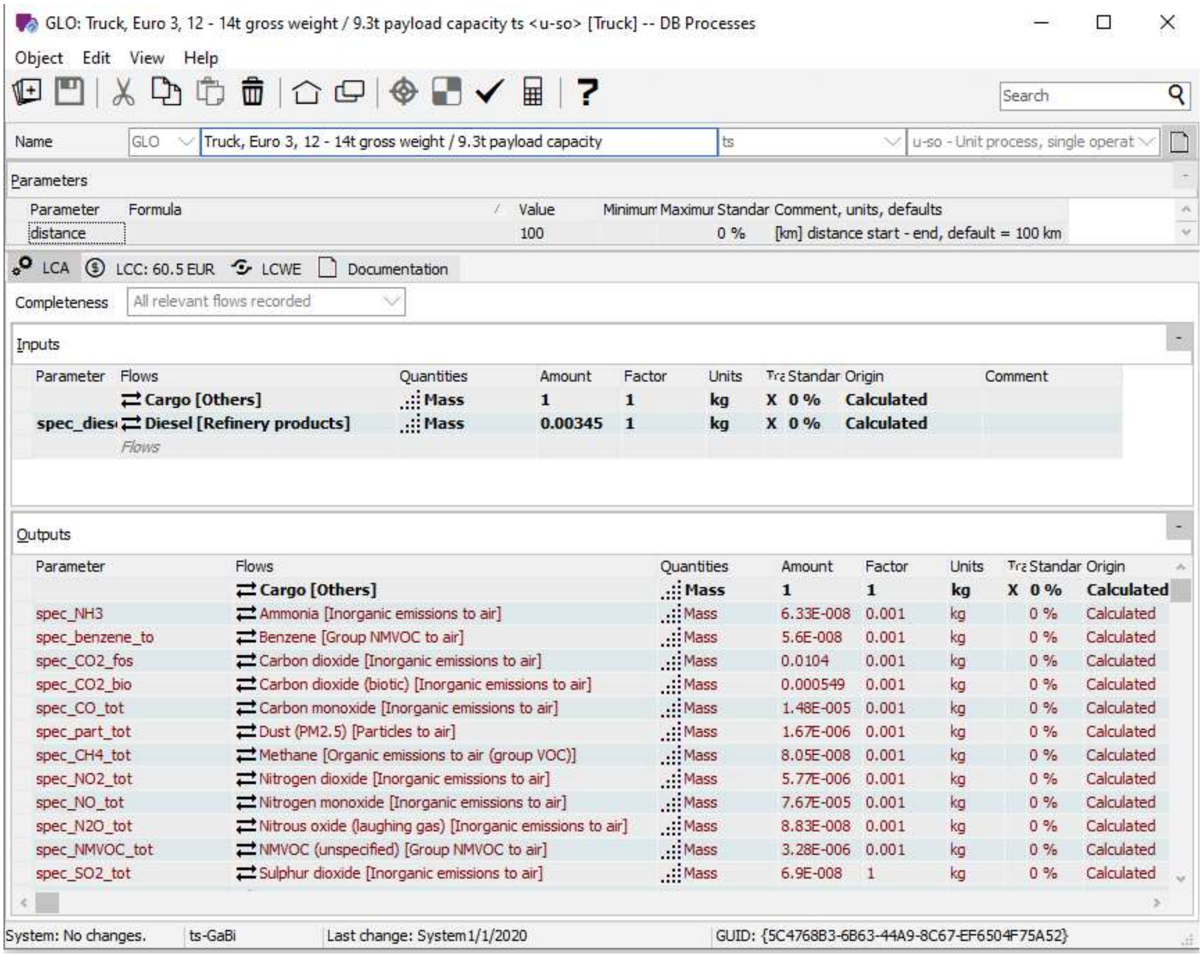
4.3.2 Use of existing processes in the database

There are some ready-made processes defined in the program's educational database that was used for analysis, and there was no need to create new processes because these processes were matching which can be readily added to the model; these processes include transportation with a truck to transfer ash in and out of the plant, the diesel amount needed for transportation, nitrogen gas to flush the reactor and electricity consumed in the plant.

The pre-defined processes that were used in the analysis are:

1- Truck, Euro 3, 12 - 14t gross weight process

This pre-defined process was used in the model to illustrate the transportation process from the point of collecting the ashes into the incineration site to deliver it to the plant with 1.02 Km and, on the other hand, carriage out the ash to the landfill with a distance of 22.8 Km.



Name: GLO | Truck, Euro 3, 12 - 14t gross weight / 9.3t payload capacity | ts | u-so - Unit process, single operat

Parameters

Parameter	Formula	Value	Minimum	Maximum	Standar	Comment, units, defaults
distance		100			0 %	[km] distance start - end, default = 100 km

Completeness: All relevant flows recorded

Inputs

Parameter	Flows	Quantities	Amount	Factor	Units	Tra	Standar	Origin	Comment
	Cargo [Others]	**Mass**	**1**	**1**	**kg**	**X**	**0 %**	**Calculated**	
spec_dies	**Diesel [Refinery products]**	**Mass**	**0.00345**	**1**	**kg**	**X**	**0 %**	**Calculated**	
	Flows								

Outputs

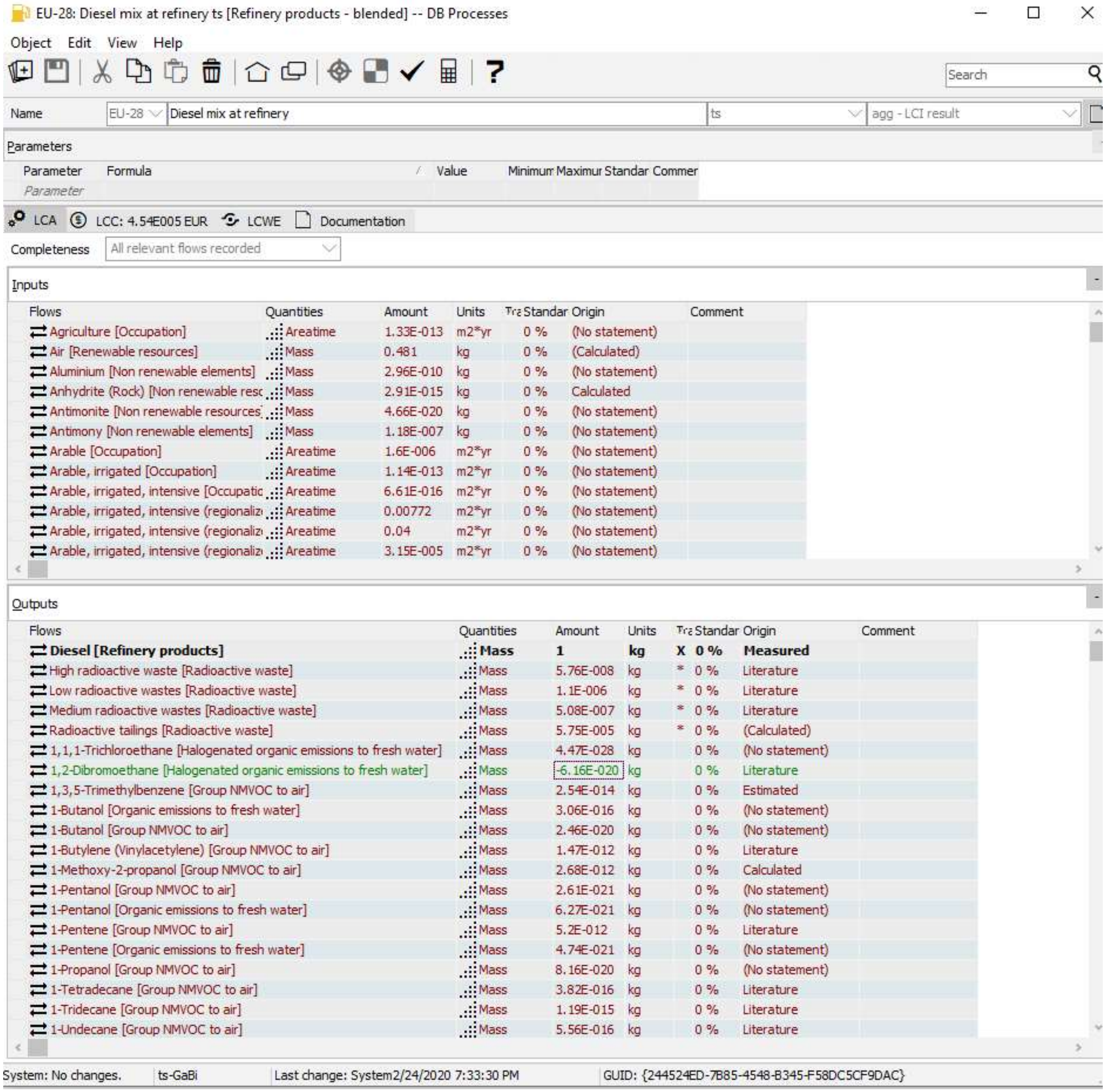
Parameter	Flows	Quantities	Amount	Factor	Units	Tra	Standar	Origin
	Cargo [Others]	**Mass**	**1**	**1**	**kg**	**X**	**0 %**	**Calculated**
spec_NH3	Ammonia [Inorganic emissions to air]	Mass	6.33E-008	0.001	kg		0 %	Calculated
spec_benzene_to	Benzene [Group NMVOC to air]	Mass	5.6E-008	0.001	kg		0 %	Calculated
spec_CO2_fos	Carbon dioxide [Inorganic emissions to air]	Mass	0.0104	0.001	kg		0 %	Calculated
spec_CO2_bio	Carbon dioxide (biotic) [Inorganic emissions to air]	Mass	0.000549	0.001	kg		0 %	Calculated
spec_CO_tot	Carbon monoxide [Inorganic emissions to air]	Mass	1.48E-005	0.001	kg		0 %	Calculated
spec_part_tot	Dust (PM2.5) [Particles to air]	Mass	1.67E-006	0.001	kg		0 %	Calculated
spec_CH4_tot	Methane [Organic emissions to air (group VOC)]	Mass	8.05E-008	0.001	kg		0 %	Calculated
spec_NO2_tot	Nitrogen dioxide [Inorganic emissions to air]	Mass	5.77E-006	0.001	kg		0 %	Calculated
spec_NO_tot	Nitrogen monoxide [Inorganic emissions to air]	Mass	7.67E-005	0.001	kg		0 %	Calculated
spec_N2O_tot	Nitrous oxide (laughing gas) [Inorganic emissions to air]	Mass	8.83E-008	0.001	kg		0 %	Calculated
spec_NMVOC_tot	NMVOC (unspecified) [Group NMVOC to air]	Mass	3.28E-006	0.001	kg		0 %	Calculated
spec_SO2_tot	Sulphur dioxide [Inorganic emissions to air]	Mass	6.9E-008	1	kg		0 %	Calculated

System: No changes. ts-GaBi Last change: System1/1/2020 GUID: {5C4768B3-6B63-44A9-8C67-EF6504F75A52}

Fig (4.17): Transportation with truck process

2- Diesel mix at refinery process

The process is defined into a model because it is one of the inputs of the process Truck, Euro 3, 12 - 14t gross weight.



Name: EU-28 | Diesel mix at refinery | ts | agg - LCI result

Parameter	Formula	Value	Minimum	Maximum	Standard	Comment
Parameter						

LCC: 4.54E005 EUR

Completeness: All relevant flows recorded

Inputs

Flows	Quantities	Amount	Units	Tra	Standar	Origin	Comment
Agriculture [Occupation]	Areatime	1.33E-013	m2*yr		0 %	(No statement)	
Air [Renewable resources]	Mass	0.481	kg		0 %	(Calculated)	
Aluminium [Non renewable elements]	Mass	2.96E-010	kg		0 %	(No statement)	
Anhydrite (Rock) [Non renewable resc	Mass	2.91E-015	kg		0 %	Calculated	
Antimonite [Non renewable resources]	Mass	4.66E-020	kg		0 %	(No statement)	
Antimony [Non renewable elements]	Mass	1.18E-007	kg		0 %	(No statement)	
Arable [Occupation]	Areatime	1.6E-006	m2*yr		0 %	(No statement)	
Arable, irrigated [Occupation]	Areatime	1.14E-013	m2*yr		0 %	(No statement)	
Arable, irrigated, intensive [Occupatic	Areatime	6.61E-016	m2*yr		0 %	(No statement)	
Arable, irrigated, intensive (regionaliz	Areatime	0.00772	m2*yr		0 %	(No statement)	
Arable, irrigated, intensive (regionaliz	Areatime	0.04	m2*yr		0 %	(No statement)	
Arable, irrigated, intensive (regionaliz	Areatime	3.15E-005	m2*yr		0 %	(No statement)	

Outputs

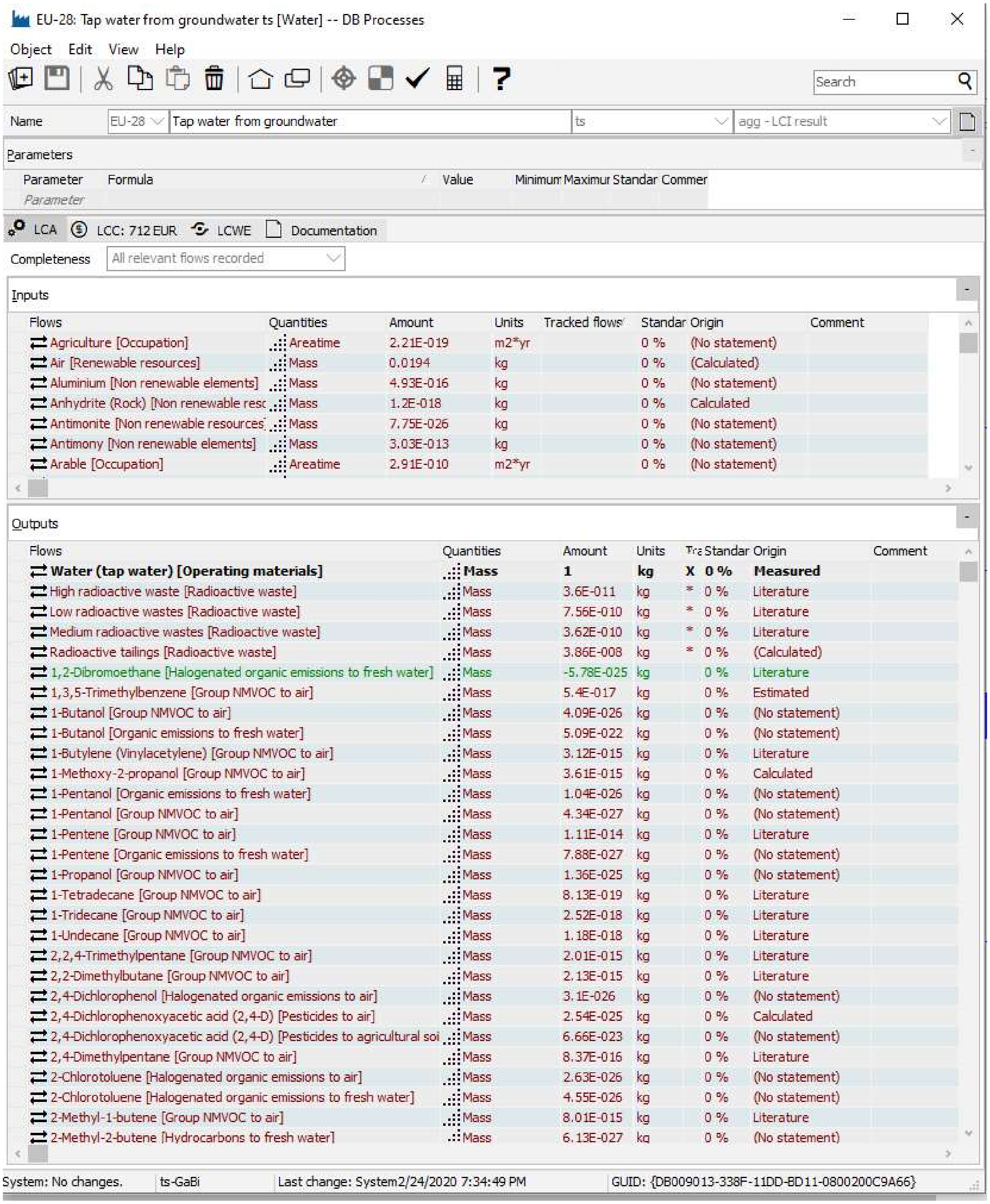
Flows	Quantities	Amount	Units	Tra	Standar	Origin	Comment
Diesel [Refinery products]	**Mass**	**1**	**kg**	**X**	**0 %**	**Measured**	
High radioactive waste [Radioactive waste]	Mass	5.76E-008	kg	*	0 %	Literature	
Low radioactive wastes [Radioactive waste]	Mass	1.1E-006	kg	*	0 %	Literature	
Medium radioactive wastes [Radioactive waste]	Mass	5.08E-007	kg	*	0 %	Literature	
Radioactive tailings [Radioactive waste]	Mass	5.75E-005	kg	*	0 %	(Calculated)	
1,1,1-Trichloroethane [Halogenated organic emissions to fresh water]	Mass	4.47E-028	kg		0 %	(No statement)	
1,2-Dibromoethane [Halogenated organic emissions to fresh water]	Mass	-6.16E-020	kg		0 %	Literature	
1,3,5-Trimethylbenzene [Group NMVOC to air]	Mass	2.54E-014	kg		0 %	Estimated	
1-Butanol [Organic emissions to fresh water]	Mass	3.06E-016	kg		0 %	(No statement)	
1-Butanol [Group NMVOC to air]	Mass	2.46E-020	kg		0 %	(No statement)	
1-Butylene (Vinylacetylene) [Group NMVOC to air]	Mass	1.47E-012	kg		0 %	Literature	
1-Methoxy-2-propanol [Group NMVOC to air]	Mass	2.68E-012	kg		0 %	Calculated	
1-Pentanol [Group NMVOC to air]	Mass	2.61E-021	kg		0 %	(No statement)	
1-Pentanol [Organic emissions to fresh water]	Mass	6.27E-021	kg		0 %	(No statement)	
1-Pentene [Group NMVOC to air]	Mass	5.2E-012	kg		0 %	Literature	
1-Pentene [Organic emissions to fresh water]	Mass	4.74E-021	kg		0 %	(No statement)	
1-Propanol [Group NMVOC to air]	Mass	8.16E-020	kg		0 %	(No statement)	
1-Tetradecane [Group NMVOC to air]	Mass	3.82E-016	kg		0 %	Literature	
1-Tridecane [Group NMVOC to air]	Mass	1.19E-015	kg		0 %	Literature	
1-Undecane [Group NMVOC to air]	Mass	5.56E-016	kg		0 %	Literature	

System: No changes.
ts-GaBi
Last change: System2/24/2020 7:33:30 PM
GUID: {244524ED-7B85-4548-B345-F58DC5CF9DAC}

Fig (4.18): Diesel mix at refinery process

3- Tap water from groundwater process

This process stated the amount of water that its source is groundwater and used to moisturize the ash; the amount of water used is 1.75 liters added to the ash before using it in the reactor.



Name   EU-28   Tap water from groundwater   ts   agg - LCI result

Parameters

Parameter	Formula	Value	Minimum	Maximur	Standar	Commer
Parameter						

Completeness   All relevant flows recorded

Inputs

Flows	Quantities	Amount	Units	Tracked flows	Standar	Origin	Comment
Agriculture [Occupation]	Areatime	2.21E-019	m2*yr		0 %	(No statement)	
Air [Renewable resources]	Mass	0.0194	kg		0 %	(Calculated)	
Aluminium [Non renewable elements]	Mass	4.93E-016	kg		0 %	(No statement)	
Anhydrite (Rock) [Non renewable resc	Mass	1.2E-018	kg		0 %	Calculated	
Antimonite [Non renewable resources]	Mass	7.75E-026	kg		0 %	(No statement)	
Antimony [Non renewable elements]	Mass	3.03E-013	kg		0 %	(No statement)	
Arable [Occupation]	Areatime	2.91E-010	m2*yr		0 %	(No statement)	

Outputs

Flows	Quantities	Amount	Units	Tra	Standar	Origin	Comment
Water (tap water) [Operating materials]	**Mass**	**1**	**kg**	**X**	**0 %**	**Measured**	
High radioactive waste [Radioactive waste]	Mass	3.6E-011	kg	*	0 %	Literature	
Low radioactive wastes [Radioactive waste]	Mass	7.56E-010	kg	*	0 %	Literature	
Medium radioactive wastes [Radioactive waste]	Mass	3.62E-010	kg	*	0 %	Literature	
Radioactive tailings [Radioactive waste]	Mass	3.86E-008	kg	*	0 %	(Calculated)	
1,2-Dibromoethane [Halogenated organic emissions to fresh water]	Mass	-5.78E-025	kg		0 %	Literature	
1,3,5-Trimethylbenzene [Group NMVOC to air]	Mass	5.4E-017	kg		0 %	Estimated	
1-Butanol [Group NMVOC to air]	Mass	4.09E-026	kg		0 %	(No statement)	
1-Butanol [Organic emissions to fresh water]	Mass	5.09E-022	kg		0 %	(No statement)	
1-Butylene (Vinylacetylene) [Group NMVOC to air]	Mass	3.12E-015	kg		0 %	Literature	
1-Methoxy-2-propanol [Group NMVOC to air]	Mass	3.61E-015	kg		0 %	Calculated	
1-Pentanol [Organic emissions to fresh water]	Mass	1.04E-026	kg		0 %	(No statement)	
1-Pentanol [Group NMVOC to air]	Mass	4.34E-027	kg		0 %	(No statement)	
1-Pentene [Group NMVOC to air]	Mass	1.11E-014	kg		0 %	Literature	
1-Pentene [Organic emissions to fresh water]	Mass	7.88E-027	kg		0 %	(No statement)	
1-Propanol [Group NMVOC to air]	Mass	1.36E-025	kg		0 %	(No statement)	
1-Tetradecane [Group NMVOC to air]	Mass	8.13E-019	kg		0 %	Literature	
1-Tridecane [Group NMVOC to air]	Mass	2.52E-018	kg		0 %	Literature	
1-Undecane [Group NMVOC to air]	Mass	1.18E-018	kg		0 %	Literature	
2,2,4-Trimethylpentane [Group NMVOC to air]	Mass	2.01E-015	kg		0 %	Literature	
2,2-Dimethylbutane [Group NMVOC to air]	Mass	2.13E-015	kg		0 %	Literature	
2,4-Dichlorophenol [Halogenated organic emissions to air]	Mass	3.1E-026	kg		0 %	(No statement)	
2,4-Dichlorophenoxyacetic acid (2,4-D) [Pesticides to air]	Mass	2.54E-025	kg		0 %	Calculated	
2,4-Dichlorophenoxyacetic acid (2,4-D) [Pesticides to agricultural soi	Mass	6.66E-023	kg		0 %	(No statement)	
2,4-Dimethylpentane [Group NMVOC to air]	Mass	8.37E-016	kg		0 %	Literature	
2-Chlorotoluene [Halogenated organic emissions to air]	Mass	2.63E-026	kg		0 %	(No statement)	
2-Chlorotoluene [Halogenated organic emissions to fresh water]	Mass	4.55E-026	kg		0 %	(No statement)	
2-Methyl-1-butene [Group NMVOC to air]	Mass	8.01E-015	kg		0 %	Literature	
2-Methyl-2-butene [Hydrocarbons to fresh water]	Mass	6.13E-027	kg		0 %	(No statement)	

System: No changes.   ts-GaBi   Last change: System2/24/2020 7:34:49 PM   GUID: {DB009013-338F-11DD-BD11-0800200C9A66}

Fig (4.19): Tap water from groundwater process

4.3.3 linking processes into the plan

After setting all processes either by using pre-defined processes or initiating new processes, the next step is to link these processes; for every process, on the left-hand side of the process box is a red bar that depicts the input part of the process. On the right is a brown bar that indicates the output side of the process, GaBi checks for input/output matches while linking processes, and after the processes are connected, a black dot appears in the process box.

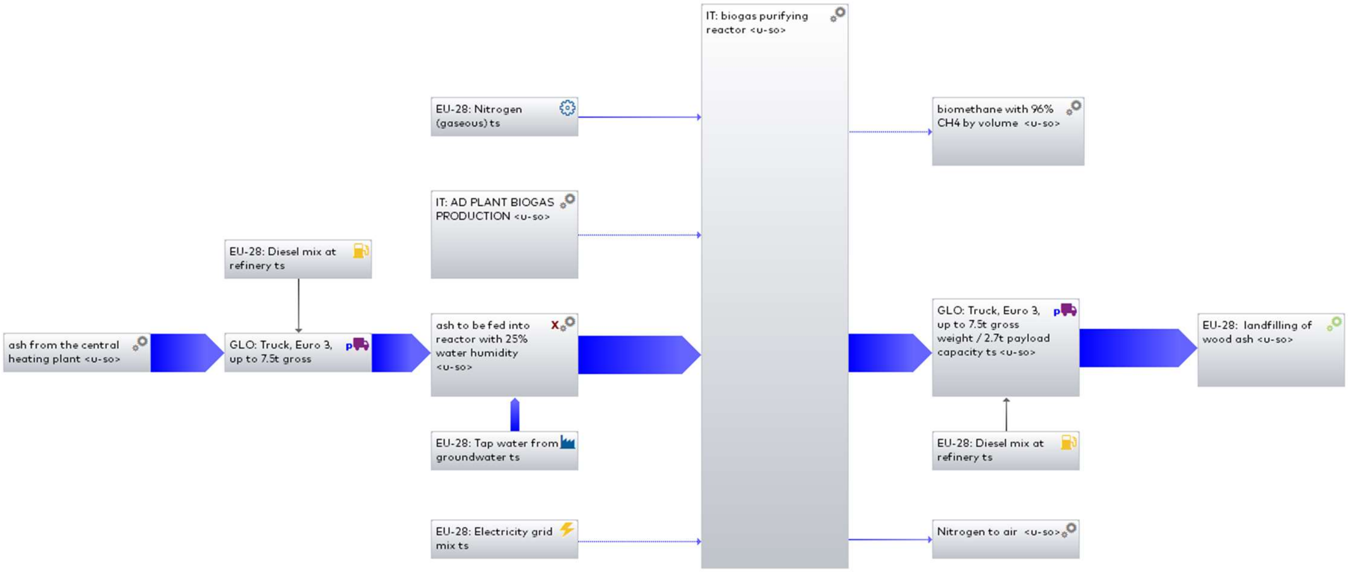


Fig (4.20): processes chain

4.3.4 Consistency check for processes and achieving a balance

Every process in the model undergoes a consistency check because mass balance indicates the consistency of a process. This check allows the inputs and outputs of a process to be evaluated. Any quantity can be chosen for a consistency check in addition to mass, and the distinction between an output value and an input value is reported.

After setting the model and consistency check for the processes, the result calculation is executed to assess the environmental consequences for the paradigm to perform the desired outcome. After generating the analysis, a Gabi balance file is created, which contains all of the calculated results for the modeled system and all of the life cycle impact results.

CHAPTER FIVE: RESULTS

Synopsis

This chapter presents the result of the life cycle assessment of the evaluated case study using GaBi software; it will discuss and underline the generated result of the impact assessment for every process and how these processes contribute to every impact category group.

5.1 Glance at the overall result

The analysis results for the low-cost process show that the avoided effects related to CO2 capture and biomethane development advantage to a significant number of the indicators investigated. Still, somehow, the final disposal of ash into landfills negatively impacts some indicators.

The limited effects of using this technology on environmental indicators are on those related to toxicity, such as human toxicity, freshwater aquatic ecotoxicity, and marine aquatic ecotoxicity; this is due to the inclusion in the study of impacts due to landfilling of ash, although the contribution of the disposal is due only to the weight variation of the ash after the process due to carbonation and humidity variation has been considered.

5.2 processes evaluation and its contribution in impact categories

Since the purpose of this study is to apply the life cycle assessment method to evaluate the purification system, which contains a different combination of processes that form the system, it was crucial to assess each process separately to realize its impact and how these processes contribute in different impact categories of CML method.

Table (5.1) shows the Impact assessment results for the processes, figures from (5.1) to (5.11) indicate impact assessment for the processes, and figure (5.12) indicates the relative contribution of these processes in several impact categories.

Processes	ADP E	ADP F	AP	EP	FAETP	GWP	HTP	MAETP	ODP	POCP	TETP
Nitrogen IN	1.09E-11	0.000351	6.64E-08	7.36E-09	7.01E-08	3.18E-05	1.38E-06	0.00377	9.46E-19	4.73E-09	3.47E-08
Transport IN	0.00E+00	0.00E+00	9.44E-06	2.48E-06	2.29E-08	0.0018	1.63E-05	4.56E-09	0.00E+00	-4.89E-06	2.61E-09
Diesel IN	1.67E-10	0.027	1.07E-06	1.73E-07	1.05E-05	0.000168	3.78E-05	0.0321	3.25E-19	1.81E-07	4.50E-06
Water from groundwater	6.64E-11	0.00196	2.37E-07	1.82E-07	2.35E-06	0.000161	1.14E-05	0.0105	1.37E-18	2.13E-08	2.07E-06
Electricity IN	2.64E-08	0.875	0.000166	1.83E-05	0.000175	0.0793	0.00345	9.4	2.36E-15	1.18E-05	8.63E-05
Purifying reactor	0.00E+00	0.00E+00	-6.38E-04	-7.94E-05	1.57E-08	-6.17E-01	-0.00127	1.34E-05	-2.92E-08	3.86E-05	3.23E-07
Nitrogen to Air	0.00E+00	0.00E+00	0.00E+00	0.000224	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Transport Out	0.00E+00	0.00E+00	0.000211	5.55E-05	5.12E-07	0.0403	0.000365	1.02E-07	0.00E+00	-0.000109	5.83E-08
Diesel Out	3.74E-09	0.603	2.39E-05	3.87E-06	0.000234	0.00375	0.000845	0.717	7.27E-18	4.04E-06	0.0001
Ash to Disposal	0.00E+00	0.00E+00	3.40E-06	5.04E-05	0.0148	3.55E-06	0.227	53.5	0.00E+00	4.83E-07	5.79E-05
Total	3.04E-08	1.51E+00	-2.23E-04	2.76E-04	1.52E-02	-4.91E-01	2.30E-01	6.37E+01	-2.92E-08	-5.88E-05	2.51E-04

Table (5.1): Environmental impact burden

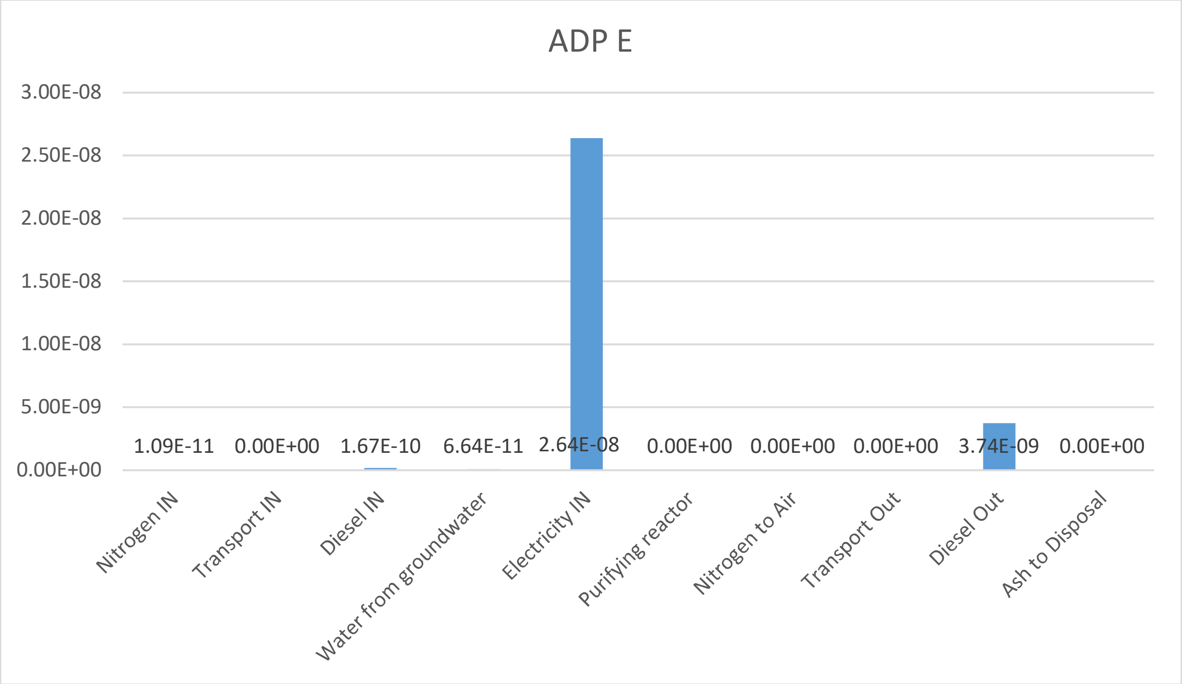


Fig (5.1): ADP E assessment

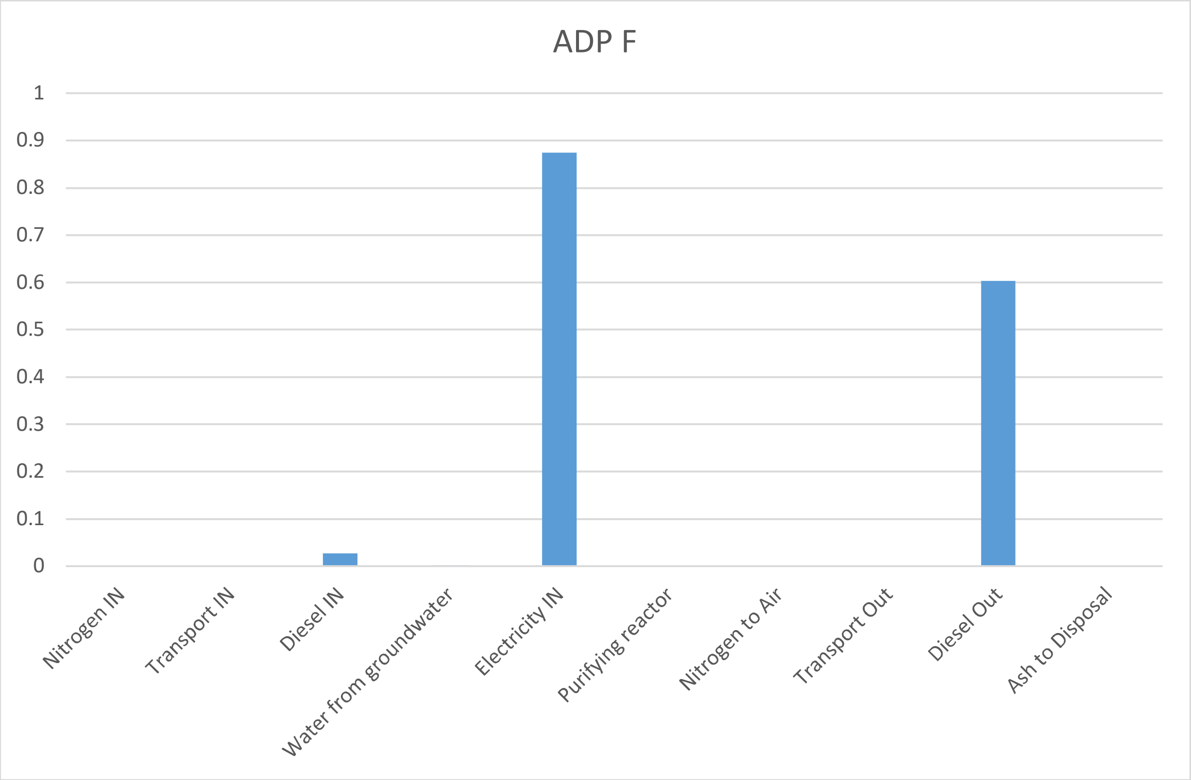


Fig (5.2): ADP F assessment

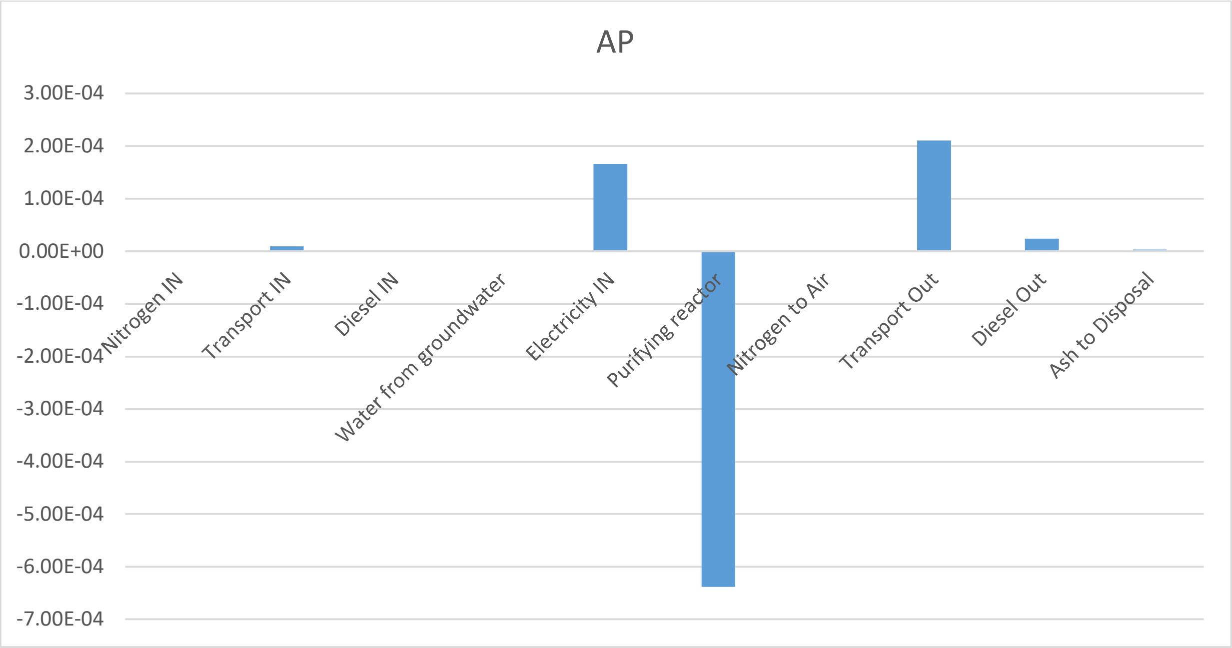


Fig (5.3): AP assessment

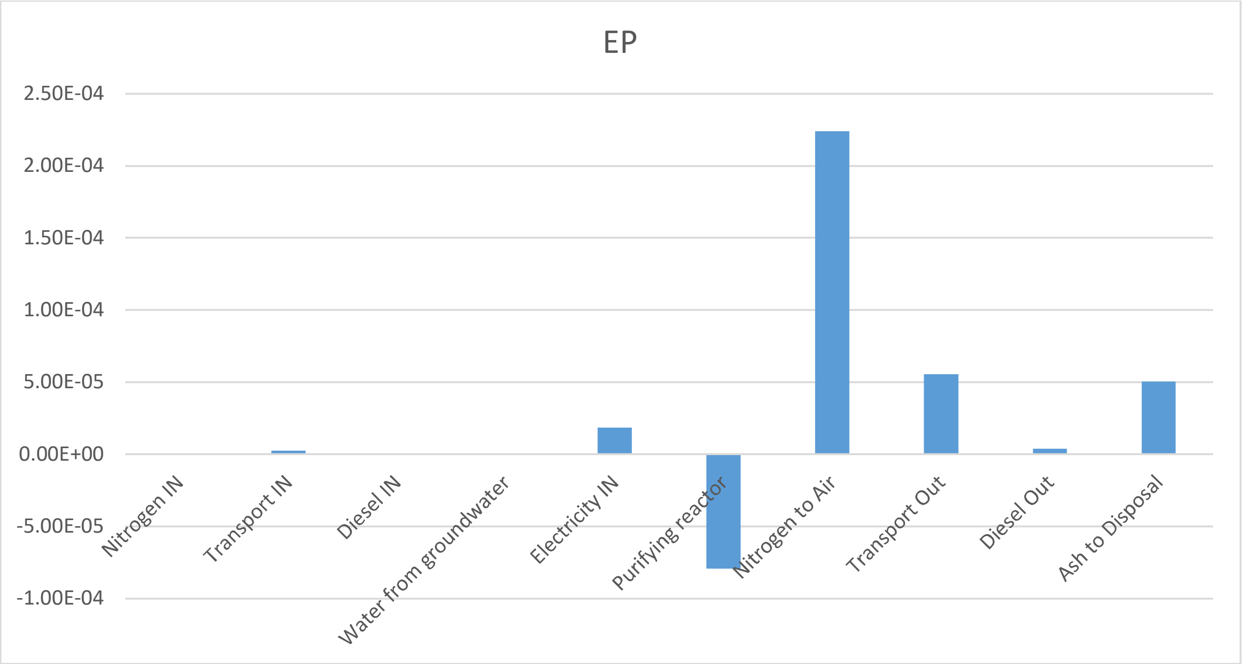


Fig (5.4): EP assessment

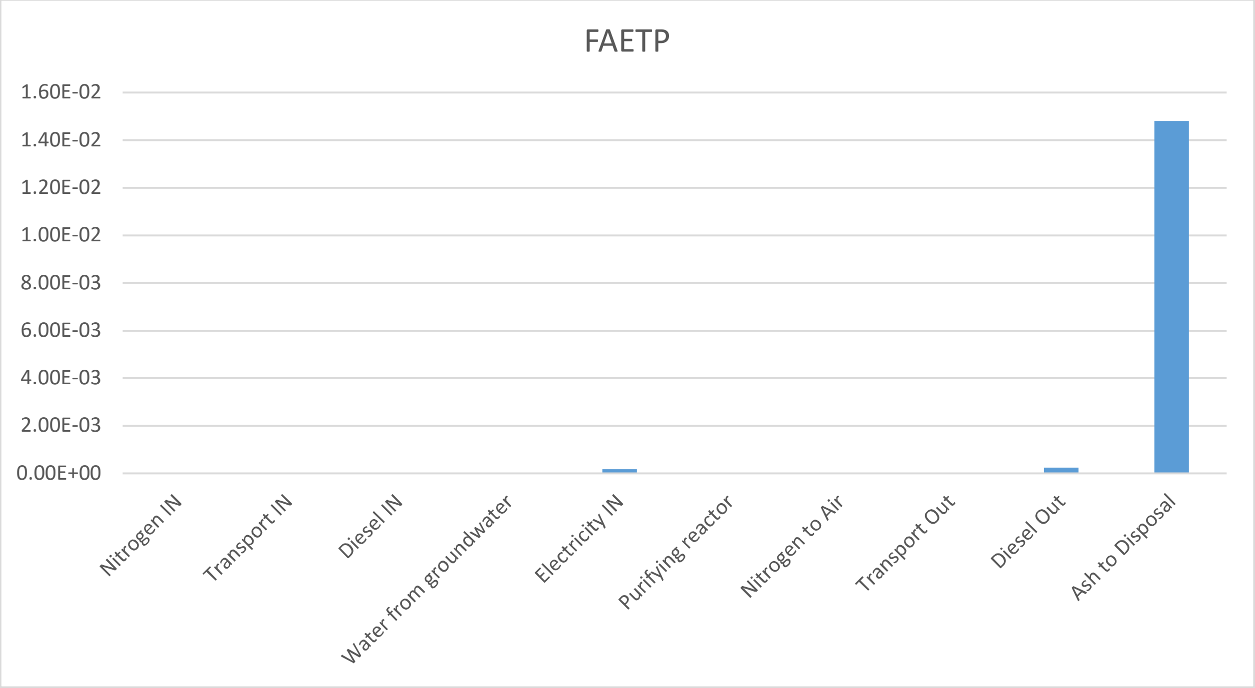


Fig (5.5): FAETP assessment

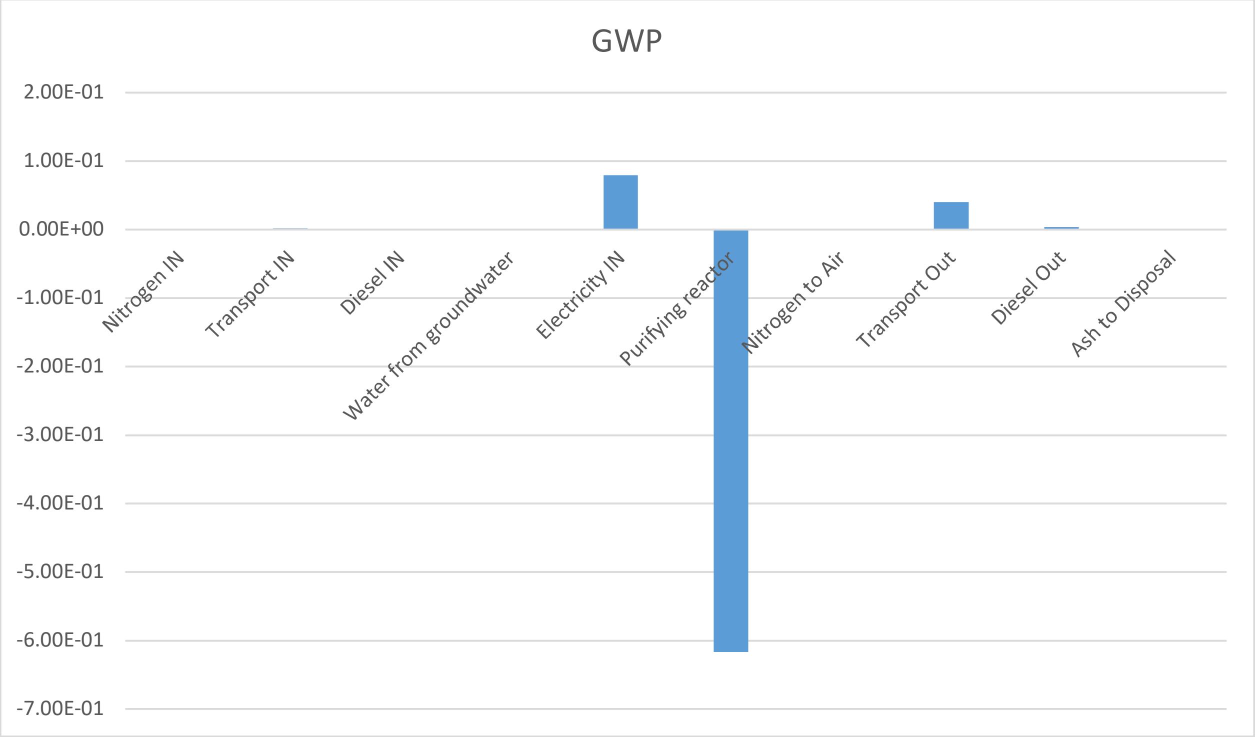


Fig (5.6): GWP assessment

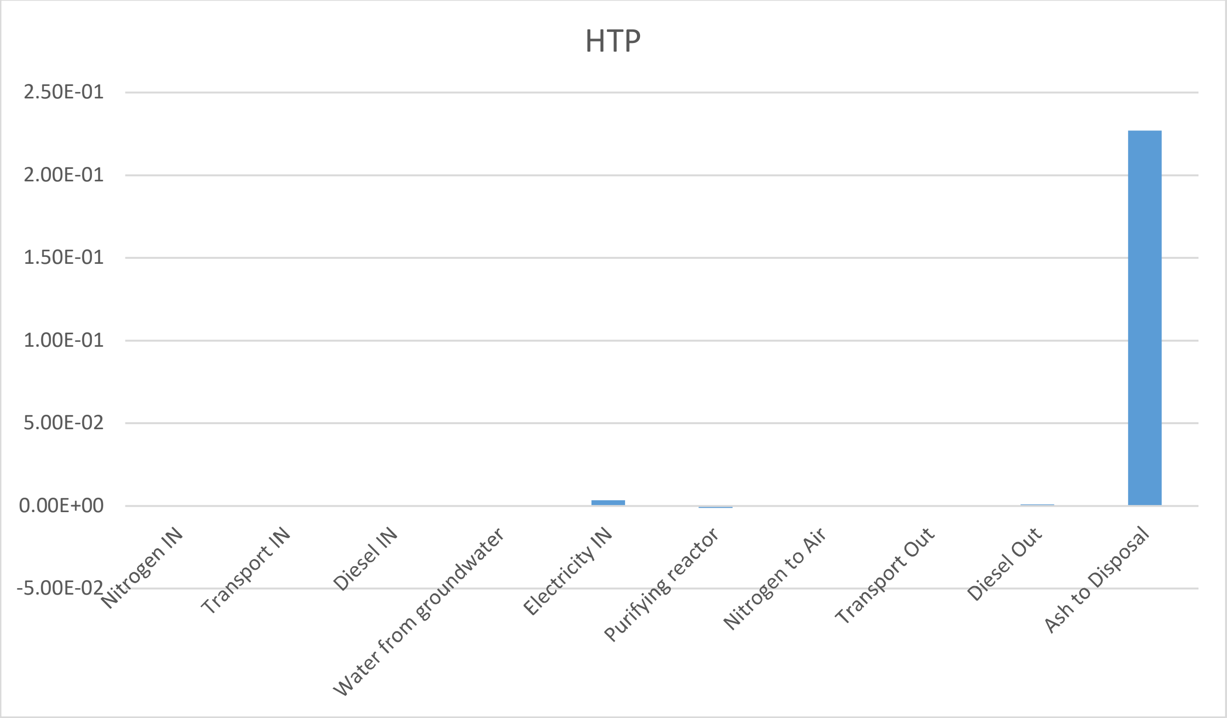


Fig (5.7): HTP assessment

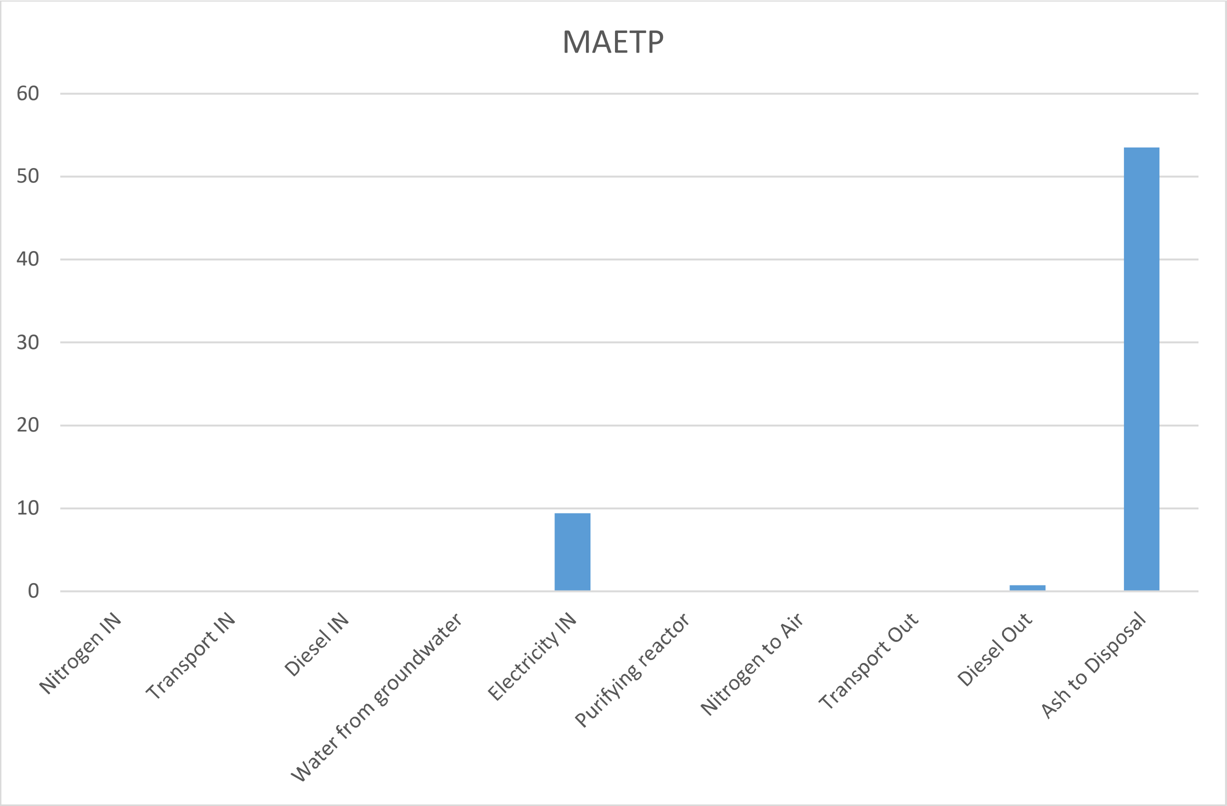


Fig (5.8): MAETP assessment

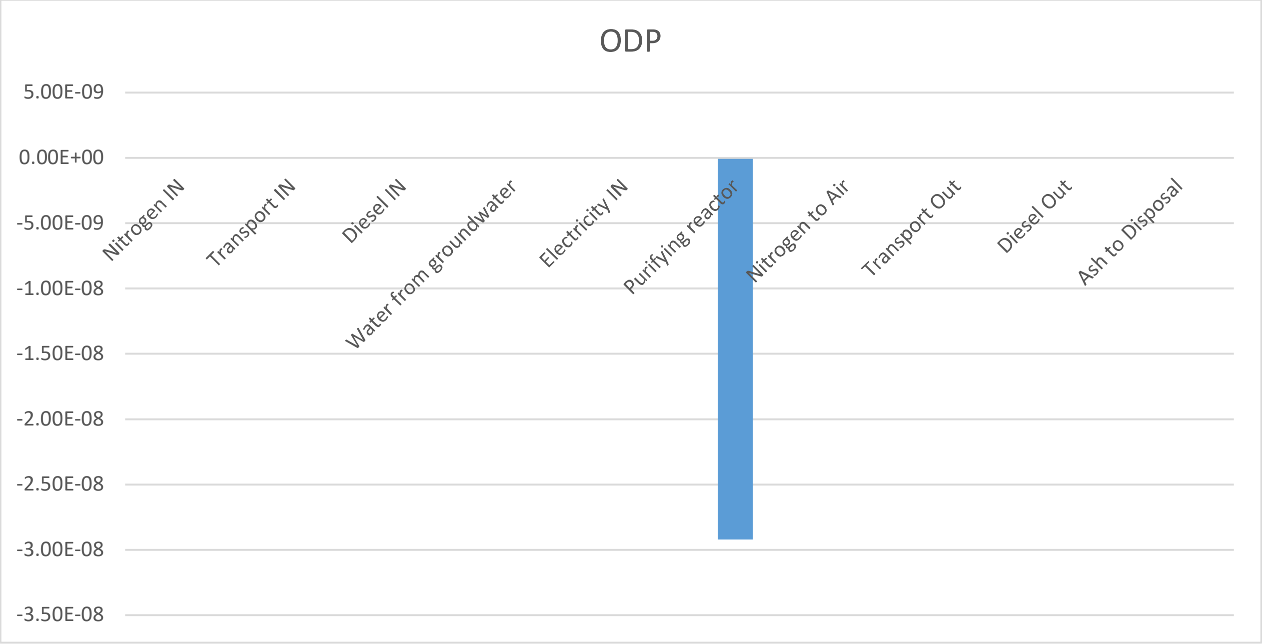


Fig (5.9): ODP assessment

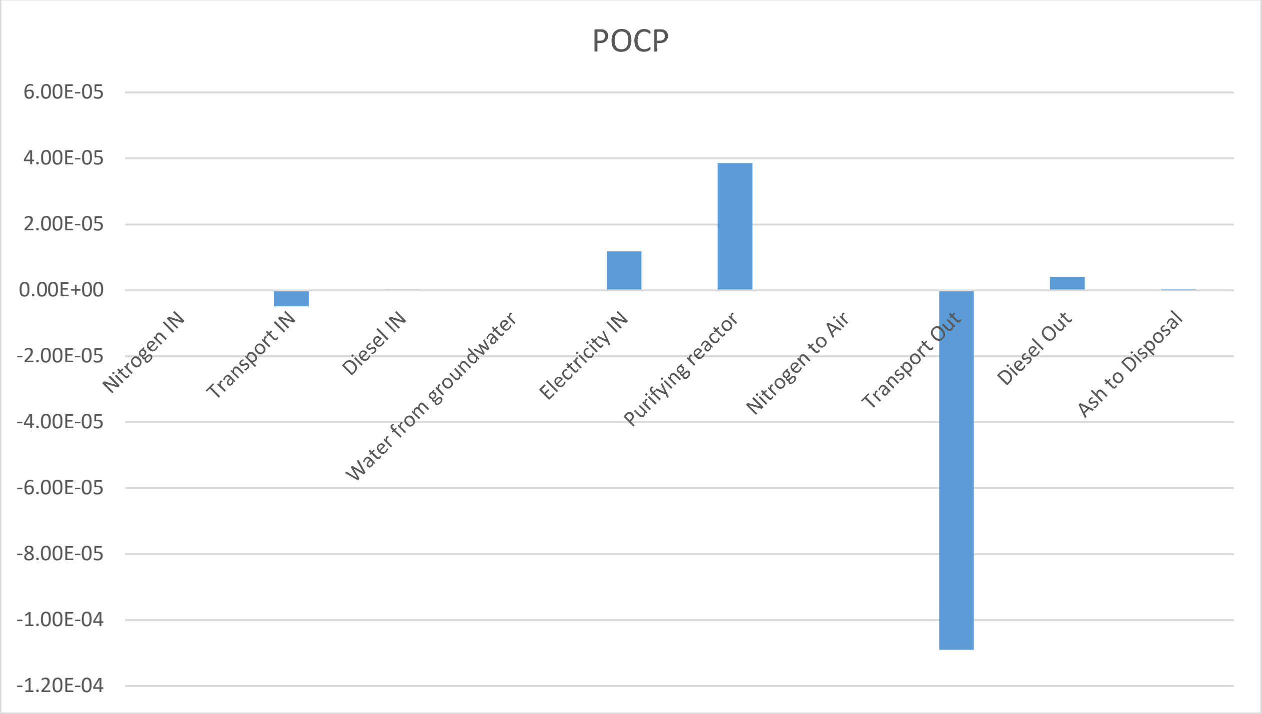


Fig (5.10): POCP assessment

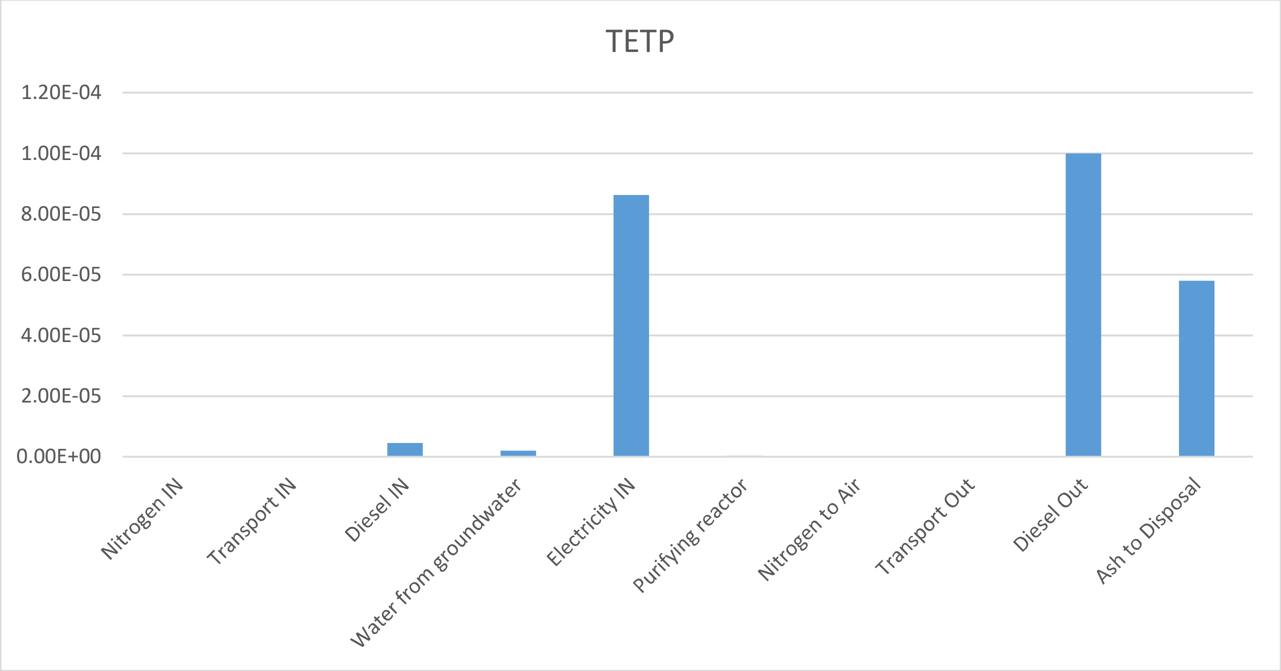


Fig (5.11): TETP assessment

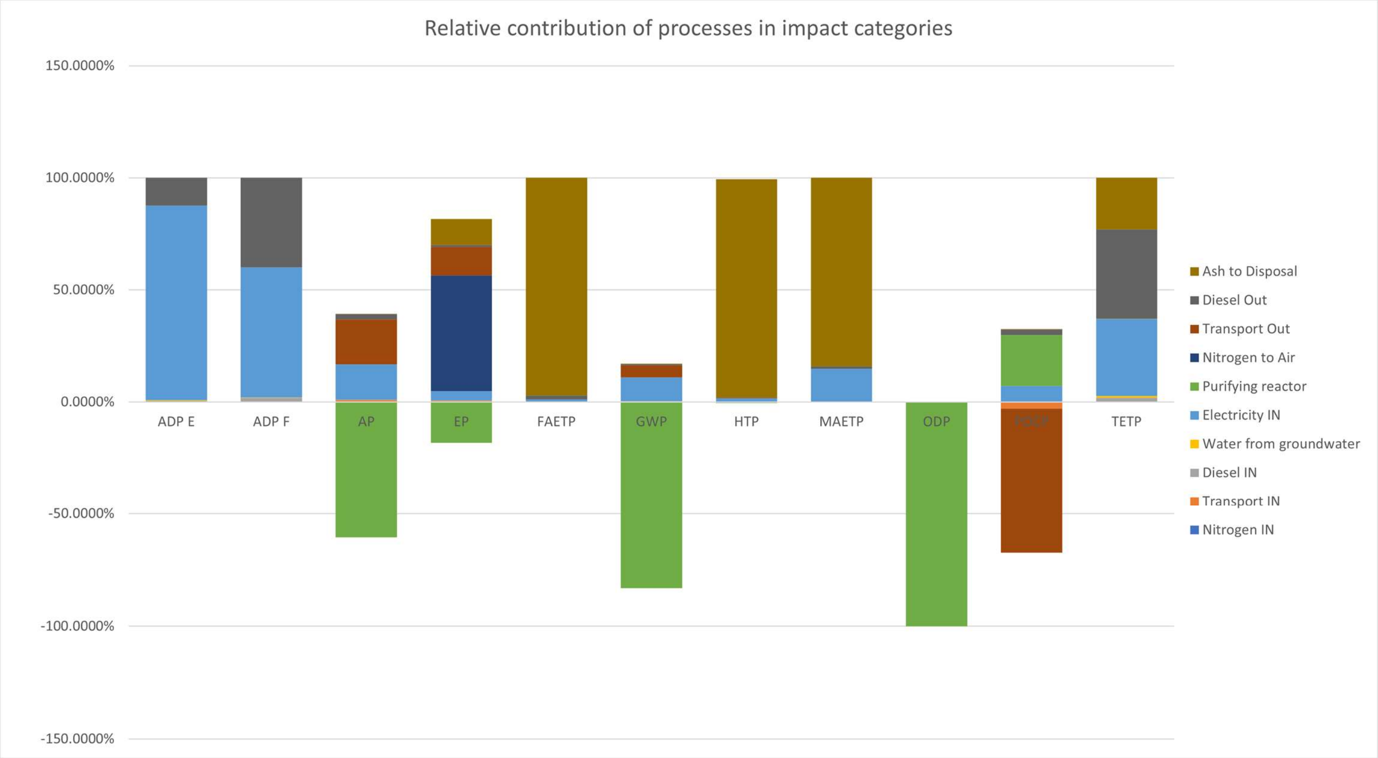


Fig (5.12): Relative contribution for impact categories

CHAPTER SIX: CONCLUSION AND FUTURE WORK

Synopsis

This chapter summarizes the study's findings while stressing the essential aspects and mentions the future opportunities that can be done using this case study as a foundation.

6.1 Discussion

This low-cost technique showed its effectiveness in improving the properties of biogas produced from the anaerobic digestion process and obtaining biomethane at a low cost compared to other approaches; on the other hand, a considerable number of the indicators studied benefit from the negative contributions (avoided consequences) connected to CO_2 capture which and biomethane generation, CO_2 captured by 805 gCO_2 for 7 kg of wood ash, this uptake will be avoided in the category of global warming potential.

The production and subsequent consumption of a renewable resource such as biomethane instead of a fossil fuel improve the advantages across all indicators, particularly those most affected by pollutants discharged into the atmosphere by fossil fuel burning.

It is crucial to know the reason for affecting the disposal of ash into landfills; this is due to the elements in the wood ash such as calcium (Ca), potassium (K), magnesium (Mg), aluminum (Al), iron (Fe), sodium (Na), manganese (Mn), phosphorus (P) and sulfur (S)(67). So, the wood ash is highly alkaline, and the Ph (potential of hydrogen) value is base and almost reached 14. Then when discharged into the landfill, they affect the toxicity indicators.

Landfilling of ash affects various sets of environmental categories, so instead of their mere disposal in landfills, ash must be used in other processes that outcome ash will add a value to their inputs to extend the life cycle of using ash be restored into the economic cycle, leading to an initial flow inside a fresh production cycle, converting waste into a resource, through this procedure to lower the impact specific environmental parameters.

According to researchers, wood ash has excellent potential as a partial resource replacement in cementitious materials, presenting sustainable alternatives for both the energy and cement industries. And by utilizing ash for concrete production with a different mixing ratio of concrete, the final product has excellent physical characteristics such as strength and durability; in addition, ash is used as a partial replacement for clinker production because of a high amount of CaO. Also, ash is used as a mineral admixture in cementitious composites and the road-building based on the ash proportion; ash can substitute mineral fillers and aggregates (sand or gravel) into asphalt mixtures, concrete, and other pavement layers(68–70).

For 1 tonne of wood ash, inventory data from a previous study (71) containing natural resources, energy, and emissions to air and water was also used for three options of using the wood ash to analyze its environmental impact assessments using the CML technique. The three scenarios are Scenario 1: wood ash is recycled on forest land, scenario 2: ash is used in road building, and scenario 3: ash is placed in the landfill; the results of these scenarios' assessments are displayed in fig (6.1), which show using of ash for road construction instead of disposing of ash to landfill will lower the environmental impact in all categories, on the other hand, recycling ash on the forest land lead to enhance the result in most of the categories except FAETP and MAETP.

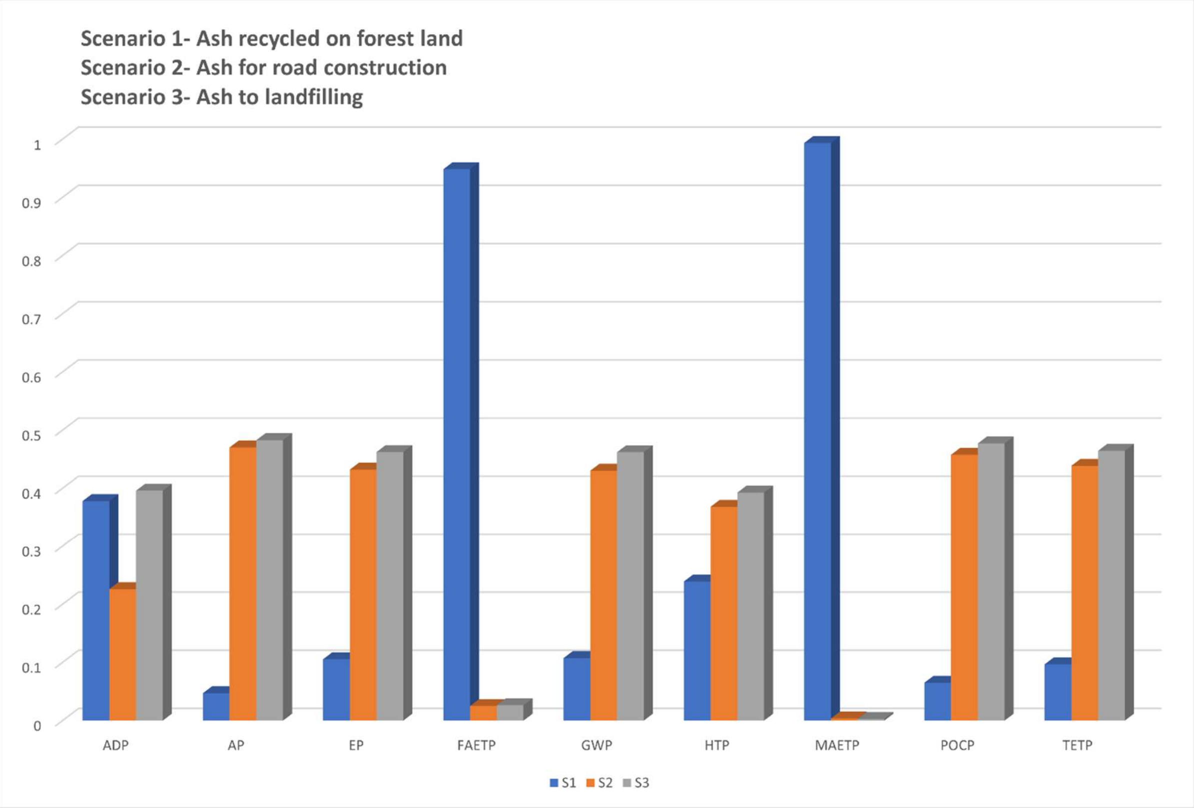


Fig (6.1): Ash EOL scenarios

On the other hand, materials and natural resources such as minerals, energy, and water are generated at an accelerating pace in modern industrialized society powered by an ever-increasing worldwide population and level of life, and this will affect the environmental system, so for this issue, the efforts shall be expanded to reuse the by-product waste for another now cycles and through the intensive scientific research for different processes and product and intervention of governments to block disposal of waste or in border way to process them before landfill to mitigate their effects into the environment.

In the result it shows that assessment of POCP related to transportation through truck processes is negative, this related to the value of CML which for CML 2001 - Nov. 2010 and later versions, this because of The splitting of NO_X emissions into two separate emissions, NO_2 and NO, which NO has a negative influence on the POCP because it lowers the formation the close ground ozone.

6.2 Recommendations and future work

This analysis was done by GaBi software with an educational database that is limited in use; in the future, it is recommended to use an LCA software with a commercial database consisting of an inclusive life cycle inventory database such as ecoinvent, which facilitates environmental evaluations of products and processes.

In addition, implement end-of-life (EOL) scenarios by utilising ash into different uses instead of disposing into landfill, to compare these scenarios and how they impact categories will differ from the base case to define the appropriate way to reuse the wood ash.

This analysis was assessed through CML as an environmental impact method; for future investigations, the case study can be explored using another environmental impact such as ReCipe, TRACI, or other methods, because these methodologies use different impact categories, metrics, inventory classifications, and normalization procedures, all of which can lead to differing LCA outcomes and more transparent and more comprehensive understanding of the system and gives a superior area for comparison in the results.

Assessing this low-cost is pivotal from the economic view because the cost is one of the main factors to select the appropriate method to enhance the characteristics of biogas to biomethane by comparing the price of producing a unit of biomethane in the output of this technique compared to the other technologies. Through placing a life cycle cost (LCC) analysis based on an amount of the biogas in the input; this analysis shall include all costs incurred in the case study such as investment cost (cost of purchasing equipment and installing them into the site), operating cost (such as cost of electricity, nitrogen used, personnel, transportation the ash in and out, ash landfill cost, water cost), and maintenance cost.

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