Politecnico di Torino

Corso di Laurea Magistrale
in Ingegneria Energetica e Nucleare
A.a. 2021/2022
Sessione di Laurea Marzo 2022

Life cycle assessment of an innovative biological biogas purification system

Relatori:

Dr. Marta Gandiglio

Dr. Davide Papurello

Dr. Marco Dequino (Tecnodelta Srl)

Candidati:

Martina Scalia

Abstract

The growing demand for energy and the concern about global warming, require an increasing share of renewable energy to reduce the emissions as the greenhouse gases. For this reason, the scientific community is called on to make a bigger effort in the development and exploitation of new renewable energies.

One of the most innovative sources is biogas, which is produced by the anaerobic digestion of organic substrates. The biogas is mainly composed of methane, carbon dioxide, hydrogen sulphide, and other constituents. Unfortunately, some constituents such as hydrogen sulphide may be hazardous to health, safety and may cause corrosion of equipment. Furthermore, hydrogen sulphide must be removed to ensure that biogas can replace natural gas in industrial and household supplies or transportation.

To clean up the biogas is employed upgrading systems, among which the most common are physicochemical such as absorption, adsorption, and membrane separation. Currently, several biological and bioelectrochemical cleaning technologies are under development, such as the BIOFIDS unit.

The BIOFIDS project is a regional funded activity started from an ODR ENEA patent. Currently, the following partners are participating in the project: Politecnico di Torino, the company Tecnodelta Srl, RAMS&E Srl, and the company ACDA Spa, owner of the wastewater treatment plant in Cuneo (IT) where the prototype unit will be tested. The BIOFIDS unit consists of a photobioreactor that employs green sulphur bacteria for the biological desulphurisation of biogas produced from anaerobic digestion of sewage sludge. These bacteria, in presence of light, have the capability to oxidise H_2S and produces elementary sulphur for agronomic use.

This thesis aims to carry out the life cycle assessment of the BIOFIDS unit through the utilisation of the software OpenLCA®. The analysis takes into account three phases: the construction of the unit from the extracted materials, the transport to the site, and finally the utilisation phase. For the life cycle impact assessment is operated the Environmental Footprint (Mid-point indicator) method, which examines the impact earlier along the cause-effect chain.

Subsequently, the results extracted from the software for the BIOFIDS unit are compared with those reported in the literature for the most diffused physicochemical systems. The indicators used for comparison are Climate Change, Particulate Matter, Ozone Depletion, Eutrophication freshwater, and Photochemical ozone formation- human health. Base case results extracted show that are emitted 3847 kg of CO_2 during the construction phase and 14.5 kg of CO_2 for unit transportation to the site. During the operation phase, 0.78 kg of CO_2 per m^3 of biogas treated is emitted in one year, by considering a flow rate of 6 m^3 per hour which contains 85 mg/m^3 of hydrogen sulphide.

Two other scenarios are analysed: the first scenario considers a reduced electricity consumption, the second a higher H_2S concentration in the biogas. The 10% reduction in electricity consumption simulates the case where not all equipment is working continuously, due to unplanned shutdowns for extraordinary maintenance or blackout. The biggest reduction is on ozone depletion (about 6.5%), as well as 4.8% on climate change and 3.7% on particulate matter production. The second scenario considers biogas with a higher H_2S

concentration, but this does not change the impact of the work phase on the environment. This shows that the BIOFIDS prototype works well even in the case of very dirty biogas.

In literature, for the conventional system, have been found climate change values between 1.09 and 1.11 per m^3 of biogas, moreover a climate change value of 3.92 in relation to 1 Nm^3 of biomethane. Even for biogenic climate change exits value among 0.85 and 0.86 in relation to the m^3/h of biogas. For BIOFIDS unit, is obtained 0.78 per m^3 of biogas for climate change and 0.03 per m^3 of biogas for the biogenic one. As concern freshwater eutrophication, have been found values between 8.01E-04 and 8.21E-04 per m^3 of biogas, as well as 4.34E-04 in relation to 1 Nm^3 of biomethane. Instead, from our analysis is obtained 2.80E-05 per m^3 of biogas for freshwater eutrophication. The last category, of which more data are available, is the ozone depletion. From literature the value of ozone depletion lies between 3.51E-06 and 3.55E-06 per m^3 of biogas, additionally another article reports the value of 5.50E-07 per Nm^3 of biomethane. From BIOFIDS study is obtained nearly 5.48E-11 kg of CFC-11 eq. per m^3 of biogas, which is again lower than the values just reported.

Keywords: Biogas, BIOFIDS, Life cycle assessment, Desulfurization, Hydrogen-sulphide removal, Organic waste, Biogas clean-up, Renewable energy, LCA.

Contents

Abstract ... 1

Nomenclature ... 4

List of Figures ... 5

List of Tables ... 7

1 Introduction ... 8

2 Description of case study ... 12

2.1 BIOFIDS scenario ... 12

2.2 Reference scenario ... 16

2.2.1 Water scrubbing absorption ... 16

2.2.2 Adsorption on activated carbon ... 17

2.2.3 Pressure swing adsorption ... 18

2.2.4 Membrane separation ... 19

3 Life cycle assessment ... 21

3.1 Methodology ... 21

3.2 BIOFIDS base case ... 23

3.3 BIOFIDS modified cases ... 29

4 Results ... 31

4.1 BIOFIDS scenario ... 31

4.2 Comparison of the scenarios ... 40

5 Comparison with literature ... 42

6 Conclusion ... 47

Bibliography ... 49

Appendix ... 52

Nomenclature

Abbreviations

BIOFIDS	Photobioreactor for biological desulphurisation of biogas
GHG	Greenhouse gas
SDG	Sustainable development goals
CO_2	Carbon dioxide
CH_4	Methane
H_2S	Hydrogen sulphide
GSB	Green sulphur bacteria
LCA	Life cycle assessment
WWTP	Wastewater treatment plant
WS	Water scrubbing absorption
HPWS	High pressure water scrubbing absorption
AC	Adsorption on activated carbon
PSA	Pressure swing adsorption
MS	Membrane separation
LCIA	Life cycle impact assessment
SMD	Surface mount device
CHP	Combined heat and power
CC	Climate change
FE	Freshwater eutrophication
OD	Ozone depletion
PM	Particulate matter
POF	Photochemical ozone formation-human health
PTFE	Polytetrafluoroethylene
PVDF	Polyvinylidene fluoride
PRFV	Plastic reinforced with fibre glass
PVC	Polyvinyl chloride
FPM	Fluor elastomer
CFC	Chlorofluorocarbons
HCFC	Hydrochlorofluorocarbons
NMVOC	Non-methane volatile organic compounds

List of Figures

Figure 1: Primary energy consumption [1]. 8

Figure 2: Regional consumption pattern 2020 [2]. 8

Figure 3: Sustainable development goals [4]. 9

Figure 4: Number of biogas and biomethane plants [7]. 10

Figure 5: ACDA wastewater treatment plant in Cuneo. 12

Figure 6: Process scheme [15]. 13

Figure 7: ACDA biogas sampling point [16]. 14

Figure 8: 3D layout of plant Tecnodelta. 15

Figure 9: 3D photobioreactor Tecnodelta. 15

Figure 10: Physicochemical treatment. 16

Figure 11: Water scrubbing scheme [17]. 17

Figure 12: Activated carbon adsorption scheme. 18

Figure 13: Pressure swing adsorption scheme [17]. 19

Figure 14: One stage membrane separation scheme [18]. 20

Figure 15: Two stages membrane separation scheme [18]. 20

Figure 16: Steps of the LCA study. 22

Figure 17: System boundary for the LCA of BIOFIDS. 22

Figure 18: LED SMB1N-760D [21]. 25

Figure 19: Construction phase model graph. 28

Figure 20: Transport phase model graph. 28

Figure 21: Operation phase model graph. 28

Figure 22: Breakdown of impact categories in the base case. 32

Figure 23: Climate change comparison 3 phases. 32

Figure 24: Construction major contributors to climate change. 34

Figure 25: Operation contributors to climate change. 35

Figure 26: Biogenic-climate change of operation from OpenLCA®. 35
Figure 27: CC major and zoom on other contributors. 37
Figure 28: FE major and zoom on other contributors. 38
Figure 29: PM major and zoom on other contributors. 38
Figure 30: POF major and zoom on other contributors. 39
Figure 31: OD major and zoom on other contributors..................................... 39
Figure 32: CC and OD scenarios comparison. 40
Figure 33: PM and POF scenarios comparison. 41
Figure 34: FE scenarios comparison. 41
Figure 35: Schematic flowchart of the system analysed in [8]. 43
Figure 36: System boundaries of the review [9]. 44
Figure 37: System boundaries of study [10]. 45

List of Tables

Table 1: ACDA biogas composition [16]. 14

Table 2: Inventory of construction phase. 23

Table 3: Inventory of transport phase. 25

Table 4: Real average percentage of CH_4. 26

Table 5: Inventory of operation phase. 26

Table 6: Inventory of operation phase with FU=90%. 29

Table 7: Outputs of H_2S=2000 ppm scenario. 30

Table 8: Impacts of construction, transport, and operation in base case. 31

Table 9: Climate change for construction processes. 33

Table 10: Climate change for operation processes. 34

Table 11: Impacts for all flows. 36

Table 12: Impacts for all scenarios. 40

Table 13: Summary results of BIOFIDS base case operation with reference to 1 m^3 of biogas. 42

Table 14: Summary results in relation of m^3 of biogas [8]. 42

Table 15: Summary results in relation to 500 m^3/h of raw biogas [9]. 44

Table 16: Summary results in relation of 1 Nm^3 biomethane [12]. 46

Table 17: Comparison between BIOFIDS and conventional system. 46

Table 18: Total life cycle emissions of the BIOFIDS unit. 48

1 Introduction

In the last century, global energy demand has always increased, mainly due to population growth. Accordingly, global primary energy consumption has also followed the same trend, as shown in Figure 1 for the years 1969 to 2019.

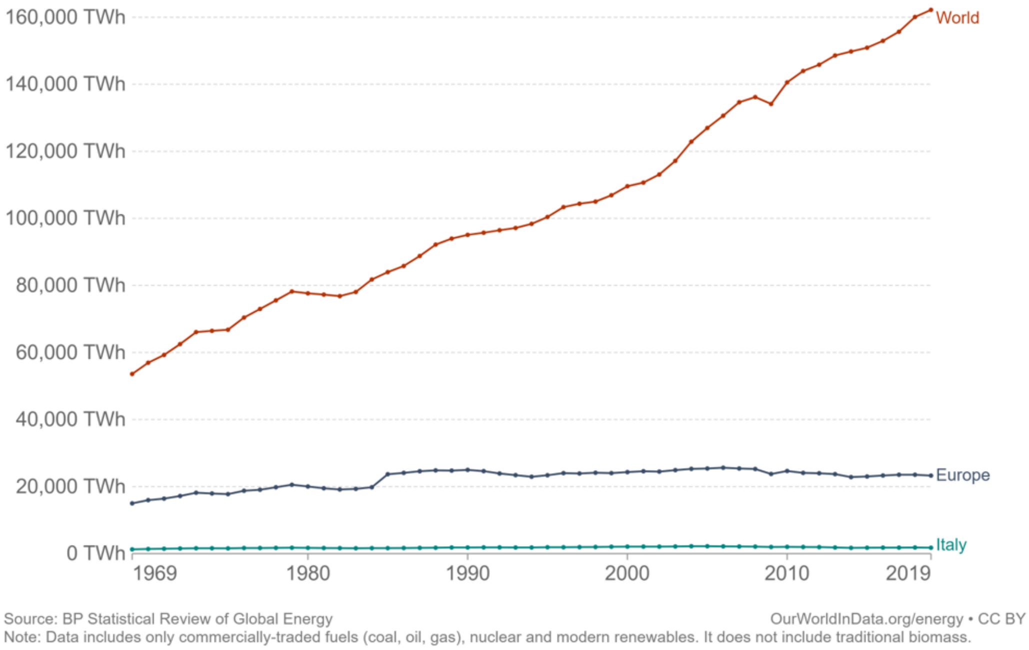

Figure 1: Primary energy consumption [1].

The last fifty years have been characterised by the discovery and spread of renewable energies, which have changed the World's energy mix. Although renewables have become more widespread, the share of energy produced from fossil fuels is still predominant about 70%, as displayed Figure 2.

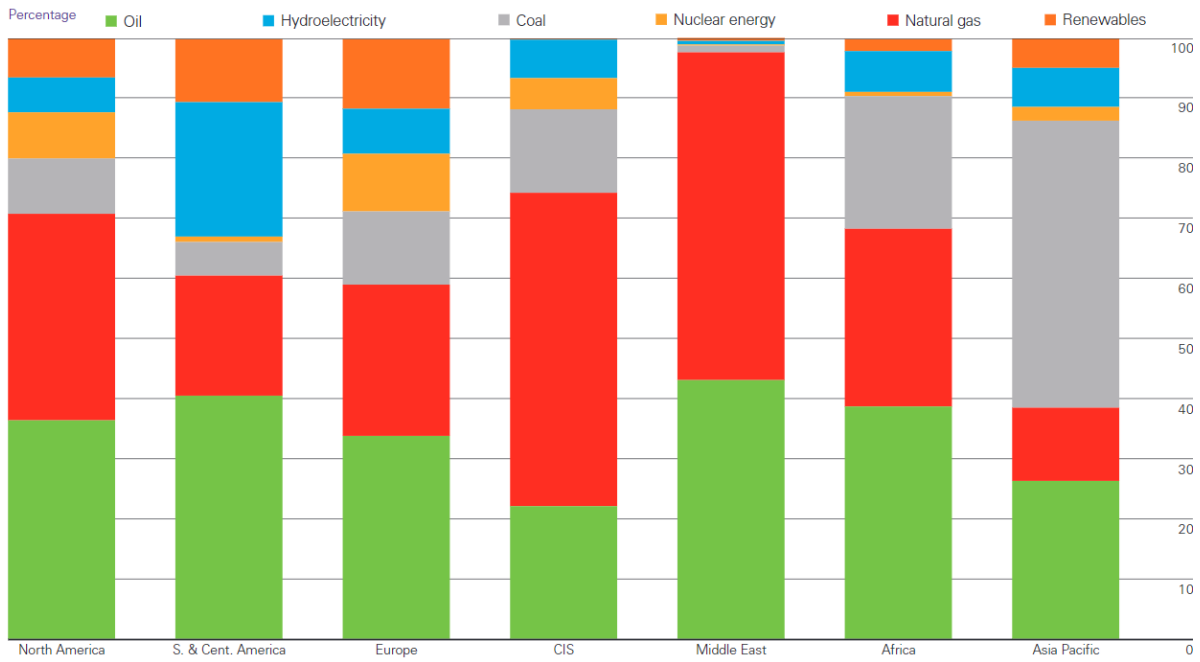

Figure 2: Regional consumption pattern 2020 [2].

Unfortunately, fossil fuels are not evenly distributed around the World and are also subjected to depletion. Furthermore, the use of these fuels causes the emission of greenhouse gases (GHG), which include carbon dioxide, methane, nitrogen oxides, fluorinated gases, and ozone. Since 1990 the GHG global emissions have increased by more than 40% [3] and these emissions are one of the dominant causes of climate change.

In 2015, the 2030 Agenda for Sustainable Development was officially launched, and it was signed by more than 190 members of the ONU. It included 17 common goals (SDGs) that aim to stimulate actions for sustainable development and the elimination of critical issues affecting humanity and the planet. The main topics were related to global inequality, energy, climate, science and urbanization and they are summarised below.

Figure 3: Sustainable development goals [4].

One of the solutions against climate change, following the goals imposed by the 2030 Agenda, is the deployment of renewable energies. The energy produced from renewable sources in Europe supplied 11% of total demand in 2020 [5], which is a rise of about two percentage points over the last five years. In addition to the already highly exploited wind and solar energies, biogas and bioliquids are also considered among the renewable resources. Biofuels will play a crucial role in the European energy transition because they reduce drastically the GHG emissions.

The biogas plants in Europe have increased exponentially in the past years, especially between 2010 and 2012. In particular, Figure 4 shows how the number of biogas and biomethane plants in the European Union has changed from 2009 to 2021. Furthermore, Italy ranks second in Europe in terms of both biogas production and the number of active biogas plants (about 1710). This growth trend is of course also visible in the production of energy from biogas, which reached 159 $\frac{TWh}{y}$ in Europe for the year 2020 [6].

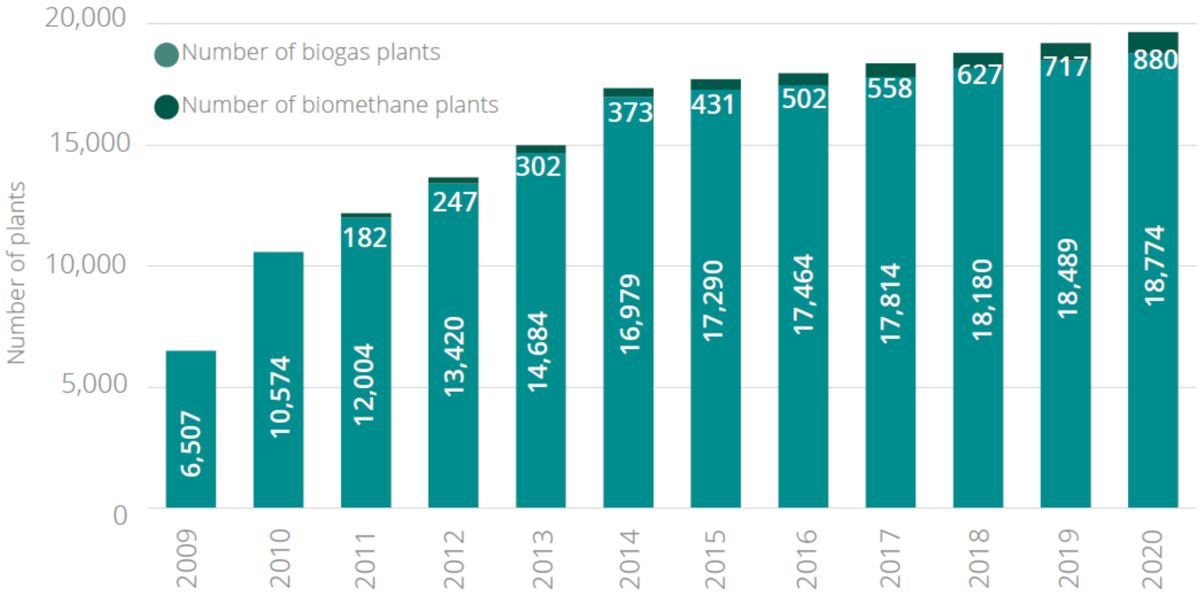

Figure 4: Number of biogas and biomethane plants [7].

Biogas is one of the products of the anaerobic digestion of organic substrates, such as agro-industrial waste, sewage sludge, organic fraction of municipal waste, or energy crops. The composition of biogas varies depending on the feedstock used and contains mainly CH_4 and CO_2, as well as other gaseous components such as H_2S, oxygen, and carbon monoxide.

It is possible to use biogas both for the production of thermal energy and electricity in cogeneration plants and for the production of biomethane. The presence of H_2S hinders the exploitation of biogas since it is toxic for humans and the ecosystem as well as corrosive for mechanical equipment. For this reason, biogas requires a cleaning phase to remove all impurities before it can be exploited.

Conventional clean-up systems are based on physicochemical desulphurisation treatments, such as absorption, adsorption, and membrane separation. These three categories include the following desulphurisation methods: water scrubbing absorption (WS), adsorption on activated carbon (AC), pressure swing adsorption (PSA), and membrane separation (MS). However, physicochemical methods involve high management costs and energy consumption, plus the production of waste due to the use of chemical agents.

Nowadays, there are several studies in the field of biological and biochemical desulphurisation of biogas. This dissertation is focused on the BIOFIDS project, which is an innovative photobioreactor using green sulphur bacteria (GSB) for the biological desulphurisation of biogas. Unlike the physicochemical treatments, this method does not use chemical reagents and eliminates waste production, therefore BIOFIDS is sustainable and environmentally friendly. The only product is elemental sulphur, which is recovered through the decanter to be reused in agronomic applications. Both the BIOFIDS unit and the other traditional desulphurisation treatments are described in more detail below.

To demonstrate the potential of the BIOFIDS unit, a life cycle assessment (LCA) is carried out, whose methodology is presented in detail and is followed by an inventory of the materials/components used. Next, there is a phase of analysis of the BIOFIDS results, where the LCA of the base case is commented and compared with two other scenarios, which respectively consider a different installation site and lower electrical consumption.

Finally, the results are compared with LCAs in the literature for physicochemical methods. The topic of study is still very innovative, so the number of LCA studies in the literature is not large. Although the methodology for LCA is standardised (ISO 14040-44), there are different software, databases and indicators which make comparison more complicated.

C. Florio et al. [8] made a comparison of several conventional systems, including MS and PSA, and the on-site cogeneration. This article studies the environmental benefits of fossil fuels substitution and obtains better environmental performance in cogeneration case. The biogas is produced from anaerobic digestion of waste feedstock. A comparative review for different desulfurization methods is carried out by F. Ardolino, G.F. Cardamone, F. Parrillo, U. Arena [9] with a focus on MS, WS and PSA systems. This is a cradle-to-wheel analysis and explore environmental and economic aspects of the commercial technologies. The assessment is based on data gained from Italian existing plants. P. I. Cano, J. Colón, M. Ramírez, J. Lafuente, D. Gabriel, and D. Cantero [10] investigates the LCA of different physical chemical and biological technologies for biogas clean-up. The biogas considered in this dissertation is the result of the anaerobic digestion of sewage sludge, which is produced by wastewater treatment. The conventional systems considered are caustic chemical scrubbing and AC. In contrast with the other articles, this one uses a cradle-to-grave approach. N. Kohlheb, M. Wluka, A. Bezama, D. Thrän, A. Aurich, and R. A. Müller [11] model an environmental and economic assessment of a large-scale plant which is located in Germany. The system consists of pre-treatment which aims to remove H_2S and water, combined whit a PSA system for upgrading. The biogas used is derived from energy-crop, for this reason, the concentration of H_2S is low. The last study used in the comparison is published in 2018 at the end of an international conference, by G. Lorenzi, M. Gorgoronic C. Silva, M. Santarelli [12]. This article explores two upgrading systems with the aim of evaluating the impacts of the substitution of natural gas with biomethane. Only one of the two systems are useful for this dissertation, and it is the high-pressure WS system. Furthermore, a sensitivity analysis for a different share of renewables in the electricity mix is done.

2 Description of case study

The case study uses as a basis the purification plant managed by the company ACDA Spa *"Azienda Cuneese Dell'Acqua"*, which is located in Cuneo (IT) as visible in Figure 5.

Figure 5: ACDA wastewater treatment plant in Cuneo.

The company has 900 tanks and reservoirs, with a total network of 5575 km. The treatment plant collects wastewater from about 16 municipalities, produced by more than 180 thousand inhabitants. The entire network is subject to constant checks to analyse water parameters such as hardness, turbidity, bacteria, electrical conductivity, and the concentration of chemical substances. The Cuneo wastewater treatment plant is able to self-produce electrical and thermal energy through a cogeneration system. On average, 96 Nm^3/h of biogas is produced from the anaerobic digestion of sludge, of which 44 Nm^3/h is used in the co-generator while the residue part is stored in the gasometers [13]. From April to December 2021, the plant produced a total of approximately 182840 m^3 of biogas. In this thesis two scenarios for sewage biogas cleaning are presented:

1. BIOFIDS scenario,
2. Reference scenario.

For the BIOFIDS scenario, the life cycle assessment is modelled, considering the three main phases: construction, transport and one year of work. The reference scenario deals with conventional desulphurisation systems, for which no LCA study has been modelled. In fact, LCA results of conventional systems have been searched in the literature, and then the results are used in the comparison with the BIOFIDS scenario.

2.1 BIOFIDS scenario

In 1980, research was carried out for a new biological clean-up biogas treatment. It exploited the ability of green sulphur bacteria (GSB) to oxidise H_2S in presence of light. This research is not yet at an industrial scale due to the high cost of illumination and high energy demand.

Based on previous research, ENEA carried out several tests to establish the parameters that reduce costs and increase efficiency, with lower energy demand. At the conclusion of the tests [14], the best performance was obtained by irradiating the bacteria with low-intensity monochromatic LEDs (with wavelengths coinciding with the absorption band of the GSB). For this reason, in 2017 ENEA registered the patent (N° 0001428761) for novel photobioreactor.

In 2018, the Piedmont Region awarded with regional funding the proposal to study and build the prototype of BIOFIDS *"Fotobioreattore per la DeSolforazione BIOlogica del bIogas"*. The project was approved in 2020, it is coordinated by Tecnodelta Srl and with Politecnico di Torino, RAMS&E Srl, and ACDA Spa as participants.

Tecnodelta Srl develops the prototype of the photobioreactor that will be installed in the ACDA Spa plant in Cuneo (IT). The process scheme, derived from the ENEA preliminary studies, is displayed in Figure 6. The system consists of a biogas feed section, an active part of the photobioreactor illuminated by LEDs, a bacterial culture recirculation system and a sulphur settling section.

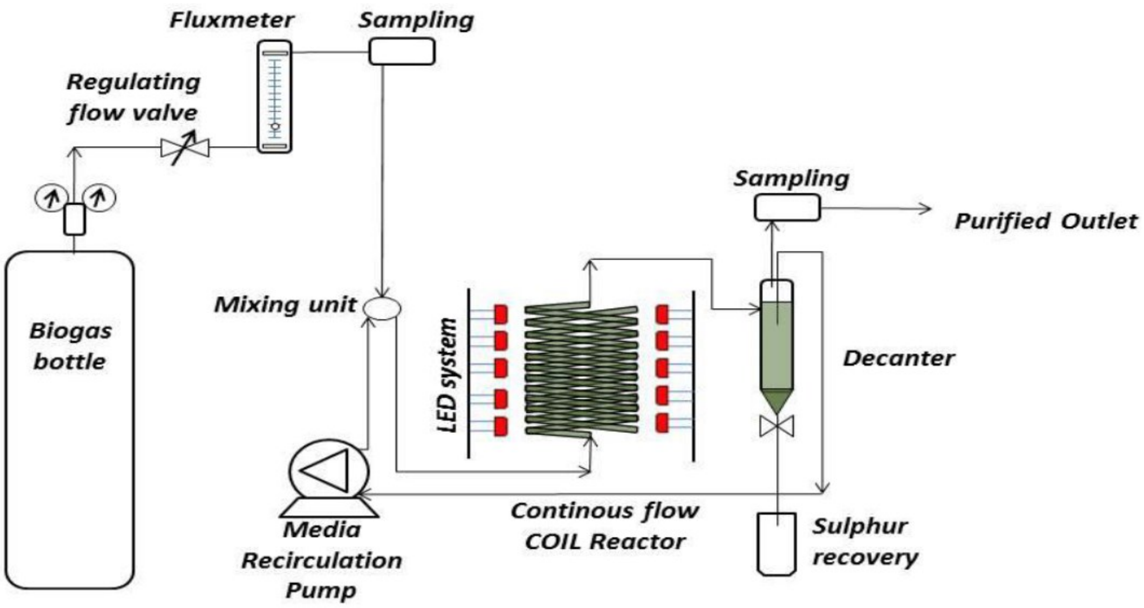

Figure 6: Process scheme [15].

The composition of the biogas and the concentration of impurities depend on the feedstock used for the AD. The ACDA plant is the wastewater treatment plant for the city of Cuneo and produces biogas from the AD of the resulting sludge. To design the prototype, the biogas composition was required, and samples were taken at two different times during 2021 (winter and summer) immediately downstream of the digester as visible in Figure 7.

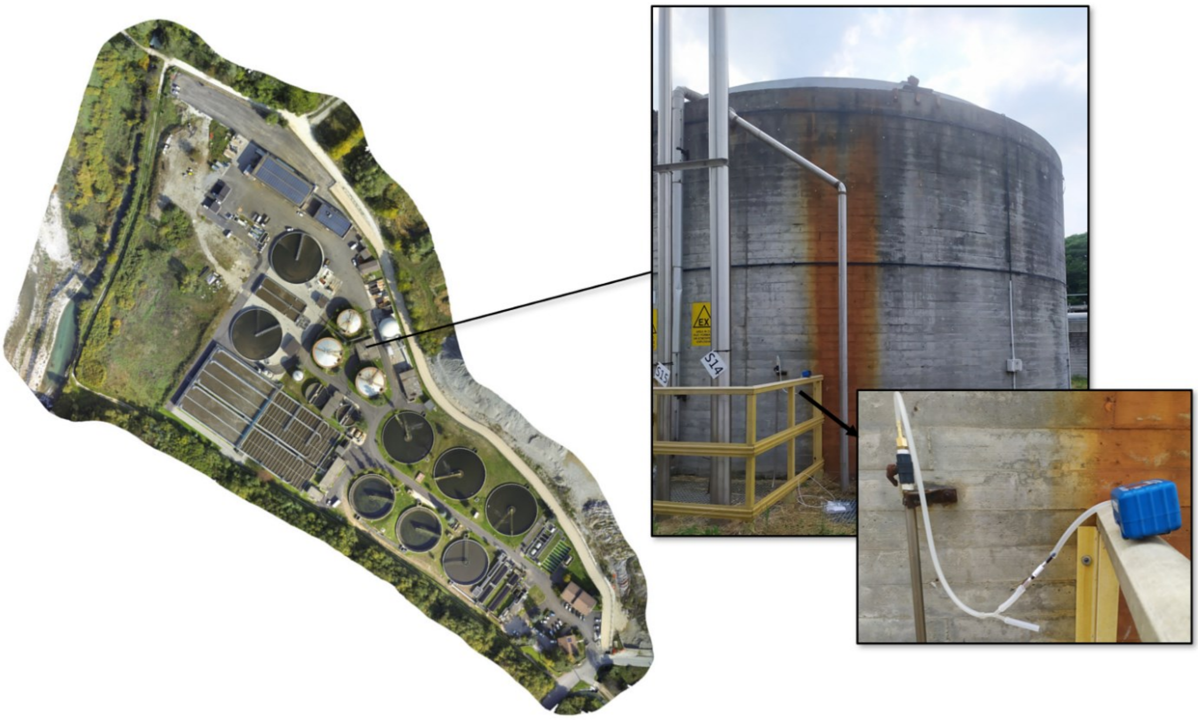

Figure 7: ACDA biogas sampling point [16].

Therefore, laboratory analyses of the extracted samples were carried out by an external laboratory to establish the real composition of the biogas, which represent the input flow of the photobioreactor. Table 1 shows the biogas composition, where the complement of 1 is given by nitrogen and other pollutants (with negligible concentrations).

Table 1: ACDA biogas composition [16].

Component	Value
CH_4	70 %v/v
CO_2	26 %v/v
O_2	<0.1 %v/v
CO	<1 ppm(v)
H_2S	81 mg/m^3
H_2S and mercaptan	85 mg/m^3

The main technical-scientific obstacle is the construction of a photobioreactor that allows the treatment of a small/medium biogas flow rate similar to that produced by ACDA WWTP. Tecnodelta Srl designs an improved geometric configuration to facilitate emptying and cleaning of the photobioreactor and investigates a good bacterial culture concerning this type of biogas.

So, the BIOFIDS prototype exploits the anoxygenic photosynthesis performed by the bacterium *Chlorobium limicola*, which is a bacterial member of GSB found in freshwater springs. The chosen bacteria cultures are very resistant and easy to manage, although it requires a type of medium for its growth that is complicated to reproduce. Moreover, are harmless for humans. In the prototype are used monochromatic LEDs, SMD type with a wavelength of 760 nm. The 3D layout of the plant is shown in Figure 8, where the photobioreactor has a yellow colour. Downstream of the photobioreactor there will be a clarifier (shown in Figure 8 in orange) that will have the task of separating the clean biogas from the condensate and sulphur. A part of the condensate will be recirculated, for a quota of about 4.7 m^3/h. Figure 9 shows more in detail the photobioreactor: it is designed as a modular system and it can work in parallel to provide greater system stability, even because the ACDA plant is planned to produce biogas continuously.

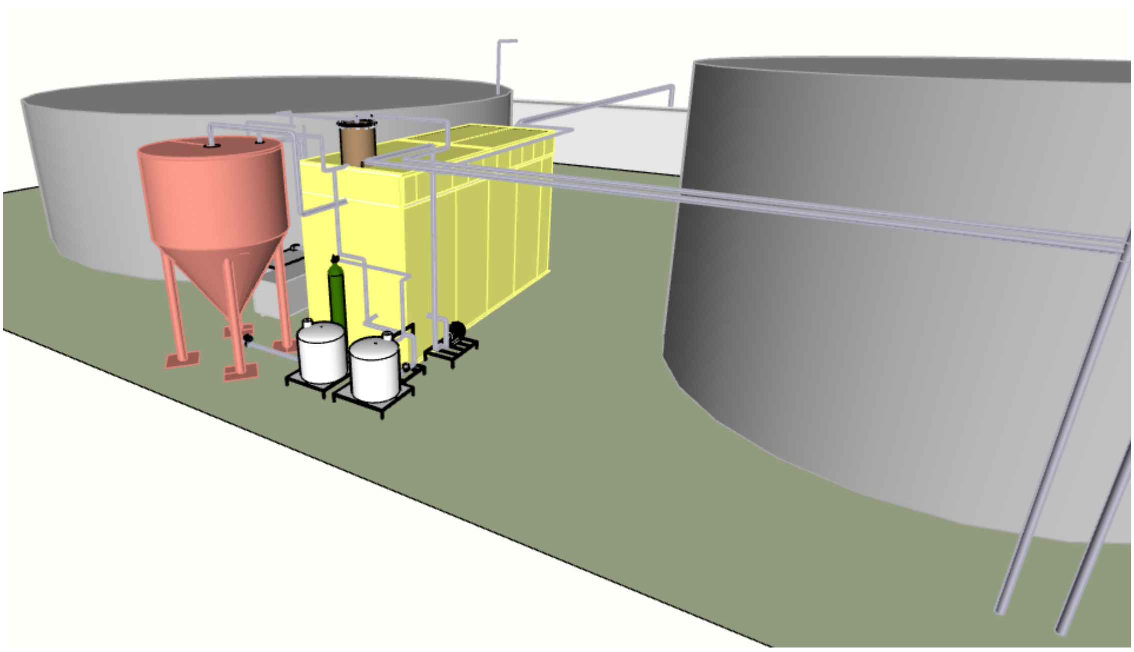

Figure 8: 3D layout of plant Tecnodelta.

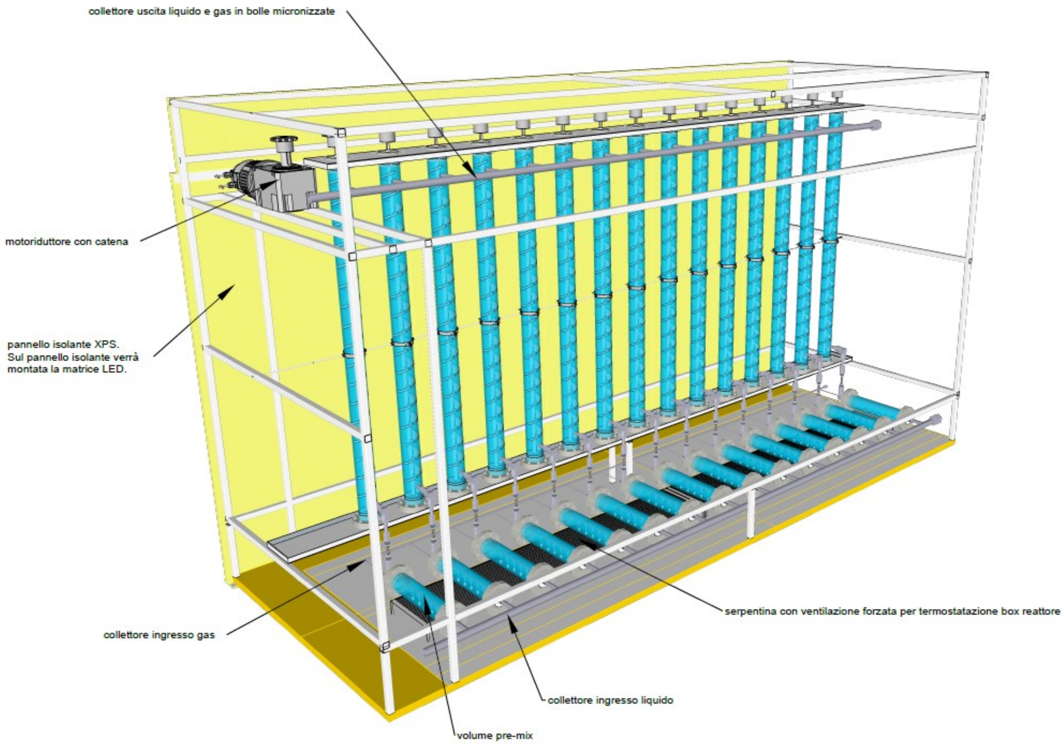

Figure 9: 3D photobioreactor Tecnodelta.

The are several advantages of the BIOFIDS system: reduced maintenance costs, zero disposal costs, high removal efficiency, and the recovery of elemental sulphur through a decanter. The bio-sulphur produced will be also a source of income because it could be commercialized in the agronomic and cosmetic sectors. In fact, when bio-sulphur oxidises, it triggers an acidification reaction that increases the presence of nutritional elements in the soil. It is particularly suitable for fertilising orchards during planting

2.2 Reference scenario

Conventional desulphurisation systems use physical or chemical phenomena such as absorption, adsorption, and membrane separation. Adsorption is based on penetration of gaseous or liquid compound (adsorbate) into pores solid material (adsorbent), it is very competitive due to its simplicity. Instead, absorption uses the formation of reversible chemical bonds between the solute and the solvent, to remove the impurities. The absorption process needs a solvent regeneration phase, where the chemical bonds previously created are broken. Membrane separation uses the different permeability of the molecules to clean-up the biogas.

These three main categories include, as summarized in Figure 10, the following desulphurisation methods: water scrubbing absorption (WS), adsorption on activated carbon (AC), pressure swing adsorption (PSA), and membrane separation (MS).

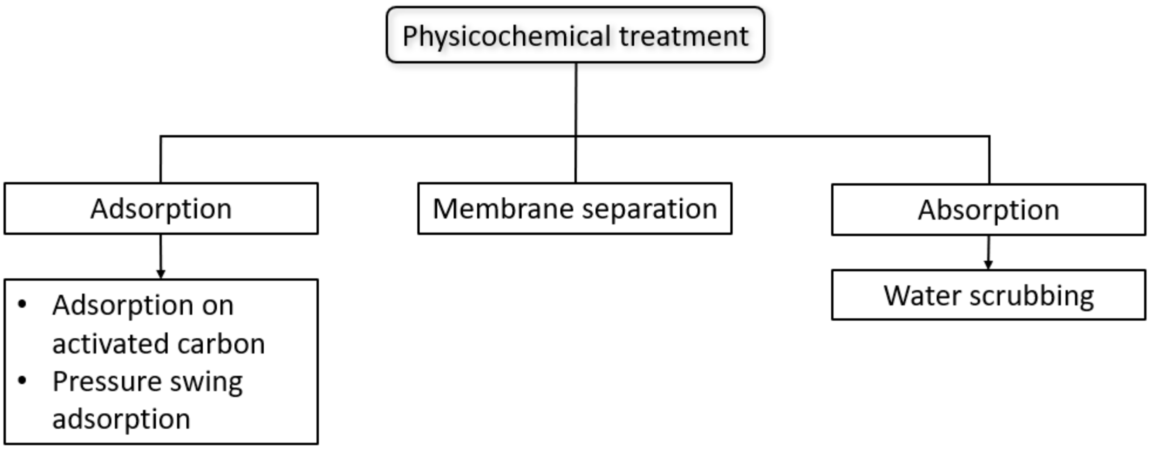

Figure 10: Physicochemical treatment.

The major disadvantages of physicochemical processes are their high chemical and energy intensity, which has led to the research of new biological and bioelectrochemical methods for biogas desulphurisation. In addition, these methods use reagents that are not only disadvantageous in terms of economy and sustainability but have a negative impact on efficiency. Nevertheless, in 2020, Italy used either membrane separation or water scrubbing for biogas purification in about 70% [7] of cases.

2.2.1 Water scrubbing absorption

Water scrubbing is a cheap physical treatment, which can generate biogas with a CH_4 concentration higher than 97% v/v. The main criticality of the WS is the high volume of water requested, high pressure and low-temperature request, and the high cost. This method exploits the major solubility of H_2S and CO_2 than methane under the same conditions, so it is possible to clean simultaneously biogas from these two gases.

The two flows pass through a counter-current absorption column, which is typically filled with packing materials to increase the interface area between liquid and gas. Before entering the WS the biogas is compressed (also up to 10 bar) and the biomethane is expelled from the top of the column. Water flows down through the column absorbing both CO_2 and H_2S and is subsequently expelled from the bottom side. This liquid may contain a small percentage of CH_4, which must be recovered to increase the efficiency of the system. For this reason, the liquid flow goes into a flash tank where expansion occurs, then the recovered gas is sent to the compressor where it is mixed with the untreated biogas.

Several types of WS are available on the market, if the water flow is reused it is called regenerative otherwise it is single-pass WS. In regenerative WS a desorption step is required, which is carried out by a stripping tank. When the H_2S concentration in the biogas is low, is sufficient an air blown in the stripping tank. In the case of high H_2S concentration, the desorption has to be supported with a flow of inert gas or steam to avoid sulphur formation. the layout of the WS absorption is shown in Figure 11 which also includes the stripping tank for water regeneration.

The WS system is explored in the review [9]. In addition, the works [8] and [12] treat high-pressure WS.

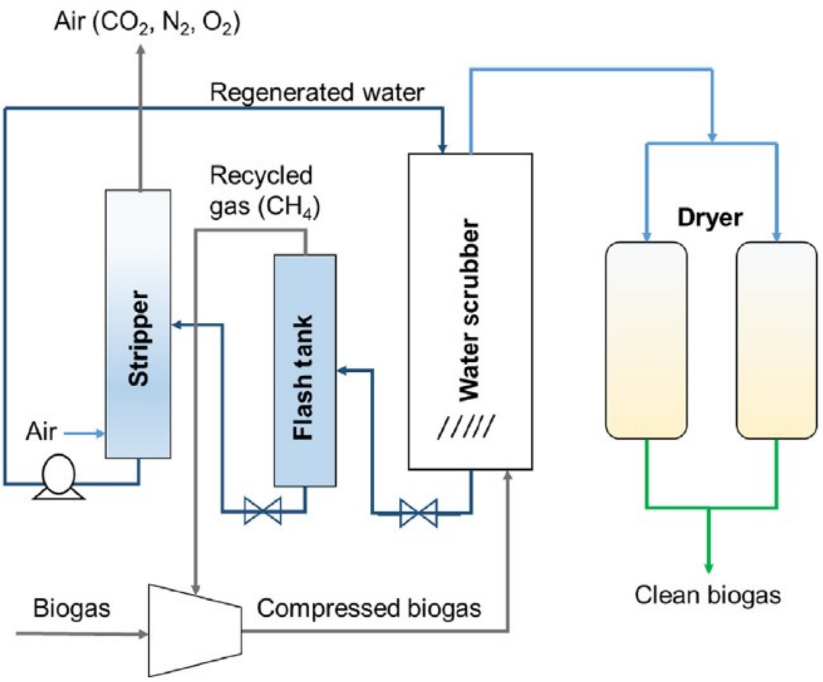

Figure 11: Water scrubbing scheme [17].

2.2.2 Adsorption on activated carbon

Activated carbon is an inert solid that is derived from carbonaceous materials such as coconut shell, peat, wood, olive pits, lignite coal and bituminous coal. AC is generally used in adsorption because it has specific characteristics of high surface area due to the presence of micropores, high removal capacity, low operating temperature, and low cost compared to the other materials. The removal process is based on surface interactions between contaminants and carbon, which occur through Van de Waals forces and dipole interaction. The scheme of the AC process is drawn in Figure 12.

Unfortunately, activated carbon has to be replaced after a certain operation time to avoid an excessive decrease in performance. To increase the operating life of the AC, biogas could be pre-treated by using dry sludge to reduce the concentration of H_2S. Furthermore, is possible to impregnate or dope the AC with permanganate, potassium iodide, or alkaline compound to increase the selectivity of impurities and, consequently, to improve the performance levels.

The economic and environmental issues of AC is the end-of-life treatment because it is classified as special waste and so it has to be disposed in a specific landfill site. Alternatively, it is possible to implement a regeneration process using incinerators, but this is very expensive.

An impregnated AC system is the subject of the article [10], but no other article uses it for analysis.

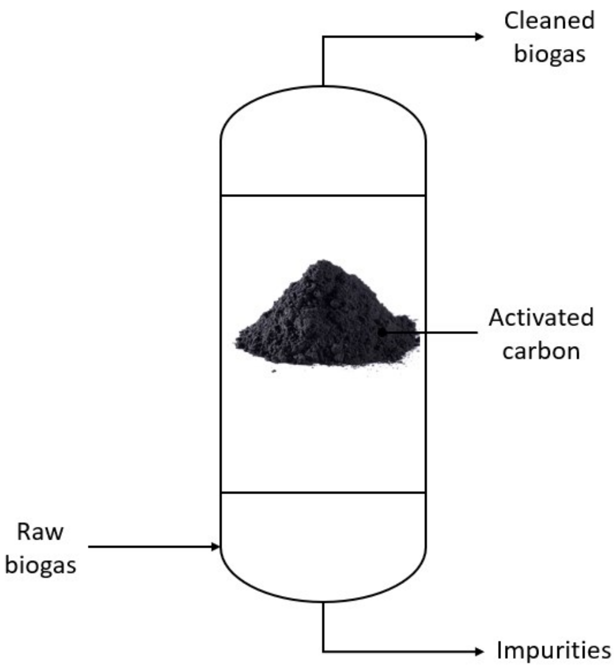

Figure 12: Activated carbon adsorption scheme.

2.2.3 Pressure swing adsorption

Pressure swing adsorption is based on several vertical columns with packed adsorption materials inside. The driving principle is the affinity of gases to be attracted to the adsorbent surface, and the process of PSA usually counts four steps. Initially, the biogas is compressed up to high pressure and flows into the adsorption column, then the cleaned biogas is released from the top of the reactor while the other gaseous compound remains attached to the adsorbent surfaces or into the pores. The gases captured by the adsorption materials are discharged from the bottom side and the process starts again with the entry of the new biogas to be treated. Figure 13 displays the PSA scheme process, with all the steps.

The adsorbent materials packed inside the columns can be regenerated by a desorption process, even if the H_2S adsorption is normally irreversible. PSA process is principally designed for biogas with a concentration of H_2S higher than 3000 ppm.

The cleaned biogas produced by PSA is characterized by a methane concentration between 96-98 %, and another advantage is the flexibility for small applications. Unfortunately, the disadvantages of PSA are the high investment and operation costs, as well as the extensive control required for the process.

PSA technology is compared with other methods in [8] and [9]. Moreover, PSA is the only considered method in [11].

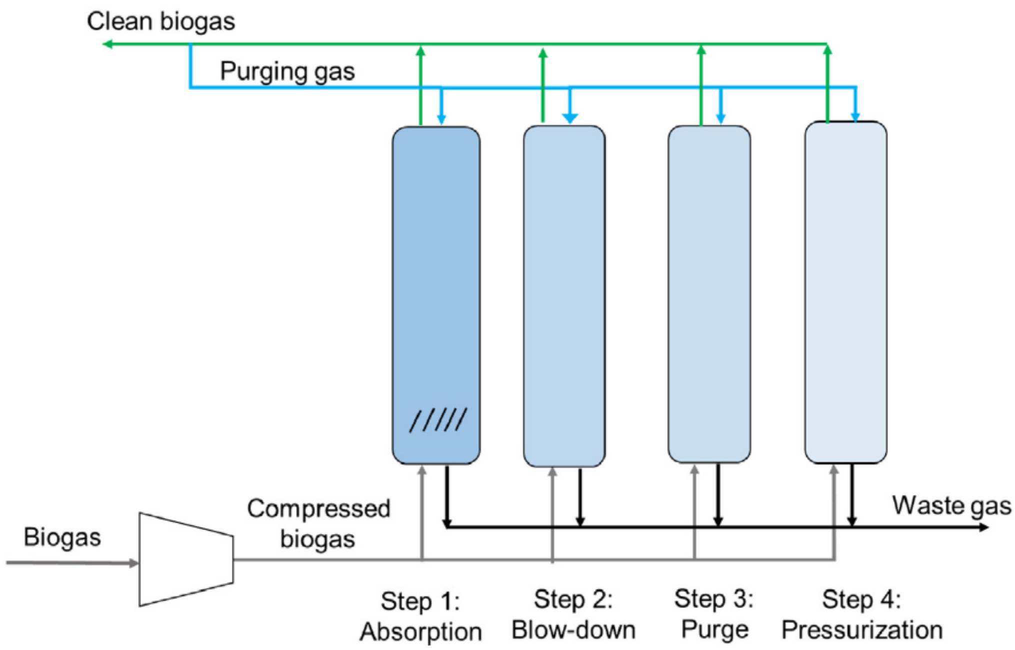

Figure 13: Pressure swing adsorption scheme [17].

2.2.4 Membrane separation

Membrane separation is based on selective permeability of the membrane, which allows the separation of biogas components. Normally this method is not used for H_2S separation, but it becomes attractive for the reduced costs, low environmental impact, lower energy consumption, and good selectivity.

The separation process can be gas-gas or gas-liquid, depending on membrane type. The polymeric membrane is used in gas-gas separation, in a gas-liquid system is used a microporous hydrophobic membrane and a liquid solution (as pure water, or sodium hydroxide). This membrane separates the gaseous stream flowing in one direction with the liquid stream flowing counter-currently. MS process typically operates at a pressure between 5 and 30 bar, the smallest molecules reach the lower pressure side, the CH_4 rich gas remains in the membrane side with higher pressure. Depending on the purity of methane required, more than one MS stage can be predicted, as illustrated for one (Figure 14) and two stages (Figure 15).

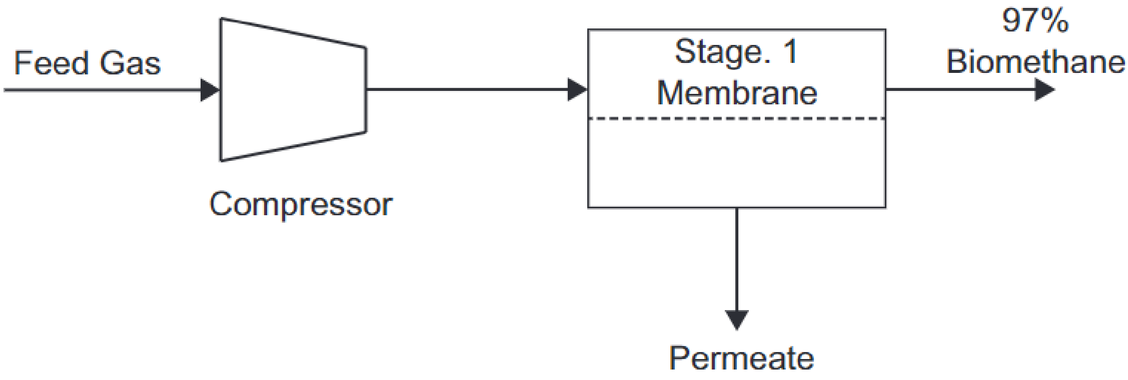

Figure 14: One stage membrane separation scheme [18].

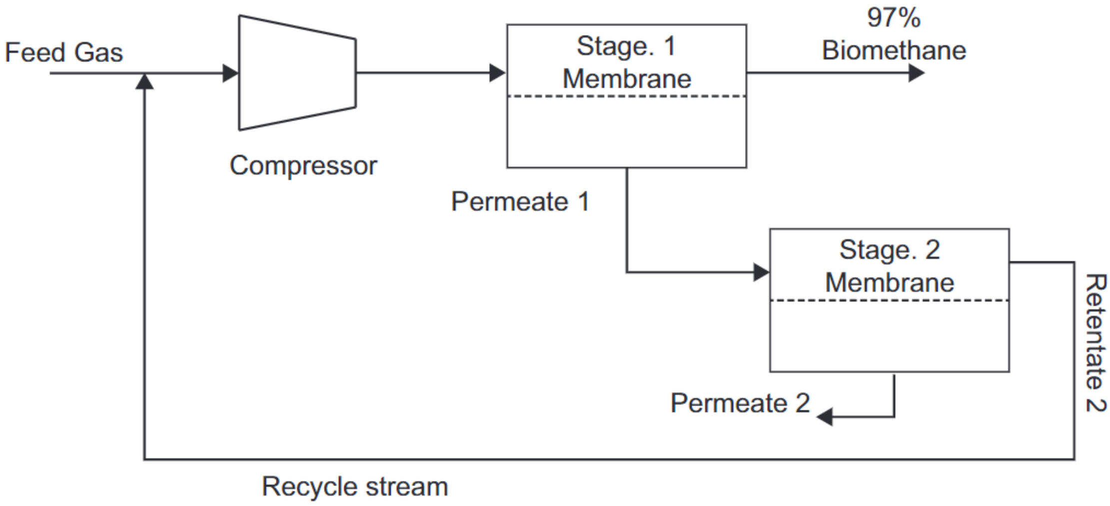

Figure 15: Two stages membrane separation scheme [18].

Even with the MS method, it is possible to lose a small percentage of methane, so to limit this it is sufficient to use more stages and recirculate the off-gases flow. The operating life of the membrane can be extended with a pre-treatment of the biogas to remove the sulphur. The obtained biogas has a methane concentration of about 97%, although the use of multiple stages is considered the main disadvantage.

The MS technology is treated in [8] and [9].

3 Life cycle assessment

In the traditional origin of LCA, it considers the entire life cycle of the system being analysed, from the raw materials to end-of-life management, including the manufacturing, distribution and use phases. In 2006 the LCA method was standardised with the ISO 14040 and 14044. The method focuses on the assessment of energy and material consumption, as well as emission and waste generation.

3.1 Methodology

The LCA method consists of four different steps (summarized in Figure 16):

1. Goal and scope definition,
2. Life cycle inventory (LCI),
3. Life cycle impact assessment (LCIA),
4. Interpretation.

Firstly, the goal of the study and the reason why it is required are defined. At the same time, are fixed the system boundaries, the functional unit, and the reference flow of the study. The system boundaries distinguish different types of LCA, depending on where the life cycle study begins and ends. It is possible to study the life cycle from cradle-to-grave or from cradle-to-utilisation, but there are also many other types of study. The functional unit is a quantification of the system performance and is useful for the comparison, instead the reference flow is the output flow of the process.

The LCI describes in detail the input and output flows of the process, in terms of raw materials, resources, energy and emissions. The type of each flow must be identified:

- Elementary: material/energy that have not been transformed by humans,
- Product: good, service (i.e. transport), or materials which have been processed by human activity,
- Waste: substances or objects which have to be disposed.

The impact assessment has the task of quantifying the magnitude of the environmental impact of the product system. To do this it is utilised several impacts categories, in relation to the chosen LCIA method. There are several LCIA methods, which operate on midpoint or endpoint indicators. The midpoint indicator means that it “looks at the impact earlier along the cause-effect chain before the endpoint is reached” [19], so it is a point positioned between the emission and the endpoint caused by excessive emission. The endpoint indicator “looks at environmental impact at the end of this cause-effect chain” [19], therefore typically represents the final impact on human health, the ecosystem and resource depletion. In this step, there is also an optional phase, where elements of normalisation, weighing and quality analysis can be set.

The last step is the interpretation of the results, where the results should be analysed to identify critical points, to provide recommendations and conclusions.

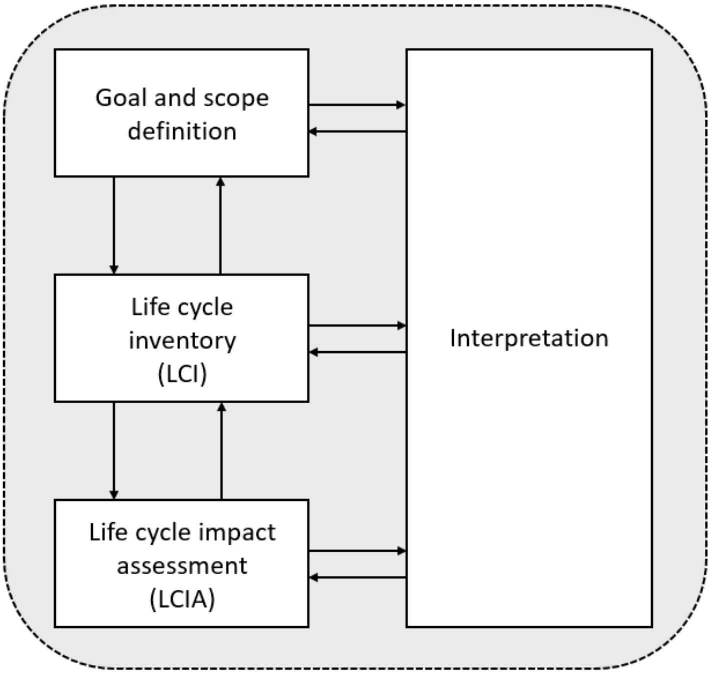

Figure 16: Steps of the LCA study.

The BIOFIDS analysis is carried out through OpenLCA® software by using the Environmental Footprints database. This database is designed by the European Commission for the green product initiative, in order to develop a common methodology on the quantitative assessment of environmental impacts of products [20].

The goal is to evaluate the impacts of the novel photobioreactor. In the following chapters, the results of LCA are compared with two modified scenarios and with conventional desulfurization systems. The comparison is made to decide if the BIOFIDS unit is less impactful than other known clean-up systems. Figure 17 shows the boundaries of the study which are fixed as *cradle-to-utilisation*, including construction, transport to the location and one-year operation. The disposal phase is not taken into account in this study, as the end-of-life treatment of the unit has not yet been studied.

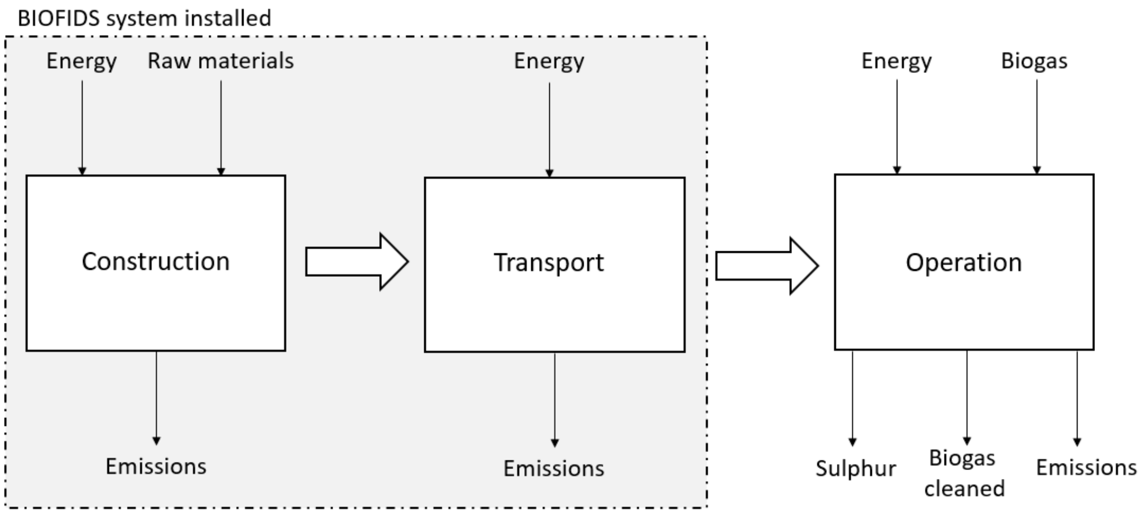

Figure 17: System boundary for the LCA of BIOFIDS.

For this analysis, the **functional unit** is set equal to the m^3 of cleaned biogas, to simplify the following comparison. Furthermore, all the flows considered in this analysis are of the product type.

The impact assessment is the Environmental Footprint (Mid-point indicator), which is linked to the chosen database. The environmental **impact categories**, chosen for this dissertation, are:

- Climate Change (CC) [kg CO_2 eq.],
- Freshwater eutrophication (FE) [kg P eq.],
- Ozone depletion (OD) [kg CFC-11 eq.],
- Particulate matter (PM) [items of PM],
- Photochemical ozone formation-human health (POF) [kg NMVOC eq.].

3.2 BIOFIDS base case

The LCA of the BIOFIDS prototype follows the steps described above. Three phases will be modelled in detail: construction, transportation, and operation.

The company Tecnodelta Srl provides a list of all the equipment required for the **construction phase** of the prototype (shown in the Appendix). The quantity of each piece of equipment is available. For each component, the quantity of the individual materials is available. The sum of the mass of each material required for the construction is shown in Table 2. The output of the construction phase is BIOFIDS unit, characterised by its total mass.

Table 2: Inventory of construction phase.

Flow	Quantity	Proxy dataset in Environmental Footprints
AISI316L and C85+Ni/P Fe	217.4 kg	Stainless steel hot rolled, production mix, at plant, hot rolling, stainless steel - ROW
Polyvinyl	0.04654 kg	PVC granulates, low density, production mix, at plant, polymerisation of vinyl chloride, 62 g/mol per repeating unit - EU-28+EFTA
PTFE	0.04654 kg	Polytetrafluoroethylene (PTFE) granulate, production mix, at plant, polymerisation of tetrafluoroethylene, 2.16 g/cm3 - EU-28+EFTA
FPM	0.047 kg	Fluoropolymer, unspecified, Production mix, at plant, Technology mix, - GLO
PTFE+NBR	0.047 kg	Nitrile butadiene rubber (NBR), production mix, at plant, polymerisation of acrylonitrile and butadiene, 33% acrylonitrile - EU-28+EFTA
Aluminium alloy	27.9 kg	Aluminium ingot (magnesium main solute), single route, at plant, primary production, aluminium casting and alloying, 2.7 g/cm3 - EU-28+EFTA
Copper	5.8 kg	Copper sheet, single route, at plant, melting and mechanical treatment (fabrication), 8.92 g/cm3
Galvanised steel	2.4 kg	Steel hot dip galvanised, single route, at plant, steel sheet hot dip galvanization, 1.5 mm sheet thickness, 0.02 mm zinc thickness

Polyethylene	36 kg	Polyethylene terephthalate (PET) granulate secondary; no metal fraction, single route, at consumer, from post-consumer plastic waste, via grinding, metal separation, washing, pelletization, plastic waste without metal fraction
XPS	87 kg	Polystyrene production, high impact, production mix, at plant, polymerisation of styrene, 1.05 g/cm3
PP	0.2 kg	Polypropylene (PP) fibers, production mix, at plant, polypropylene production, spinning, 5% loss, 3.5 MJ electricity
EPDM	0.0074 kg	Ethylene propylene dien elastomer (EPDM), production mix, at plant, copolymerization of ethylene and propylene, 69% ethylene, 38% propylene
Plastic (not specified)	4.1 kg	Preform production, production mix, at plant, blow moulding, plastic preform
Galvanised iron	60.6 kg	Steel electrogalvanized coil, single route, at plant, steel sheet electrogalvanization, 1.5 mm sheet thickness, 0.02 mm zinc thickness
PVC	113.3 kg	PVC granulates, low density, production mix, at plant, polymerisation of vinyl chloride, 62 g/mol per repeating unit
Aluminium	1.1 kg	Aluminium ingot mix (high purity), single route, at plant, primary production, aluminium casting, 2.7 g/cm3, >99% Al
PVDF	90 kg	Polyvinylidene fluoride (PVDF), production mix, at plant, polymerisation of vinyl fluoride, 1.76 g/cm3
PRFV	161.5 kg	Glass fibres, at plant, production mix, per kg glass fibres
Alloyed carbon steel	62.7 kg	Steel cold rolled coil, single route, at plant, blast furnace route, carbon steel
LEDs SMD	40 items	Light Emitting Diode (LED), low power, production mix, at plant, front-end and back-end processing of the wafer, including Czochralski method of silicon growing, 59 mg
Compact sintered silicon	0.45 kg	Silicon mix production, production mix, at plant, technology mix, 100% active substance - GLO

In the BIOFIDS prototype, 40 LEDs of the SMB1N-760D (Figure 18) type are installed. These LEDs are infrared high power and have a power consumption of 400 mW individually. In OpenLCA®, there are only three providers for LEDs. Only one of these three is of the SMD type, despite being low energy.

$$Total\ mass_{LEDs} = 59\ mg * 40 = \frac{2360\ mg}{10^6} = 0.00236\ kg$$

Figure 18: LED SMB1N-760D [21].

The mass of the BIOFIDS unit is calculated as the sum of the masses of all materials used in the construction.

For the **transport phase** (Table 3) the input flows are the constructed BIOFIDS unit and the transport to the installation site. In OpenLCA®, the articulated lorry is selected as transportation method, and it is characterised by a small weight. The distance is equal to 140 km and is calculated from Google Maps, by considering Tecnodelta Srl (Chivasso, Turin) as the starting point and ACDA Spa (Cuneo) as the ending point. The unit of transport flux, in the software, is measured as the product of the mass of the photobioreactor and the kilometres. The installed and ready-to-use photobioreactor represents the outflow of this stage, with a unit equal to item(s).

Table 3: Inventory of transport phase.

Flow	**Quantity**	**Proxy dataset in Environmental Footprints**
BIOFIDS unit	870.6 kg	BIOFIDS construction - IT
Transport	870.6*140 kg·km	Articulated lorry transport, Euro 5, Total weight <7.5 t (without fuel), consumption mix, to consumer, diesel driven, Euro 5, cargo, up to 7,5t gross weight / 3,3t payload capacity

The analysis of the **operation phase** is the heart of the discussion. Indeed, this phase can be compared with data in the literature, in which the other phases are not included. The input flows (Table 5) are biogas, electricity and the installed BIOFIDS unit. The consumption of each piece of equipment in the prototype is provided by the manufacturer. The maximum power required to keep each part of the prototype running is $4.6\ kW$. OpenLCA® software requires an *average annual consumption* for electricity, so all other inputs are calculated on annual basis too. So, the annual electricity consumption is calculated as:

$$El_{consumption} = 4.616\ kW * 24\ h * 365\ d = 40.44\ MWh$$

For the electricity input, a process that corresponds to the electricity grid mix of Italy to the consumer is chosen.

The biogas flow rate entering the prototype is $6\ \frac{m^3}{h}$. The unit of the biogas in the software is the kilogram, so the mass of biogas to be treated in one year is calculated. To do this, it is necessary to define the density of the biogas. The composition of the biogas is known from Table 1, the average percentage value of methane contained in the biogas for the period April 2021 to February 2022 is in Table 4.

Table 4: Real average percentage of CH_4.

Month	% of CH_4
April 2021	70
May 2021	67
June 2021	67
July 2021	68
August 2021	67
September 2021	61
October 2021	69
November 2021	66
December 2021	67
January 2022	67
February 2022	66

In the discussion, 70% CH_4 and 30% CO_2 have been taken as a typical value to simplify the calculations.

$$\rho_{Biogas} = \rho_{CH_4} * 0.7 + \rho_{CO_2} * 0.3 = 1.089 \frac{kg}{m^3}$$

$$Biogas_{inlet} = 6 \frac{m^3}{h} * 24\ h * 365\ d * 1.089 \frac{kg}{m^3} = 57'252.9\ kg$$

Table 5: Inventory of operation phase.

Flow	Quantity	Proxy dataset in Environmental Footprints
BIOFIDS transported unit	1 item	BIOFIDS transport - IT
Electricity	40.44 MWh	Electricity grid mix 1kV-60kV, consumption mix, to consumer, AC, technology mix, 1kV - 60kV - IT
Biogas	57'252.9 kg	Anaerobic fermentation, production mix, at plant, anaerobic fermentation of biowaste, 1 kg of waste fermented - EU-28+EFTA

The provider selected from the database for biogas production describes the fermentation of biowaste. It comprises the following steps:

1. Substrate transportation: assuming which is available within local distances, while the transportation of the digestate back to the farmer is not taken into account.
2. Sanitation: at 70 °C for 1 h and it is assumed that the substrate from sanitation reaches the fermenter without heat losses. Moreover, the applied heat to the sanitation process is therefore reused to 100% in the fermenter.
3. Mechanical pre-treatment: in fact organic waste and sludge have to be treated before they can be introduced into the fermenter.
4. Substrate fermentation into the digester, mainly is considered an inside temperature of approx. 42°C.

5. Digestate treatment: it is also considered, and it is separated into a solid phase and a liquid phase. The liquid phase is partially reused for regulating the sludge inside the fermenter, so there is no need for an additional water flow.

Furthermore, the process assumed that the biogas only consists of methane and carbon dioxide. As concern the self-electricity consumption, it is calculated by taking into account the average demand of conventional biogas plants with CHP. The fermenter heat consumption is calculated by taking into account firstly the energy for heating up the substrate (up to 42 °C) and secondly the heat required to balance the losses via the fermenter surface to the environment.

The outputs of the operation phase are the clean biogas and the elemental sulphur produced. However, the software does not have a reference flow for clean biogas, and it is also necessary to calculate the amount of sulphur produced. The amount H_2S contained in the biogas, for one-year operation, is:

$$H_2S_{biogas} = H_2S_{concentration} * \dot{V}_{biogas} = 85\ \frac{mg}{m^3} * 6\ \frac{m^3}{h} * \frac{24\ h * 365\ d}{10^6} = 4.468\ kg$$

For the BIOFIDS photobioreactor, a H_2S removal rate of 97% is considered, and so in one year $4.334\ kg$ of H_2S is removed. Consequently, the sulphur produced in one year operation is calculated, through a conversion that takes into account molecular weights, as:

$$mol_{H_2S,removed} = \frac{H_2S_{removed}}{MW_{H_2S}} = \frac{4.334\ kg}{34\ \frac{kg}{kmol}} = 0.127\ kmol$$

$$S_{produced} = mol_{H_2S,removed} * MW_S = 0.127\ kmol * 32\ \frac{kg}{kmol} = 4.079\ kg$$

To take into account the absence of the cleaned biogas flow, it is then necessary to calculate the H_2 produced, to be added to the biogas output.

$$H_{2_{produced}} = H_2S_{biogas} - S_{produced} = 4.468 - 4.079 = 0.255\ kg$$

$$\begin{aligned} Biogas_{outlet} &= Biogas_{input} - S_{produced} + H_{2_{produced}} = 57'252.9 - 4.079 + 0.255 \\ &= 57'249.0\ kg \end{aligned}$$

Even if the output flows are two, the reference flow of the operation process is represented by the mass of biogas that was treated (inlet biogas to the clean-up unit).

At the end of the LCI modelling, a product system is created for each phase. When creating the product system, the auto-link option is not used as it is recommended by the manufacturers of the Environmental Footprint database. This is caused by the presence of product and waste streams, so the processes must be manually linked. Once the product's systems have been created, it is possible to produce the model graph in which all the processes used are highlighted. The model graphs are shown in Figure 19 for the construction phase, in Figure 20 for the transport phase, and in Figure 21 for the operation phase.

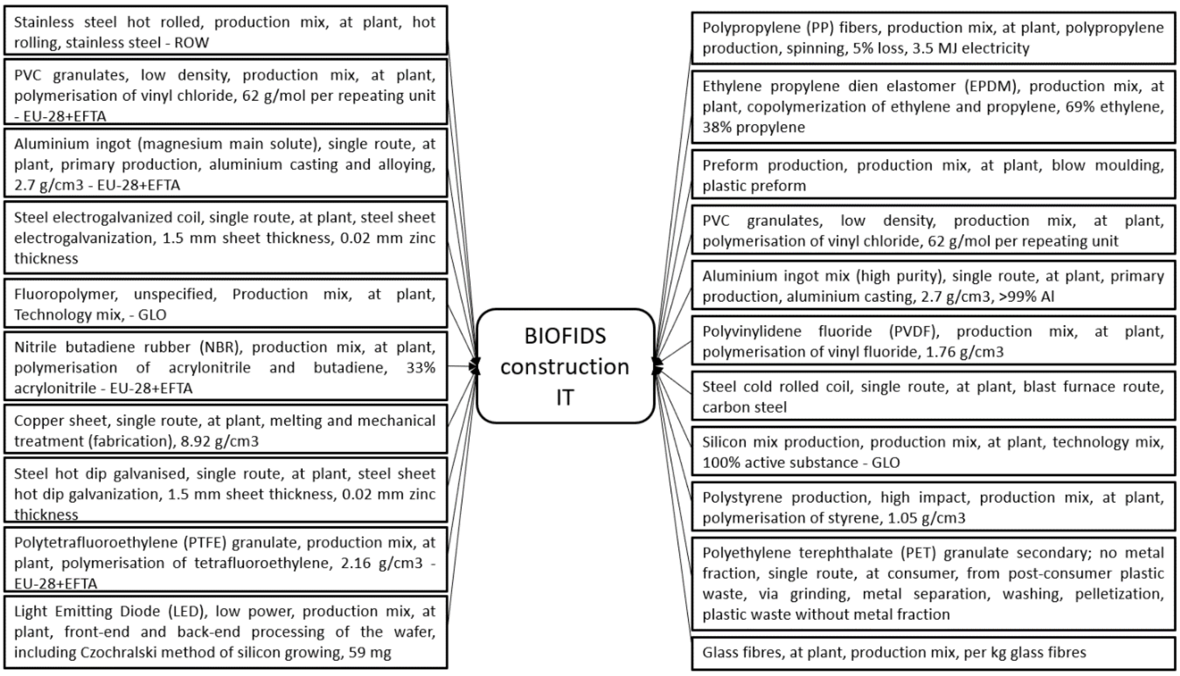

Figure 19: Construction phase model graph.

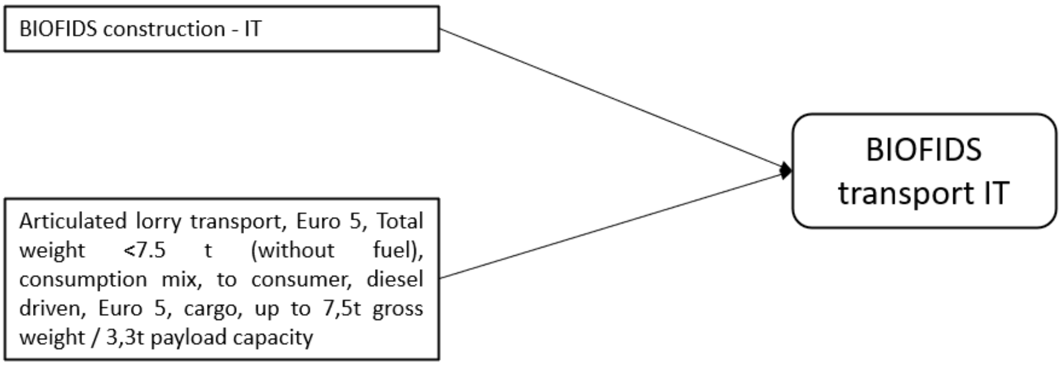

Figure 20: Transport phase model graph.

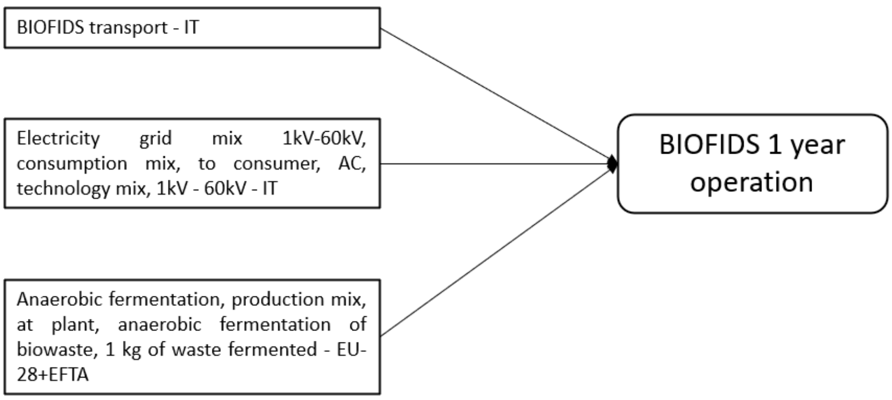

Figure 21: Operation phase model graph.

3.3 BIOFIDS modified cases

Starting from the base case, modifications have been implemented to explore other scenarios more similar to real system operation.

The WWTP is designed to work 365 days a year, so there are no production stops even for routine maintenance. However, a decrease in the flow rate of biogas produced for sludge cleaning is foreseen for 10% of the year. During this period of decreasing range, half of the photobioreactor LEDs may be switched off. On the BIOFIDS side, periods of routine cleaning of the photobioreactor tubes, of a few hours approximately every three months, should be also scheduled. The probability of experiencing blackouts is the only other fact to be taken into account when determining the utilisation factor. Taking all these reasons into account, a scenario with a 90% utilisation factor is implemented and it will be labelled as *"FU=90%"*. This utilisation factor results in a 10% reduction in electricity consumption compared to the base case (where the utilisation factor was set to 100%). So, the electricity consumed during one year of operation is:

$$El_{FU=90\%} = El_{consumption} * 0.9 = 40.44\ MWh * 0.9 = 36.39\ MWh$$

The LCI of the other phases is not changed besides the operation one, which is shown in Table 6.

Table 6: Inventory of operation phase with FU=90%.

Flow	Quantity	Proxy dataset in Environmental Footprints
BIOFIDS transported unit	1 item	BIOFIDS transport – IT
Electricity	36.39 MWh	Electricity grid mix 1kV-60kV, consumption mix, to consumer, AC, technology mix, 1kV - 60kV - IT
Biogas	57'252.9 kg	Anaerobic fermentation, production mix, at plant, anaerobic fermentation of biowaste, 1 kg of waste fermented - EU-28+EFTA

For this scenario, there are no changes to either the model graph or the output flows.

In the discussion of the base case, a biogas with a very low H_2S concentration was considered (85 ppm). This concentration was the result of laboratory analyses carried out, by the Politecnico di Torino and an external laboratory, on biogas samples taken in ACDA. It was therefore decided to evaluate the impact of using a dirtier biogas flow feeding the photobioreactor, in order to simulate other biogas sources (biogas from agricultural and food residuals). The H_2S concentration is set at 2000 ppm, which is about twenty times higher than in the base case. In fact, the system can treat biogas with varying concentrations of H_2Swithout having to change the layout. This scenario was therefore renamed *"H_2S=2000 ppm"*. Again, the only phase to be modified is the operation phase. The flow rate of biogas is the same, so the quantity of H_2S is:

$$H_2S_{biogas,2000ppm} = H_2S_{2000ppm} * \dot{V}_{biogas} = 2000\ \frac{mg}{m^3} * 6\ \frac{m^3}{h} * \frac{24\ h * 365\ d}{10^6} = 2.233\ kg$$

The removal factor is kept constant at 97%, so both the amount of sulphur produced, and the mass of cleaned biogas will be re-assessed. The H_2S removed in one year is equal to $2.166\ kg$. In the following equations is calculated the sulphur produced in one year operation and the biogas written in the output flow of OpenLCA®.

$$mol_{H_2S,removed} = \frac{H_2S_{removed,2000ppm}}{MW_{H_2S}} = \frac{2.166\ kg}{34\ \frac{kg}{kmol}} = 0.064\ kmol$$

$$S_{produced,2000ppm} = mol_{H_2S,removed} * MW_S = 0.064\ kmol * 32\ \frac{kg}{kmol} = 2.039\ kg$$

$$H_{2_{produced,2000ppm}} = H_2S_{biogas,2000ppm} - S_{produced,2000ppm} = 2.166 - 2.039 = 0.127\ kg$$

$$\begin{aligned} Biogas_{outlet} &= Biogas_{input} - S_{produced,2000ppm} + H_{2_{produced,2000ppm}} \\ &= 57'252.9 - 2.039 + 0.127 = 57'250.9\ kg \end{aligned}$$

Input data for the operation are the same, while the output flows of this scenario are displayed in Table 7.

Table 7: Outputs of H_2S=2000 ppm scenario.

Flow	Quantity
Biogas	57’250.9 kg
Sulphur	2.039 kg

The model graph of this scenario is unchanged as before, so they are not displayed again.

4 Results

In this chapter, are shown the results extracted from OpenLCA® software for the three BIOFIDS scenarios. For each scenario, is implemented a contribution analysis to identify the processes that have the greatest impact on the environment. The chapter is divided into two sections: the first section reports the results and data analysis of the base case, the second one compares the base case scenario with *FU=90%* and *H_2S=2000 ppm* scenario.
The impact categories, mentioned in section 3.1 Methodology, are now used to analyse and compare results.

4.1 BIOFIDS scenario

The results are initially analysed taking into account only the three phases (construction, transport, and operation). The construction and transport phases use the mass of the BIOFIDS and the transported unit as reference flow. In addition, these two phases will end with the commissioning of the plant, which is the reason why there will be no later emissions. Instead, the data reported for the operation phase are calculated in relation to the kg of biogas treated along one year. Table 8 summarizes the environmental impacts of the distinct phases.

Table 8: Impacts of construction, transport, and operation in base case.

Impact category	Unit	Construction	Transport	Operation	Total
CC	kg CO_2 eq.	3847.19	14.54	41267.24	45128.98
FE	kg P eq.	0.023	0	1.47	1.50
OD	kg CFC-11 eq.	1.25E-03	0	2.88E-06	0.00125
PM	items of PM	5.12E-04	1.49E-07	8.10E-04	0.00132
POF	kg NMVOC eq.	10.59	0.039	85.94	96.57

Figure 22 shows the percentage contribution of each stage to the total, for all impact categories. As can be seen, the most impactful phases are construction and operation, while the transport phase is almost undetectable. Specifically, the operation is the most impactful in four of the five categories, while the construction is the main cause of ozone depletion. The operation phase is predominant on FE and POF, for 98.5% and 89% respectively. The production of particulate matter is caused 61.3% by operation and 38.3% by construction.

The main indicator useful for the analysis is climate change. As shown in Figure 22, the main contribution is due to the operation phase. 91.4% of CC is caused by the operation phase, while construction is only 8.5%.

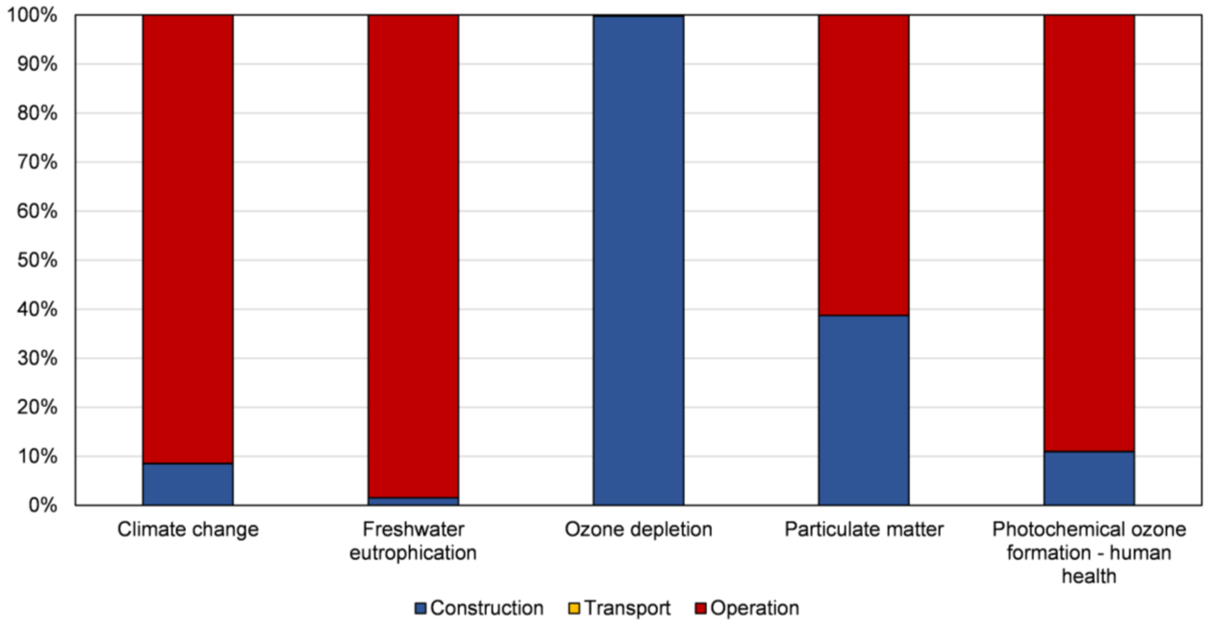

Figure 22: Breakdown of impact categories in the base case.

The CC production is caused by the three steps is shown in Figure 23, where the kg of CO_2 eq. produced by each step is highlighted. As explicitly mentioned before, the transport phase in comparison with the other two phases could be neglected. It is known that $41'267\ kg\ CO_2\ eq.$ are emitted in one-year of operation, so over the entire life (20 years) of the plant the following will be emitted $825'325\ kg\ CO_2\ eq.$

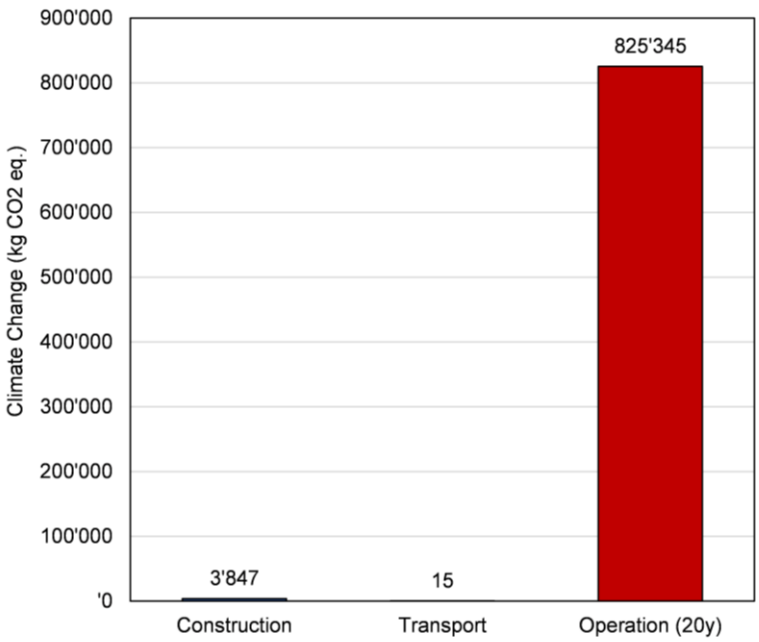

Figure 23: Climate change comparison 3 phases.

At this point, it is important to explore the individual stages, to understand which of the input flows causes the greatest impact on the environment, with a focus on CC.

The construction uses all necessary materials as input flows. Table 9 summarises the kg of CO_2 eq. produced by all processes involved in the construction of BIOFIDS, in relation to the final mass of the unit. Moreover, the graph (Figure 24) is derived from the kg of CO_2 eq. produced, showing the processes that have the greatest percentage influence on climate change.

Table 9: Climate change for construction processes.

Flow	**Climate change (kg CO_2 eq.)**
AISI316L and C85+Ni/P Fe	1497.11
Polyvinyl + PVC	249.07
PTFE	0.59
FPM	0.67
PTFE+NBR	0.19
Aluminium alloy	319.19
Copper	2.85
Galvanised steel	7.24
Polyethylene	26.38
XPS	208.70
PP	0.086
EPDM	0.027
Plastic (not specified)	2.28
Galvanised iron	181.27
Aluminium	12.64
PVDF	769.04
PRFV	386.73
Alloyed carbon steel	172.22
LEDs SMD	0.73
Compact sintered silicon	10.18

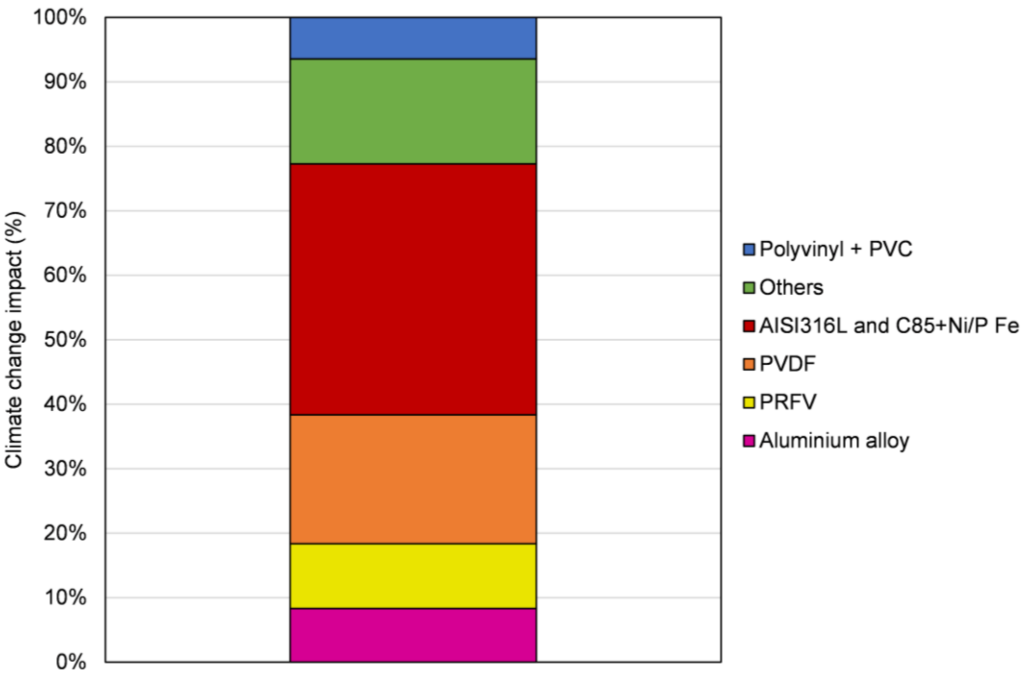

Figure 24: Construction major contributors to climate change.

The biggest impact, about 38.9%, is due to the materials AISI316L and C85+Ni/P Fe, which are used for all the valves required for the proper functioning of the system. The contributions related to the materials represented in the graph are:

- PVDF 20%, which is the material used for the cleaning system,
- Others 16.3%,
- PRFV 10.1%, used in the transparent clarifier opening,
- Aluminium alloy 8.3%,
- Polyvinyl and PVC 6.5%.

"Others" contains all processes with an impact rate of less than 6%. The impact of these processes has therefore been added up to the 16.3% shown in the graph.

The impact of the transport phase (14.54 kg CO_2 eq.) is entirely attributable to the articulated lorry unit process. This vehicle is characterised by average Euro 5 emission values.

For the operation phase, two processes are used in addition to the ready-to-use BIOFIDS unit. The impact of these two processes on CC is shown in Table 10 in terms of kg of CO_2 eq. produced for one year of operation. Finally, the impact rate of these two processes is plotted in the chart in Figure 25.

Table 10: Climate change for operation processes.

Flow	**Climate change (kg CO_2 eq.)**
Biogas from anaerobic fermentation	21’703
Electricity grid mix IT 1kV-60kV	19’564

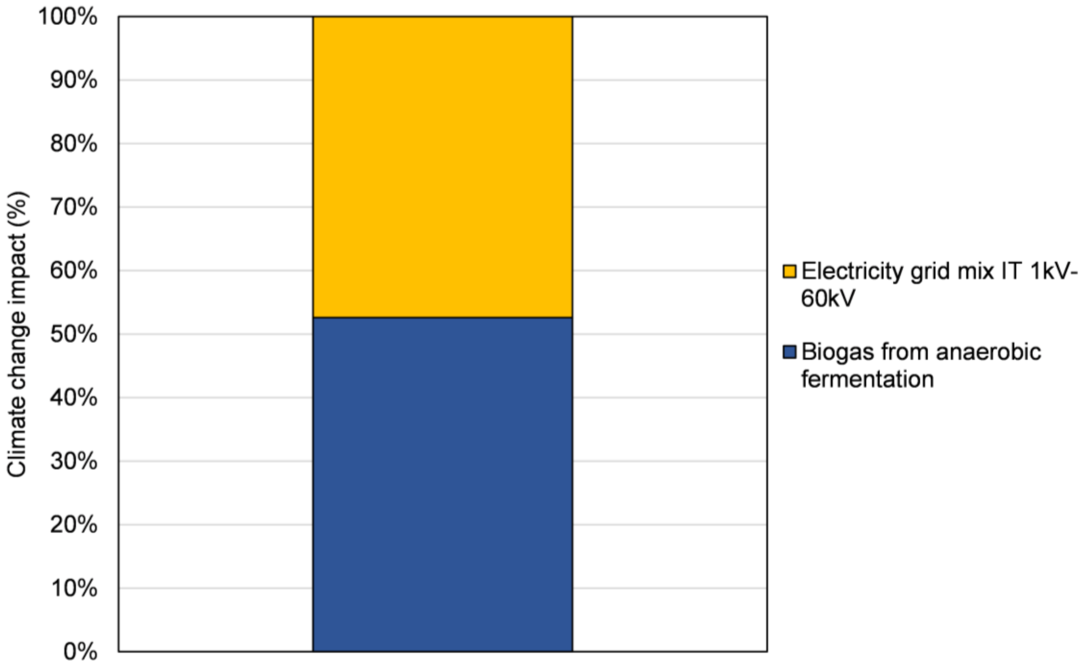

Figure 25: Operation contributors to climate change.

The biogas production from anaerobic fermentation is responsible for 52.6% of CO_2 eq. emissions, with electricity accounting for the rest part (47.4%).

In order to compare this step with the results reported in the next chapter, it is necessary to obtain an emission value related to the biogas treated. Therefore, for the CC is necessary to divide the kg CO_2 eq. produced during one year of the prototype work by the flow rate of biogas treated.

$$CC_{operation} = \frac{41267.24 \text{ kg CO}_2 \; eq.}{6 \; \frac{m^3}{h} * 24 \; h * 365 \; d} = 0.785 \; \frac{kg \; CO_2 \; eq.}{m^3_{biogas}}$$

The CC considered previously in the analysis is the sum of biogenic, fossil and land use climate change. For the operation phase due to the presence of anaerobic fermentation, it is interesting to analyse also the biogenic climate change. In fact, biogenic CO_2 emissions [22] are linked to the natural carbon cycle for materials of biological origin, so this CO_2 returns carbon to the atmosphere that was absorbed during plant growth. When only CC-biogenic is considered, the percentage impact of using biogas from anaerobic fermentation reaches 94.07%. As presented by the contribution tree in Figure 26, extracted from OpenLCA® software.

Contribution	Process	Amount	Unit
100.00%	BIOFIDS operation - IT	1542.11467	kg
94.07%	Anaerobic fermentation, production mix, at plant, anaerobic fermentation of biowaste, 1 kg of waste fermented...	1450.73726	kg
05.93%	Electricity grid mix 1kV-60kV, consumption mix, to consumer, AC, technology mix, 1kV - 60kV - IT	91.37741	kg
00.00%	BIOFIDS transport - IT	0.00000	kg

Figure 26: Biogenic-climate change of operation from OpenLCA®.

After analysing each phase to establish which processes have the greatest impact on CC, it is also important to study all the impact categories by using the cradle-to-utilisation approach.

So now, we proceed with the analysis of all intervening processes without distinguishing the three phases.

Table 11: Impacts for all flows.

Flow	**CC (kg CO_2 eq.)**	**FE (kg P eq.)**	**PM (items)**	**POF (kg NMVOC eq.)**	**OD (kg CFC-11 eq.)**
AISI316L and C85+Ni/P Fe	1497.11	0.0014	0.00018	4.13	1.22E-08
Polyvinyl + PVC	249.07	0.0029	4.55E-06	0.71	1.49E-07
PTFE	0.59	1.95E-06	2.02E-07	0.0011	1.92E-08
FPM	0.67	7.66E-05	3.65E-08	0.0012	9.98E-05
PTFE+NBR	0.19	5.94E-07	2.40E-09	0.00049	8.61E-12
Aluminium alloy	319.19	0.00047	1.39E-05	0.58	6.85E-08
Copper	2.85	1.15E-05	4.84E-08	0.0049	3.36E-10
Galvanised steel	7.24	5.86E-06	5.98E-07	0.013	2.78E-11
Polyethylene	26.38	0.00019	2.45E-07	0.019	2.00E-10
XPS	208.70	0.00054	3.11E-06	0.39	3.45E-09
PP	0.086	2.09E-07	2.35E-09	0.00015	3.03E-11
EPDM	0.027	4.99E-08	3.91E-10	4.71E-05	1.69E-12
Plastic (not specified)	2.28	4.90E-06	7.18E-08	0.0039	8.44E-10
Galvanised iron	181.27	0.00015	1.51E-05	0.33	2.91E-09
Aluminium	12.64	1.91E-05	5.03E-07	0.023	2.82E-09
PVDF	769.04	0.0025	0.00026	2.56	0.001
PRFV	386.73	0.015	2.26E-05	1.46	6.16E-07
Alloyed carbon steel	172.22	0.00013	1.51E-05	0.32	-5.12E-10

LEDs SMD	0.73	3.67E-07	1.31E-07	0.0033	1.51E-11
Compact sintered silicon	10.18	4.34E-05	1.01E-06	0.03	2.57E-07
Articulated lorry transport	14.54	0.00	1.5E-07	0.04	0.00
Biogas from anaerobic fermentation	21’703	1.42	0.0005	60.91	1.017E-06
Electricity grid mix IT 1kV-60kV	19’564	0.057	0.0003	25.03	1.87E-06

Considering all processes, the major impacts on CC are depicted in Figure 27. On the left side the largest contributors are shown, while on the right a zoom on the contributions that have been placed in the "Others" category is available.

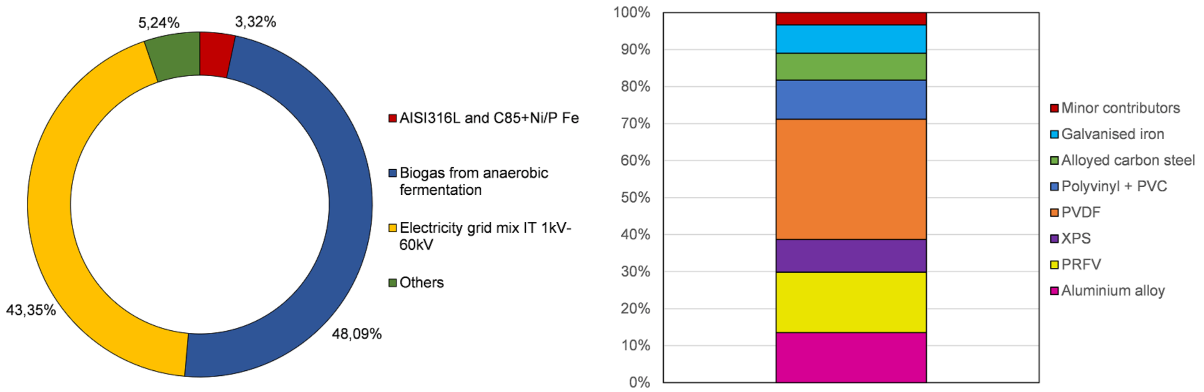

Figure 27: CC major and zoom on other contributors.

As already seen in the previous analysis, the largest contributions to CC come from biogas (48.09%), electricity (43.35%) and stainless steel (5.24%). In deriving the category "Others", all processes with a contribution lower than that of AISI316L and C85+NI/P Fe, were added together.

The same analysis is now done for the other impact categories chosen for this dissertation. The FE category is explored in Figure 28 by adding up the smallest contributions and showing them in the zoom on the right.

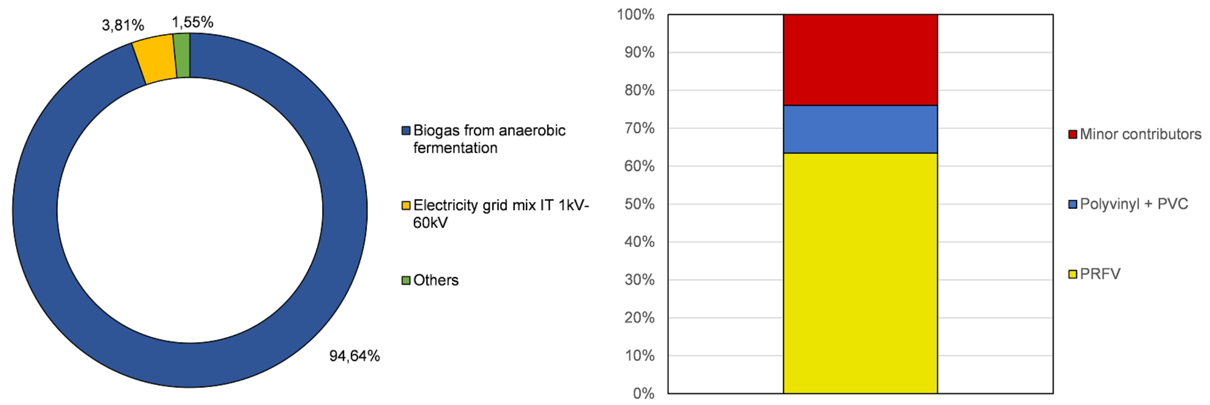

Figure 28: FE major and zoom on other contributors.

Also for phosphorus eq. emission (FE), the process causing the highest impact is biogas (94.64%), followed by electricity (3.81%). Among the other processes, more than 60% of the impact comes from PRFV.

The production of PM (Figure 29) depends mostly on four processes. The two most polluting processes are the same as for the other impact categories, namely biogas (38.83%) and electricity (22.44%). The other two largest suppliers are PVDF (19.25%) and AISI316L and C85+Ni/P Fe (13.63%).

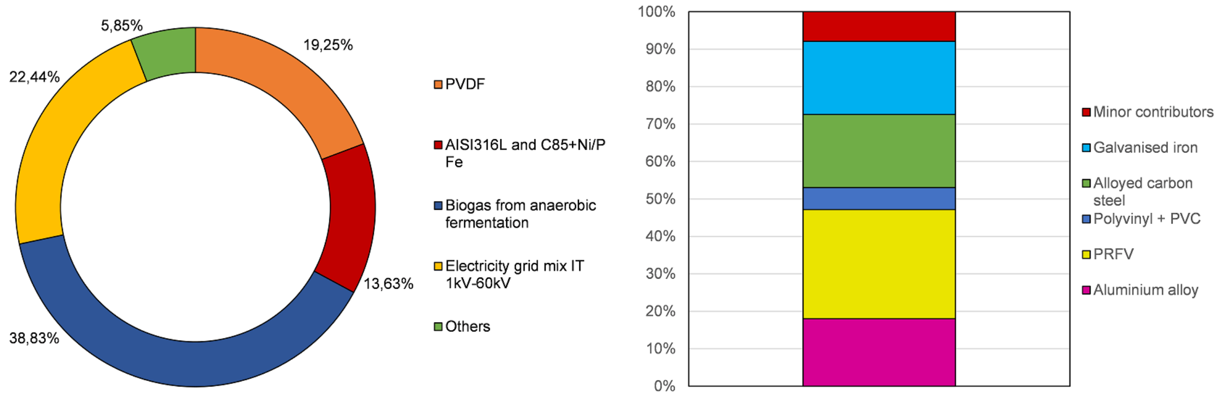

Figure 29: PM major and zoom on other contributors.

The graph on the right contains the summed processes within the "Other" category, which therefore have a lower percentage impact than the previous ones. Of these, it is clear that the most impactful are PRFV, alloyed carbon steel, aluminium alloy, and galvanised iron. In conclusion, together these four processes account for approximately 85%.

The impact of emissions of nitrogen oxides (NO_x) and non-methane volatile organic compounds (NMVOC) on human health is analysed. Hence, the major influences on the POF are given in Figure 30.

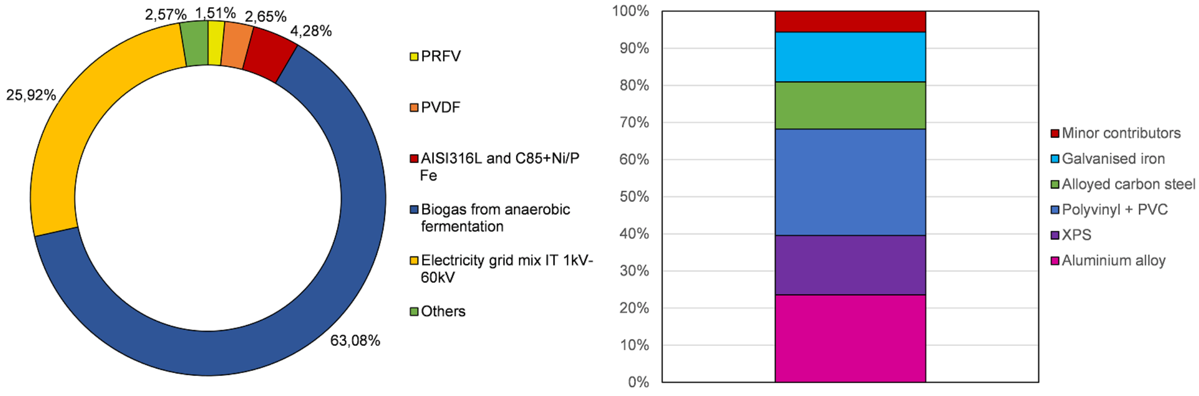

Figure 30: POF major and zoom on other contributors.

Biogas, electricity, and stainless steel have always foremost influence in environmental impact. Among the “Others”, the largest impact shares come from Polyvinyl+PVC and aluminium alloy. These two processes alone account for about 50% of the amounts represented on the right-side plot.

The last category to be analysed in this section is ozone depletion. The main causes of ozone depletion are chlorofluorocarbons (CFCs and HCFCs), in fact these compounds are transported into the stratosphere after being emitted from the surface. As regards the processes involved in the BIOFIDS prototype, the largest share of OD is originated by PVDF (91.71%).

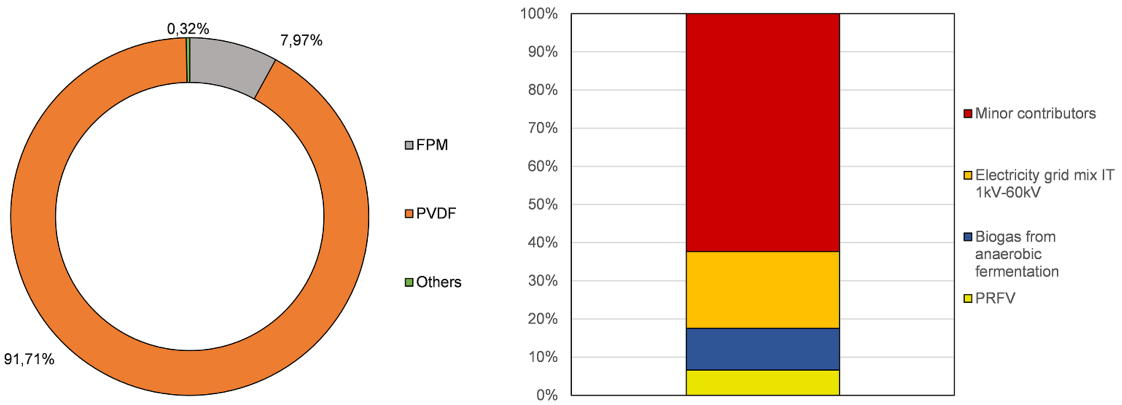

Figure 31: OD major and zoom on other contributors

The second process that acts 7.97% on OD is FPM, exactly how is displayed in Figure 31. Although biogas and electricity tend to be the most impactful processes, they are only included in the sum of "Others" for this impact category. Nevertheless, they cover about 30% of the total in the graph on the right. More than 60% is caused by all other processes included in "Minor contributors".

Overall, it is clear from the analysis that the most polluting processes, which are involved in the development of BIOFIDS, are: biogas from anaerobic fermentation, electricity, the of stainless steel and PVDF.

4.2 Comparison of the scenarios

The two scenarios to be compared with the base case have already been described in section 3.3 BIOFIDS modified cases. For the analysis is necessary to report the data, of the operation phase, extracted from the software in Table 12.

Table 12: Impacts for all scenarios.

Scenario	CC (kg CO_2 eq.)	FE (kg P eq.)	PM (items)	POF (kg NMVOC eq.)	OD (kg CFC-11 eq.)
Base	41’267.24	1.474	8.10E-04	85.94	2.88E-06
FU=90%	39’307.94	1.469	7.80E-04	83.43	2.70E-06
H_2S=2000 ppm	41’267.24	1.474	8.10E-04	85.94	2.88E-06

As can already be seen from the table, the BIOFIDS plant has the same impact on the environment with both clean and dirty biogas. To make the analysis easier, graphs are provided in the following paragraphs to compare the different scenarios.

In Figure 32 the three scenarios for the CC and OD are displayed. The *FU=90%* scenario produces a reduction of 6.5% on OD and 4.8% on CC. The CO_2 eq. emitted during the operation phase is due 55.2% to biogas from anaerobic fermentation and 44.8% to electricity. The percentage increase in emissions from biogas compared to the base case (52.6%) is of course the result of less electricity being consumed. As far as OD is concerned, the percentage of the impact of electricity on total emissions, in the case of reduced consumption, is about 62.3%. In the base case, the OD produced by electricity was 64.7%.

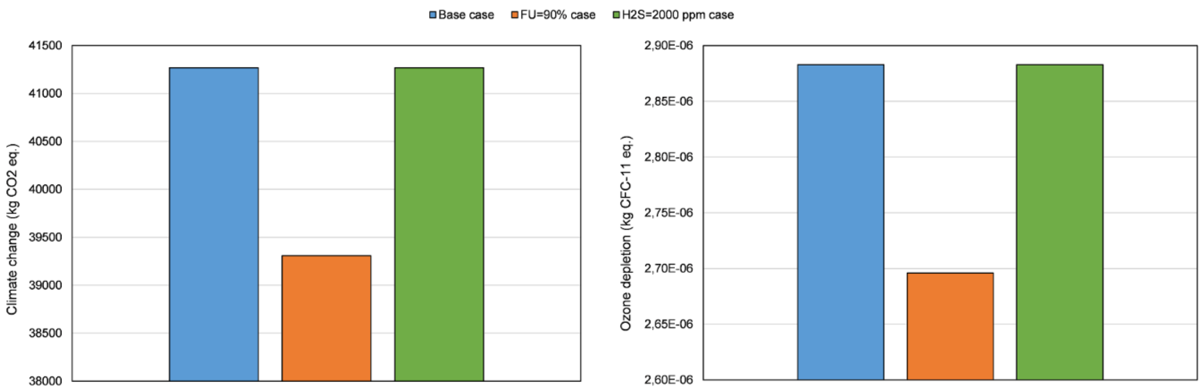

Figure 32: CC and OD scenarios comparison.

Instead, Figure 33 illustrates the PM and POF for all scenarios considered. The reductions shown for the case *FU=90%*, are smaller than those shown above. In fact, a reduction of 3.7% on particulate emission and 2.9% on POF is present. Particulate matter for the *FU=90%* case is produced for 65.8% by the biogas process, whereas in the base case the share of PM due to biogas was 63.4%. The NMVOC eq. emissions caused by biogas usage stands at 73% for the reduced electricity consumption case, while it is 70.9% for the base case. For these other two impact categories in the *FU=90%* scenario, the relative percentages of emissions from biogas are higher, but this is always due to the reduction in electricity consumed.

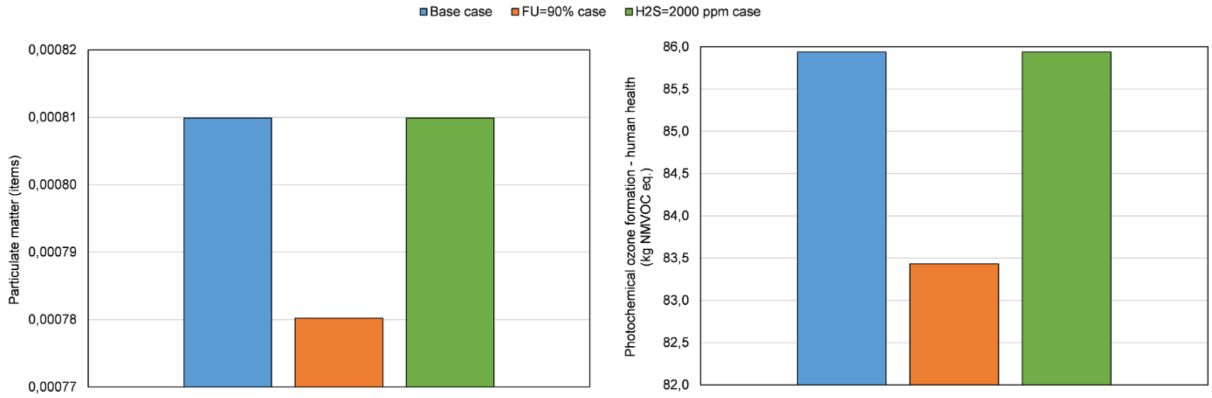

Figure 33: PM and POF scenarios comparison.

The last category analysed in the comparison is FE, for which the *FU=90%* scenario shows the smallest reduction (around 0.4%). Figure 34 compares the kg of P eq. emitted for the three scenarios used in the analysis. FE is mainly caused in all scenarios by the biogas process, respectively 96.1% in the base case and about 96.5% in the *FU=90%* scenario.

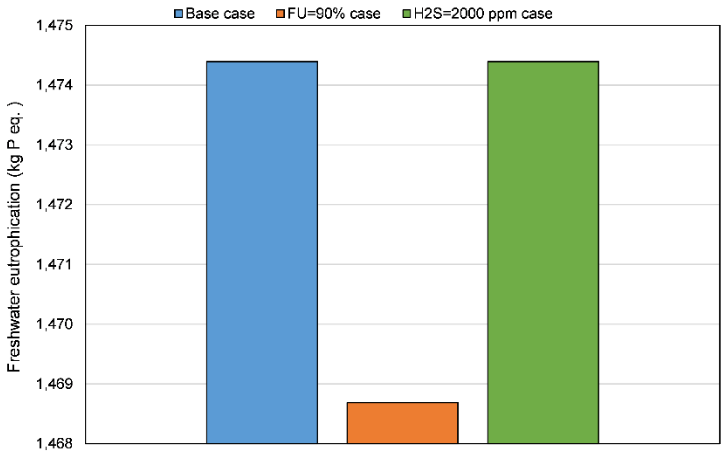

Figure 34: FE scenarios comparison.

In addition, a scenario closer to reality was analysed in which both reduced electricity consumption and dirtier biogas are fixed. In this additional scenario the emissions extracted by the software, for the five impact categories, coincide with those of the *FU=90%* case. So, it could be said that the reduction of electricity consumption has more influence on emissions.

5 Comparison with literature

Biogas desulphurisation is still an innovative topic. For this reason, there are not many articles dealing with LCA studies of desulphurisation systems, even conventional ones. Articles found in the literature concerning conventional technologies, for biogas clean-up and upgrade, are analysed in this section.

In contrast to the analysis done for the BIOFIDS prototype, the most widely used software in the literature are SimaPro and GaBi8. Furthermore, none of the studies presented the LCI of the construction phase, so it is assumed that the direct emission depends on the biogas treatment. To do the comparison is necessary to report (Table 13) the BIOFIDS operation base case results, in relation to the functional unit selected.

Table 13: Summary results of BIOFIDS base case operation with reference to 1 m^3 of biogas.

CC (kg CO_2 eq./m^3)	**FE (kg P eq./m^3)**	**PM (items/m^3)**	**POF (kg NMVOC eq./m^3)**	**OD (kg CFC-11 eq./m^3)**
0.785	2.80E-05	1.54E-08	0.0016	5.48E-11

C. Florio et al. made a LCA [8] based on biomethane production from waste feedstock. To upgrade the biogas, this study compares several conventional systems including MS, PSA, and high-pressure WS. Moreover, it is evaluated the environmental benefits derived from the use of biogas for the production of electricity and heat through a cogeneration system. In this case the Ecoinvent database v.3.4 is employed. The functional unit fixed is 1 m^3 of biogas produced from biogenic feedstock and a *cradle-to-gate* approach is used. The system boundaries are illustrated in Figure 35, in which all the upgrading scenarios under study are indicated. The LCIA method is the ReCiPe 2016 Midpoint (H) v.1.02, the impact categories used for the analysis are: climate change (CC kg CO_2 eq.), stratospheric ozone depletion (OD kg CFC-11 eq.), terrestrial acidification (kg SO_2 eq.), freshwater eutrophication (FE kg P eq.), human toxicity carcinogenic and non-carcinogenic (1,4-DCB eq.), mineral resource scarcity (kg Cu eq.), fossil resource scarcity (kg oil eq.) and water consumption (m^3). Only climate change, stratospheric ozone depletion and freshwater eutrophication could be compared with BIOFIDS LCA. Table 14 summarises the results in relation to the functional unit.

Table 14: Summary results in relation of m^3 of biogas [8].

Technology	**CC (kg CO_2 eq.)**	**FE (kg P eq.)**	**OD (kg CFC-11 eq.)**
MS	1.09	8.01E-04	3.51E-06
PSA	1.11	8.21E-04	3.55E-06
High pressure WS	1.11	8.20E-04	3.53E-06

The results obtained for BIOFIDS show a reduction in pollutant emissions. For CC, the new photobioreactor reduces CO_2 eq. emissions by 28% compared to MS and 29% compared to PSA and high-pressure WS. Furthermore, for both FE and SOD the reduction reaches values above 95% for BIOFIDS.

In this study, impacts are also assessed through the avoided burden, but these results are not reported because for BIOFIDS this type of analysis is not carried out.

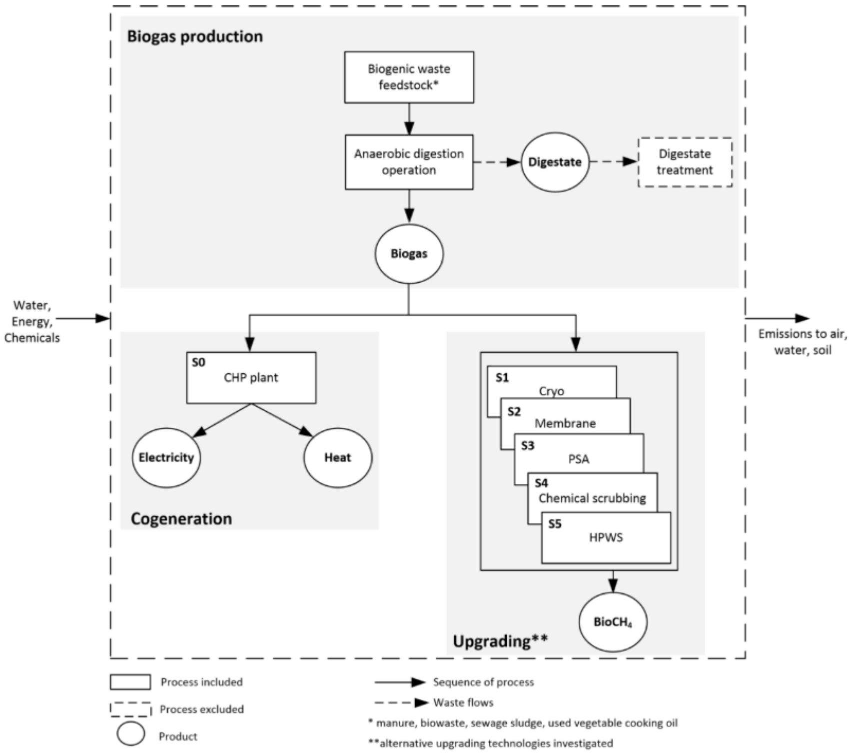

Figure 35: Schematic flowchart of the system analysed in [8].

A comparative review work is done by F. Ardolino [9] of the most utilised upgrading techniques is performance, with a focus on MS, WS and PSA. As a review, several studies are summarised, differing for example in the feedstock and/or the upgrading method used. In this paper are implemented LCA and life cycle costing too, and the data are obtained from Italian plants. The goal of this review is the quantification of the environmental and economic sustainability of biomethane production. The functional unit is set equal to 500 m^3/h of raw biogas, additionally, unlike the other studies mentioned, the boundaries are fixed as *gate-to-wheel*. This approach sets the starting point in biogas production and the end-point in methane combustion (in Figure 36).

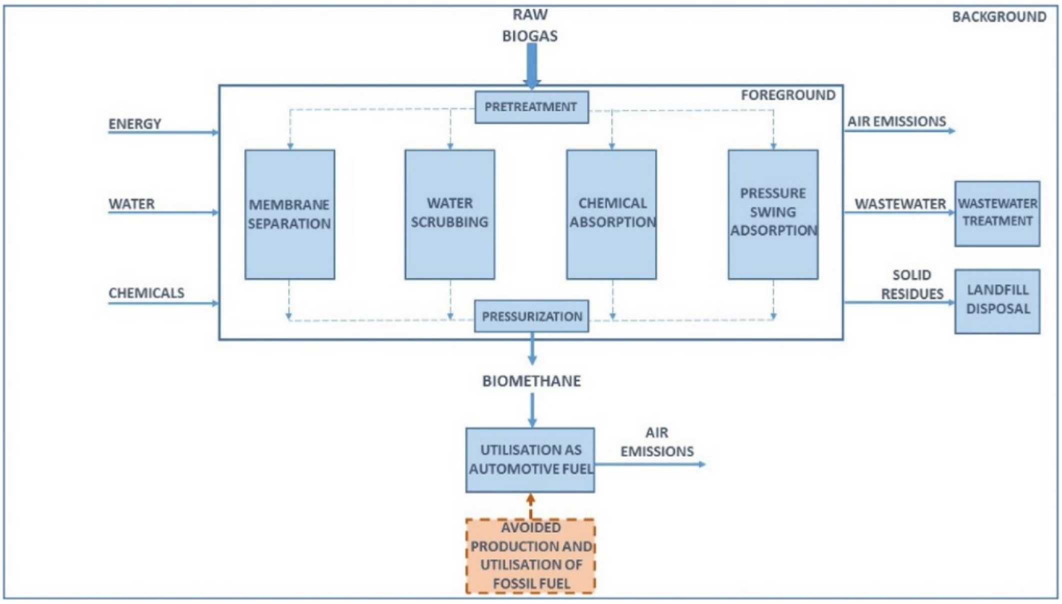

Figure 36: System boundaries of the review [9].

The Ecoinvent database v.3.3 with Impact 2002 LCIA method is adopted to do this comparison, and three impact categories are chosen. In particular, the reported values represent the environmental burdens (direct and avoided) for the scenarios. The air emissions, shown in Table 15 for each technology, are referred to the functional unit. The kg of CH_4 biogenic is an extra, which may be interesting even if it is not comparable in this dissertation.

Table 15: Summary results in relation to 500 m³/h of raw biogas [9].

Technology	kg CO_2 biogenic	kg CH_4 biogenic
MS	428.9	1.3
WS	431.1	2.7
PSA	431.1	3.3

Instead, the CC-biogenic is comparable with BIOFIDS unit. In fact, during one-year operation is emitted 1542 kg CO_2 biogenic by considering (6*24*365) m^3 of biogas, which correspond to 0.03 kg CO_2 biogenic per m^3 of biogas. While in this article is considered as reference 500 Nm_3/h of raw biogas, so is emitted between 0.85 and 0.86 kg CO_2 biogenic per Nm_3/h of raw biogas. Obviously, the flow rates are so different because the sizes of the plants are different, which may make the just calculated values not comparable.

P. I. Cano [10] investigates the LCA of different physical chemical and biological desulfurization technologies, and the biogas is produced from AD of sludge in wastewater plant. The conventional systems considered in this article are caustic chemical scrubbing and AC, and for the bio-trickling filtration for the biological type. The system boundaries are illustrated in Figure 37, as *cradle-to-grave* LCA approach. An unusual functional unit selected is selected for this study, namely the treated kg of S-H_2S to consider the H_2S inlet concentration and removal efficiency. ReCiPe Midpoint (H) LCIA methods is imposed, the impact categories selected are: climate change, terrestrial acidification, marine eutrophication, freshwater eutrophication, water depletion, photochemical oxidation formation and human toxicity. For the comparison, results of impregnated AC method are needed: CC equal to 42.1 kg CO_2 eq. and FE less than 250 mg P eq. Thanks to this study it is known that AC has less pollutant emission than the chemical scrubbing but has more emissions than the biological methods. Due to the unusual functional unit chosen for this study, the values extracted from the article are not comparable with those obtained for the prototype.

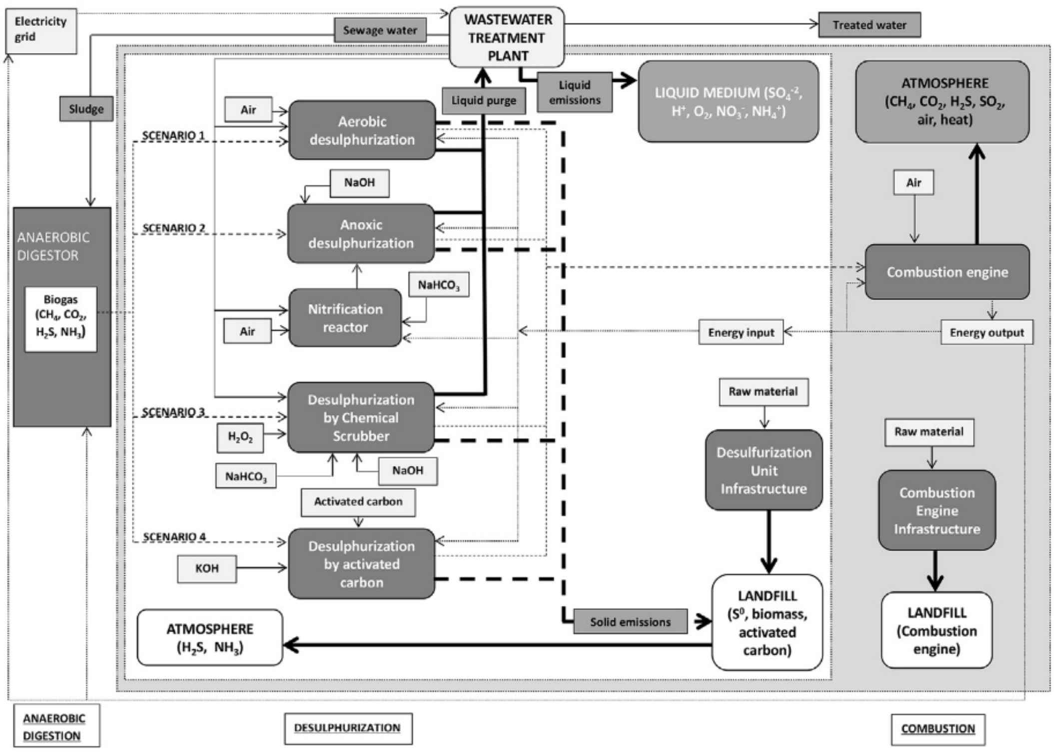

Figure 37: System boundaries of study [10].

An environmental and economic assessment is modelled by N. Kohlheb [11], with a focus on PSA technology. The analysed system is composed by a pre-treatment for H_2S and water removal, made bio-trickling, plus PSA for upgrading. The Ecoinvent database with CML impact categories is used for the analysis, which is normalized by CML2001 factors. The referring plant is located in Germany, with a treatment capacity of 32000 Nm^3 of biogas per day. The biogas, in this case, is derived from energy-crop based feedstock and has low concentration of H_2S. The impacts are calculated for a life cycle of 20 years and the functional unit is posed equal to 1 Nm^3 of biogas upgraded, in addition the system boundaries are fixed at *cradle-to-gate*. Highest environmental impacts were marine aquatic ecotoxicity potential, abiotic depletion potential and climate change. The principal values are: CC (100 years) equals 0.113 kg CO_2 eq., OD potential equals 0.64E-05 kg CFC-11 eq., and POF equals 2.184E-05 kg NMVOC eq. per year. The functional unit of this article is different to the one selected for BIOFIDS, in addition the study of long-term CO_2 emissions cannot yet be compared with the data obtained.

The last article is a relation made by G. Lorenzi [12], in which is performed a *cradle-to-gate* LCA of two upgrading systems and one of these is a high pressure WS. The water scrubbing column works at 10 bar and is made a partial recycle with a stripping column. Contrary to the other papers, in this analysis is considered both the plant manufacturing and the plant operation with an imposed annual capacity factor of 70%. The main material of the high pressure WS is the AISI316 steel as the BIOFIDS system. Moreover, three grid electricity mixes are assessed to simulate an increasing share of renewables, starting from a base case in which renewables have a share of 50%. ReCiPe Midpoint (H) LCIA method are used with Ecoinvent v.3 database, the functional unit is fixed at 1 Nm^3 of outlet biomethane. Results of interesting categories for high pressure WS are now written in Table 16:

Table 16: Summary results in relation of 1 Nm^3 biomethane [12].

CC (kg CO_2 eq.)	**FE (kg P eq.)**	**OD (kg CFC-11 eq.)**	**POF (kg NO_x eq.)**	**PM (kg PM eq.)**
3.92	4.34E-04	5.50E-07	5.96E-03	2.29E-03

The CC emission is an absolute value because in this study is considered even the avoided CO_2 production. For each impact category, more than 40% is caused by digestion and the second contribution is due to the scrubbing process, which is so similar to the results obtained for BIOFIDS.

Table 17, summarises the values extracted from the literature for conventional technologies and those for the BIOFIDS unit, to simplify the comparison. Remember that BIOFIDS impacts are based on one-year operation, while [11] are based on entire 20 years life cycle.

Table 17: Comparison between BIOFIDS and conventional system.

Functional unit	**Technology**	**Ref**	**CC (kg CO_2 eq.)**	**CC biogenic (kg CO_2 eq.)**	**FE (kg P eq.)**	**OD (kg CFC-11 eq.)**	**PM (kg PM eq.)**
1 m^3 biogas	MS	[8]	1.09	-	8.01E-04	3.51E-06	-
	PSA		1.11	-	8.21E-04	3.55E-06	-
	HPWS		1.11	-	8.20E-04	3.53E-06	-
500 m^3/h of raw biogas	MS	[9]	-	428.9	-	-	-
	PSA		-	431.1	-	-	-
	WS		-	431.1	-	-	-
kg of S-H_2S	AC	[10]	42.1	-	2.50E-04	-	-
1 Nm^3 of biogas upgraded	PSA	[11]	0.113	-	-	0.64E-05	-
1 Nm^3 biomethane	HPWS	[12]	3.92	-	4.34E-04	5.50E-07	2.29E-03
1 m^3 biogas	BIOFIDS	-	0.78	0.03	2.80E-05	5.48E-11	1.54E-08

6 Conclusion

This study analysed the impacts of the BIOFIDS unit, a novel photobioreactor which will be exploited for biogas desulfurization. The study aims to investigate the LCA of this new biological technology, which is developed by Tecnodelta Srl and subsequently will be installed in ACDA Spa site in Cuneo (IT). The analysis is performed by OpenLCA® software with the Environmental Footprints database. The LCIA method used is the Environmental Footprint (Mid-point indicator). The LCIA method has several impact categories, for BIOFIDS assessment are chosen five of these: Climate change [kg CO_2 eq.], Freshwater eutrophication [kg P eq.], Ozone depletion [kg CFC-11 eq.], Particulate matter [items of PM] and Photochemical ozone formation-human health [kg NMVOC eq.]. This work does not consider the end-life treatment of the plant, in fact is imposed a *cradle-to-utilisation* approach.

In particular, two scenarios were studied: the BIOFIDS unit, from construction to first-year operation, and the conventional clean-up systems. Results are referred to: mass of the constructed unit for the construction phase, item of the ready to work unit for the transport phase and the m^3 of biogas for the operation phase. Results obtained are very promising and prove that BIOFIDS can be an alternative to conventional desulphurisation systems.

The main impact of the unit construction is climate change, with an obtained emission of 3847.19 kg CO_2 eq. In this phase, the most impactful process is certainly the use of AISI316L and C85+Ni/P Fe, with an impact quote of 38.9%. Instead, the emission of the transport phase could be neglected for all impact categories. The operation phase is the most interesting for comparison with the literature and with the other cases. This phase has a major impact on climate change and freshwater eutrophication. During the work phase, 52.6% of emissions are caused by anaerobic fermentation and the other share (approximately 47.4%) by electricity production. Considering one year of operation with a flow rate of 6 m^3/h, approximately 0.78 kg of CO_2 eq. per m^3 and 2.80E-05 kg of P eq. per m^3 would be emitted.

Overall, it is clear from the analysis that the most polluting processes are: the anaerobic fermentation for biogas production, electricity, the utilization of stainless steel and PVDF. WWTPs produce biogas in order to stabilise the sludge coming out of the water line. Therefore, although it is a necessity to produce biogas, it is advisable to optimise all previous processes together with the biogas production to decrease the impact.

The climate change category used for the analysis represents the sum of biogenic, fossil and land use CO_2. Given the use of biogas from anaerobic fermentation, biogenic climate change was also analysed. In fact, in one year of operation nearly 1542 kg of CO_2 produced is biogenic, of which about 94% is due to biogas. However, the biogenic share is already part of the natural carbon cycle, so it may not be considered reducing BIOFIDS-related emissions any further.

In addition, two other modified cases are performed: one with reduced utilisation factor to 90% and one with a dirtier biogas. As concern dirtier biogas, results are about the same as those obtained for the base case, demonstrating that the photobioreactor works well even at high H_2S concentrations. The *FU=90%* case has better results in terms of impact, in fact is recorded the biggest reduction on ozone depletion (about 6.5%), as well as 4.8% on climate change and 3.7% on particulate matter production. Additionally, are registered minor reductions on photochemical ozone formation for human health of about 2.9% and on freshwater eutrophication of around 0.4%. These results show that the electricity mix and the amount of electricity used have an important environmental impact. Alternatively, harnessing electricity mainly from renewable resources could help.

The last step of the analysis was to compare the results obtained for the new prototype with articles in the literature. However, the subject matter is very innovative and for this reason, there are few articles in the literature on biogas desulphurisation or clean-up methods. The articles selected for comparison use different software, databases, and impact categories than the ones chosen for this discussion. The emissions of conventional systems found in the literature are generally higher than those obtained for BIOFIDS. Moreover, the BIOFIDS emission from the construction to the end of the life cycle (after 20 years) is now summarised in Table 18.

Table 18: Total life cycle emissions of the BIOFIDS unit.

CC (kg CO_2 eq.)	**FE (kg P eq.)**	**PM (items)**	**POF (kg NMVOC eq.)**	**OD (kg CFC-11 eq.)**
829’207	30	0.017	1729	0.0013

In addition to lower emissions, the new desulphurisation system has other advantages including the production of bio-sulphur. Maintenance costs are reduced, and disposal costs are zero due to the absence of special waste. In addition, there are no carbon replacements required as with some conventional systems, which reduces both costs and environmental impact.

Finally, it is possible to say that the BIOFIDS project can replace conventional methods. Although the costs of the technology have not been evaluated, the results concerning emissions are sufficient to demonstrate the feasibility of the project. Future work on this innovative desulphurisation method will certainly be necessary. In fact, it might be useful to calculate the impacts that the unit would have if a higher flow rate of biogas were used, i.e. closer to what could be achieved in the ACDA plant in Cuneo. Another interesting study could be done by installing the photobioreactor in a working plant (it would no longer be a prototype), perhaps also integrating a cost analysis that was not the subject of this study.

Bibliography

[1] “Energy Data Explorer - Our World in Data.” https://ourworldindata.org/explorers/energy?tab=chart&time=1969..latest&facet=none&country=ITA~OWID_WRL~Europe&Total+or+Breakdown=Total&Energy+or+Electricity=Primary+energy&Metric=Annual+consumption (accessed Feb. 16, 2022).

[2] bp, “Full report – Statistical Review of World Energy 2021,” 2021. [Online]. Available: https://www.bp.com/en/global/corporate/energy-economics/statistical-review-of-world-energy.html

[3] “Greenhouse gas emissions - Our World in Data.” https://ourworldindata.org/greenhouse-gas-emissions

[4] United Nations, “Communications materials - United Nations Sustainable Development.” https://www.un.org/sustainabledevelopment/news/communications-material/

[5] Eurostat, “Statistics | Simplified energy balances.” https://ec.europa.eu/eurostat/databrowser/view/NRG_BAL_S__custom_2039398/default/table?lang=en

[6] Jaro Jens, David Gräf, and Matthias Schimmel, “December 2021 A Gas for Climate report Market state and trends in renewable and low-carbon gases in Europe,” 2021.

[7] European Biogas Association, “EBA Statistical report 2021,” 2021.

[8] C. Florio *et al.*, “A life cycle assessment of biomethane production from waste feedstock through different upgrading technologies,” *Energies*, vol. 12, no. 4, Feb. 2019, doi: 10.3390/en12040718.

[9] F. Ardolino, G. F. Cardamone, F. Parrillo, and U. Arena, “Biogas-to-biomethane upgrading: A comparative review and assessment in a life cycle perspective,” *Renewable and Sustainable Energy Reviews*, vol. 139, Apr. 2021, doi: 10.1016/j.rser.2020.110588.

[10] P. I. Cano, J. Colón, M. Ramírez, J. Lafuente, D. Gabriel, and D. Cantero, “Life cycle assessment of different physical-chemical and biological technologies for biogas desulfurization in sewage treatment plants,”

Journal of Cleaner Production, vol. 181, pp. 663–674, Apr. 2018, doi: 10.1016/j.jclepro.2018.02.018.

[11] N. Kohlheb, M. Wluka, A. Bezama, D. Thrän, A. Aurich, and R. A. Müller, "Environmental-Economic Assessment of the Pressure Swing Adsorption Biogas Upgrading Technology," *Bioenergy Research*, vol. 14, no. 3, pp. 901–909, Sep. 2021, doi: 10.1007/s12155-020-10205-9.

[12] G. Lorenzi, M. Gorgoroni, C. Silva, and M. Santarelli, "Life cycle assessment of biogas upgrading routes," in *Energy Procedia*, 2019, vol. 158, pp. 2012–2018. doi: 10.1016/j.egypro.2019.01.466.

[13] "acda.it." https://www.acda.it/ (accessed Mar. 14, 2022).

[14] E. Luca *et al.*, "A novel photobioreactor system for hydrogen sulphide biogas clean-up 'A novel photobioreactor system for hydrogen sulphide biogas clean-up,'" 2017.

[15] "Programma Operativo Regionale Piemonte del progetto BIOFIDS," 2020. [Online]. Available: www.regione.piemonte.it/europa2020

[16] M. Gandiglio, D. Papurello, B. la Licata, and P. Zitella, "Relazione attività progetto Biofids."

[17] Anish Ghimire, Raju Gyawali, Piet N.L. Lens, and Sunil Prasad Lohani, "Technologies for removal of hydrogen sulfide (H2S) frombiogas," in *Emerging Technologies and Biological Systems for Biogas Upgrading*, Elsevier, 2021, pp. 295–320. doi: 10.1016/b978-0-12-822808-1.00019-2.

[18] S. Haider, A. Lindbråthen, and M. B. Hägg, "Techno-economical evaluation of membrane based biogas upgrading system: A comparison between polymeric membrane and carbon membrane technology," *Green Energy & Environment*, vol. 1, no. 3, pp. 222–234, Oct. 2016, doi: 10.1016/J.GEE.2016.10.003.

[19] Ellen Meijer, "Consider your audience when doing LCA - PRé Sustainability," Jul. 28, 2021. https://pre-sustainability.com/articles/consider-your-audience-when-doing-lca/ (accessed Feb. 24, 2022).

[20] "openLCA Nexus: The source for LCA data sets." https://nexus.openlca.org/database/Environmental%20Footprints (accessed Feb. 24, 2022).

[21] "SMB1N-760D." [Online]. Available: www.roithner-laser.com

[22] "Fossil vs biogenic CO2 emissions | Bioenergy." https://www.ieabioenergy.com/iea-publications/faq/woodybiomass/biogenic-co2/ (accessed Mar. 01, 2022).

Appendix

Equipment	Total weight	Materials and power	
Manual valves (HV01, HV06)	0.618 kg	AISI316L	0.606 kg
		Polyvinyl	6.18E-03 kg
		PTFE	6.18E-03 kg
Relief valves HV04	9.40 kg	AISI316L	8.46 kg
		AISI316L	0.799 kg
		C85 +Ni/P Fe	4.70E-02 kg
		FPM	4.70E-02 kg
		PTFE + NBR	4.70E-02 kg
Blower B01	13.0 kg	Power	0.550 kW
		Aluminium alloy	9.10 kg
		Copper	3.90 kg
		Filter	2.60E-02 kg
Pneumatic valve (CV02, CV04)	4.49 kg	Galvanised steel	0.18 kg
		Aluminium alloy	2.25E-02 kg
		Galvanised steel	2.25E-02 kg
		Aluminium alloy	1.57 kg
		AISI316L	2.69 kg
Tank S2	18.0 kg	Polyethylene	18.0 kg
Electro pump P02	18.0 kg	Power	0.75 kW
		AISI316L	17.8 kg
		AISI316L	0.178 kg
		EPDM	1.80E-03 kg
Pneumatic valve (CV01, CV05, CV06, CV07)	9.20 kg	Galvanised steel	0.368 kg
		Aluminium alloy	4.60E-02 kg
		Galvanised steel	4.60E-02 kg
		Aluminium alloy	3.22 kg
		AISI316L	5.52 kg
Non-return valve (RV01, RV02, RV03)	1.00 kg	AISI316L	1.00 kg
Demister D1	20.0 kg	AISI316L	19.8 kg
		PP	0.2 kg
Pneumatic valve CV03	2.60 kg	Galvanised steel	0.104 kg
		Aluminium alloy	1.30E-02 kg
		Galvanised steel	1.30E-02 kg
		Aluminium alloy	0.91 kg
		AISI316L	1.56 kg
Circulation pump P01	18.0 kg	Power	0.75 kW
		AISI316L	17.8 kg
		AISI316L	0.178 kg
		EPDM	1. 80E-03 kg

PHOTOBIOREACTOR			
Equipment	**Total weight**	**Materials and power**	
15 Flow controls (FIC)	2.25 kg	Plastic (not specified)	2.25 kg
15 Electric brush drives (M)	18.75 kg	Power	1.80 kW
		Copper	1.88 kg
		Plastic (not specified)	1.88 kg
		Galvanised iron	13.13 kg
		PVC	0.75 kg
		Aluminium	1.13 kg
15 Cleaning system	90 kg	PVDF	90 kg
15 Reactor pipes	70.5 kg	PVC	70.5 kg
15 Premix pipes	30 kg	PVC	30.0 kg
75 Diffuser/micronized	0.45 kg	Compact sintered silicon	0.45 kg
60 Pipe flanges	12 kg	PVC	12 kg
40 LEDs SMD	2.36E-03 kg	Power	16E-03 kW
Photobioreactor insulation	87 kg	XPS	87 kg
Manual valves (HV07, HV08, HV09, HV10, HV11)	0.4 kg	AISI316L	0.392 kg
		Polyvinyl	4.0E-03 kg
		PTFE	4.0E-03 kg
Circulation pump P02	18.0 kg	Power	0.75 kW
		AISI316L	17.8 kg
		AISI316L	0.178 kg
		EPDM	1. 80E-03 kg
Non-return valve RV04	1.00 kg	AISI316L	1.00 kg
Safety valve SV02	0.5 kg	AISI316L	0.499 kg
		EPDM	1.0E-03 kg
Clarifier C1	209 kg	PRFV	161.5 kg
		Galvanised iron	47.5 kg
Pneumatic valve (CV08)	4.49 kg	Galvanised steel	0.18 kg
		Aluminium alloy	2.25E-02 kg
		Galvanised steel	2.25E-02 kg
		Aluminium alloy	1.57 kg
		AISI316L	2.69 kg
Tank S3	18.0 kg	Polyethylene	18.0 kg

H_2S INPUT SYSTEM			
Equipment	**Total weight**	**Materials and power**	
H_2S tank	95 kg	Alloyed carbon steel	62.7 kg
		H_2S	32.3 kg
Safety valve SV01	0.5 kg	AISI316L	0.499 kg
		EPDM	1.0E-03 kg
Manual valves HV03	0.618 kg	AISI316L	0.606 kg
		Polyvinyl	6.18E-03 kg
		PTFE	6.18E-03 kg
Three-way valve HV02	0.8 kg	AISI316L	0.784 kg
		Polyvinyl	8.00E-03 kg
		PTFE	8.00E-03 kg
Pipelines	93 kg	AISI316L	93 kg