POLITECNICO DI TORINO

MASTER THESIS

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BIOMETHANE: A NEW OPPORTUNITY FOR A SUSTAINABLE DEVELOPMENT.

Analysis of the productive upgrading plant of Foligno by Asja Ambiente Italia S.p.A.

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Summary

The focus of the treatise is the production of biomethane as a result of upgrading biogas obtained from the anaerobic digestion of the organic fraction of municipal solid wastes. The main characteristics, with advantages and disadvantages, of the biogas and of the biomethane have been analysed, with a focus on the sustainable development goals and on the legislation aimed to incentive these new energy vectors.

Furthermore, the main technologies for upgrading biogas have been described, such as amine scrubbing, membrane separation, water scrubbing, organic physical scrubbing, pressure swing adsorption.

The technical data, used in the treatise, derives from the operation of the upgrading plant, situated in Foligno (PG) and managed by Asja Ambiente Italia S.p.A, whose processes have been analysed in depth. Foligno's plant consists in anaerobic digestion part, composting and upgrading, returning a produced flow rate of 499 Sm^3/h of biomethane.

An economic analysis has been provided finding a payback time of 8 years.

The last part of the treatise deals with the hypothesis of installing a carbon dioxide recovery process. The CO_2, actually injected in the atmosphere as an off gas with a flowrate of 370 Sm^3/h, can be collected, cleaned and sold to third parts.

1. Introduction

Biomethane is an energy vector obtained from the upgrading process of the biogas, which consists in splitting the CH_4 from the CO_2.

The exploitation of biogas and biomethane coming from wastes fits perfectly in the sustainable goals, imposed by the Agenda 30-30-30, and with the concept of circular economy, in which wastes are considered as new resources.

The two fundamental targets, around which community policy is structured, are: by 2020, 50% of urban and domestic waste, and 70% of construction and demolition waste, must be sent for recycling or reuse. These objectives give the opportunity to rise up new proposal, arising a public consultation that involved stakeholders at international level and that wants to bring order between the various directives on waste, landfills, packaging adjusting the guidelines based on the new environmental policy set by the 7th Environmental Action Program.

This new proposal sets challenging targets: in particular, the text envisages a 70% target for recycling of material by 2030, while the proportion of waste disposed of in landfill falls below 25%, by 2025 with a ban on the supply of recyclable and biodegradable waste (as such).

The goal at 2030 is the abolition of landfill disposal.

In this framework, the effort required comes both from companies and from every citizen, called to a responsible use of the goods, learning to extend the life of the products, taking care of them, repairing them, placing them, for those goods for which this is possible, in a virtuous circuit of donation, exchange or sale of used goods that can have a "second" life. From a production point of view, instead, companies are engaged in managed and innovative choices, efficient from the point of view of both energy consumption and the use of materials and raw materials, called in a strong reduction in their environmental impact.

The Foligno plant, managed by Asja Ambiente Italia, has been projected, constructed and brought into operation to fulfil the environmental and social requirements listed before. It is a plant system consisting of two different treatment lines: one to produce biomethane, one to produce compost. The biomethane productive part involves an anaerobic digestion plant of organic waste for the production of biogas It is a "closed system" in which fermentation takes place in a sealed environment. Biomethane is obtained through a subsequent step, called biogas upgrading.

The estimated biomethane production is 4 million Sm^3/y.

The second line is used for compost production: the project includes an area in which the material leaving the anaerobic digestion process, the digestate, is stabilized to produce compost with high fertilizer content for the soil.

The production of fertilizer (mixed composted soil improver) is equal to 15.000 t/y.

2. Biogas

Biogas is a renewable gas generated by the anaerobic digestion and gasification of organic matter: its main components are carbon dioxide (CO_2) and methane (CH_4).

Biomethane is obtained upgrading biogas, meaning that the carbon dioxide, which constitutes a large part of the raw biogas coming from the digestion process, is separated from the methane.

The main positive aspects of biogas rely both on its worldwide decentralized production and on the environmental benefits of avoiding methane emission to atmosphere while using bio-methane to replace fossil fuels.

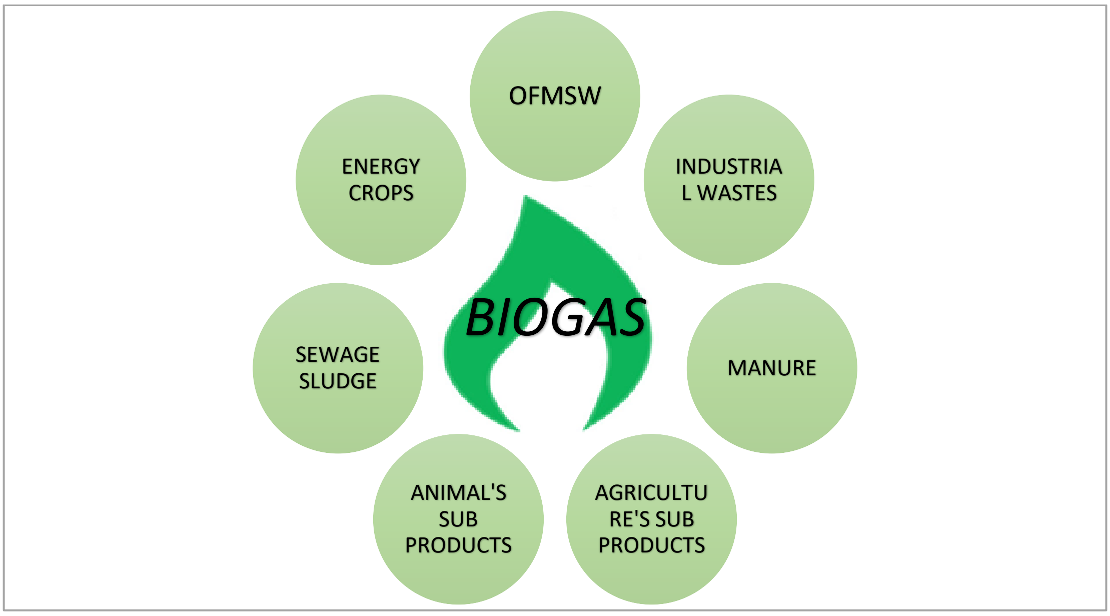


Figure 1: Sources for biogas production

2.1 Sources

Biogas derives from the digestion of organic material coming from agriculture, dedicated crops and various waste streams. Mainly, wastes are provided by fields, farms or cities.

Depending on the nature of the waste, the final biogas has different compositions in terms of methane, carbon dioxide and other compounds.

The organic wastes, that can be anaerobically digested, are:

- *Manure*, from breeding activities, divided in categories depending on the percentage of solid material contained. The composition changes according to the type of animal and to the breeding habits. It already contains micro-organisms responsible for biodegradation and anaerobic digestion creating methane, ammonia and carbon dioxide which are normally released into the atmosphere during storage.
- *Energy crops*, which are the biodegradable fraction of products, sub products and biological wastes coming from agricultural activities. The solid part contained in energy crops changes depending on the nature of harvest. For example, for corn silage, it usually is 32-34%.
- *Agriculture's sub products*, coming from agricultural activities, such as fodder, rotten fruit and vegetable and so on. There is a severe regulation which defines sub products and classifies them.

- *Industrial wastes*, which are the organic matter coming from different industrial processes.
- *Sewage sludge*, a by-product of urban wastewater treatment.
- *Animals sub products*, mainly deriving from meat slaughter. Recovering them can be a good opportunity for slaughtering companies, as they can use it as a resource instead of disposing it.
- *Organic Fraction of Municipal Solid Waste (OFMSW)*, which is the solid part of wastes from the recycling process coming from municipalities. The percentage of organic fraction contained in the OFMSW is between 60 and 70% depending on the accuracy of the recycling activities. Although, it also contains inert materials such as sand, plastic, glass and other fractions that cannot be digested. They must be separated from the organic fraction, creating an issue for the process with respect to other sources.

Figure 2: OFMSW entering in the Foligno plant, by Asja Ambiente Italia S.p.A.

Table 1: average composition and properties of natural gas and different biogas stream

Gas	**Biogas from farms**	**Landfill gas**	**Biogas from OFMSW**	**Natural gas**
CH_4 (%)	60-70	40-55	50-70	90 - 95
Hydrocarbons (%)	0	0	< 5 (ppm)	9
H_2 (%)	0	0-3	0	0
CO_2 (%)	30-40	45-60	35-45	1
N_2 (%)	About 0.2	0.5	< 1	0.3
O_2 (%)	0	0-5	0.3	0
H_2S (ppm)	0-4000	0-100	< 5	< 3
NH_3 (ppm)	100	5	< 10	0
Heating Value (kWh/Nm^3)	6.5	4.4	5.8	11.0

The main pollutants in biogas are the hydrogen sulphide (H_2S) and the siloxanes, which are organic silicon (Si) compounds which do not take part to the biological decomposition. Siloxanes are usually contained in landfill biogas in about 1.000 ppb and in OFMSW biogas in about 45 ppb.

2.2 Production

The biogas production from organic matters involves different anaerobic bacterial groups, which digest biodegradable material in the absence of oxygen.

The entire process can be divided into four steps:

1. *Hydrolysis*: carbohydrates, proteins and lipids, complex and non-soluble molecules, are cracked into monomers (water-soluble fragments) by bacteria. The covalent bonds are split in a chemical reaction with water.
$$\mathrm{AB} + H_2O \rightarrow AH + BOH$$
2. *Acidogenesis*: The monomers formed in the hydrolytic phase are processed by different bacteria and are degraded to short-chain organic acids plus alcohols. This phase is characterised by a significant decrease of the pH which causes an important smelling impact.
3. *Acetogenesis*: the acetogens bacteria transform the molecules into H_2, CO_2 and acetic acid. In this phase, the pH returns to normal values preparing the mixture for the next step, which indeed is the most important.
4. *Methanogenesis*: the methanogenic archaea transform the H_2 and acetic acid molecules into a mixture of CO_2, CH_4 and water. This can happen in two different ways:
    a. Direct reduction of the carbon dioxide:
    $$CO_2 + 4H_2 \rightarrow CH_4 + H_2O$$
    b. Degradation of acetic acid (70% of the production):
    $$CH_3COOH \rightarrow CH_4 + CO_2$$

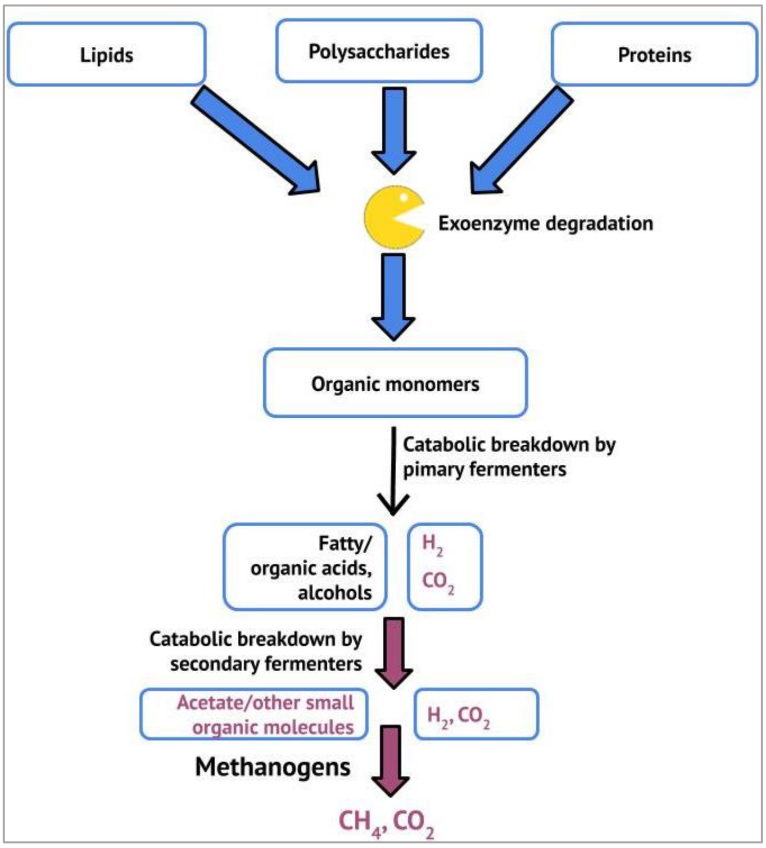


Figure 3: Process of biogas formation

The anaerobic digestion is realized in controlled volumes, called "digesters", at temperatures between 35 and 65 °C. Depending of the range of the temperature, the process can be classified into two different categories:

- *Mesophilic phase*: with temperatures between 35 and 45°C
- *Thermophilic phase*: with temperature between 50 and 65°C

With higher temperature, the production of biogas is enhanced, and it requires shorter residential time. However, the process is more unstable at high temperature and this can cause a significant variation from the normal stable conditions.

The technologies for the anaerobic digestion process are subdivided into three categories depending on the solid percentage of the inlet stream:

- Wet digestion process: the amount of dry substance is equal or lower than 10%
- Dry digestion process: the amount of dry substance is equal or higher than 20%
- Semi-dry digestion process: the amount of dry substance is in the range between 10 and 20%.

The outputs of digestion process are biogas and digestate. Biogas is mainly composed by methane, carbon dioxide, sulphur compounds, water and minor contaminants, the more valuable compound being the methane, since it can be used as energy carrier. The digestate is the organic material digested in the process. It can be reused in several ways.

2.3 Digestate and composting

The digestate is the result of the digestion of the organic matter during the anaerobic process and it is classified as the main sub product, even if it isn't a discard element. In OFMSW's plant, the digestate is processed to obtain compost.

Digestate from organic digestion form OFMSW can't be used as it is, as the Dlgs 2010/75 imposes, but it has to be processed through a composting sequence, in accordance with environmental preservation. Indeed, once it comes out from the digester, it is mixed with structuring material (mowing and green wastes). Then, it spends 14 days in the bio cells, it matures and becomes compost ready to be used.

The compost, which is one of the two final products of the plant is sold to farm and agricultural utilities as a fertilizer.

The composting procedure, applied to an existing plant, will be analysed in depth in the Foligno plant analysis.

A new legislation concerning fertilizers, published in the GU L170 – 25.06.19, has been approved and entered into force on the 15th of July 2019. It establishes that the digestate, under certain condition, can be used for agronomic porpoise as it is. This opens a new perspective over the composting process, which can be optimized or, in certain cases, avoided. The new regulation will be applicable after 3 years from the approval, so on the 16th July 2022.

Figure 4: Digested material from Foligno plant, by Asja Ambiente Italia S.p.A.

2.4 Advantages

The main *environmental advantages* are:

- Avoided emissions, turning into energy the CH_4 that the organic matter could have released in the atmosphere, if not processed correctly.
- Reduced or avoided impact of the molecules dispersed in the atmosphere which usually gives olfactory problems.
- Agronomic usage in land fields of a fermentable matter, from which the pollutants are removed while maintaining the fertilizing properties.

- More in general, the reusage of material which usually causes environmental problem for its disposal.

The main *energetic advantages* are:

- Reduction of the exploitation of fossil fuels and the decarbonization of the electrical productive process.
- Increase of energy produced from renewable sources according to the international and national standards.
- Promotion of the decentralized production of energy.
- The possibility to store the product, in the already existing natural gas grid, to be exploited during moments of higher energy demand.
- Constant production of energy, since it does not depend on natural activities.

The main *economic advantages* are:

- Creation of new job opportunities and of new research projects.
- Contribution to the reduction of the energetical dependence of our country from foreign policies.
- Reduction of the disposal tariff.

There are also some *disadvantages*: first, there is methane production, which is a flammable substance, so the authorization and management process are more complicated. The biogas formation is a biochemical process from wastes, which treatment is a delicate issue. There is the production of sub products which must be disposed or valorised with respect to the environmental and security laws and norms.

3. Biomethane: a new opportunity

Biomethane is an energy vector obtained from the upgrading process of the biogas, which consists in splitting the CH_4 from the CO_2. The biomethane can be exploited for *distribution in the gas pipes*, stocked for *refuelling vehicles* or it can be transported and stocked for *energy production* far away from the site of the productive plant.

Figure 5: Circular Economy

The production of biogas, for electrical energy production, and then of biomethane, had a great development in the last years, especially due to the objectives imposed from the Kyoto Protocol and from the Agenda 20-20-20, then updated to the Agenda 30-30-30, such as security of supply, competitive markets and sustainability of the resources. Renewable resources, such as biogas and its derivatives, fit perfectly in the goals of reducing emissions and progressively reducing the exploitation of fossil fuels. More in depth, the 2020 energy goals are to have at least a 20% reduction in CO2 emissions compared to 1990 levels, a reduction of 20% of the energy consumption deriving from renewables and a 20% increase in energy efficiency. They have led to the European Directive 2009/28/CE which deals with the Renewable Energy Sources.

Figure 6: Goals of the Agenda 30 30 30

Some time has passed since the first measure in this direction has been taken from the Italian government and from the European Policy in terms of renewable energy.

Nowadays, Italy has made real efforts in the decarbonization of mobility and transport, dealing with biofuels, especially with the most recent *decree*, stipulated in March 2018. After the confirmation of the decree, the requests for the connection of biomethane plant to the natural gas grid increased considerably.

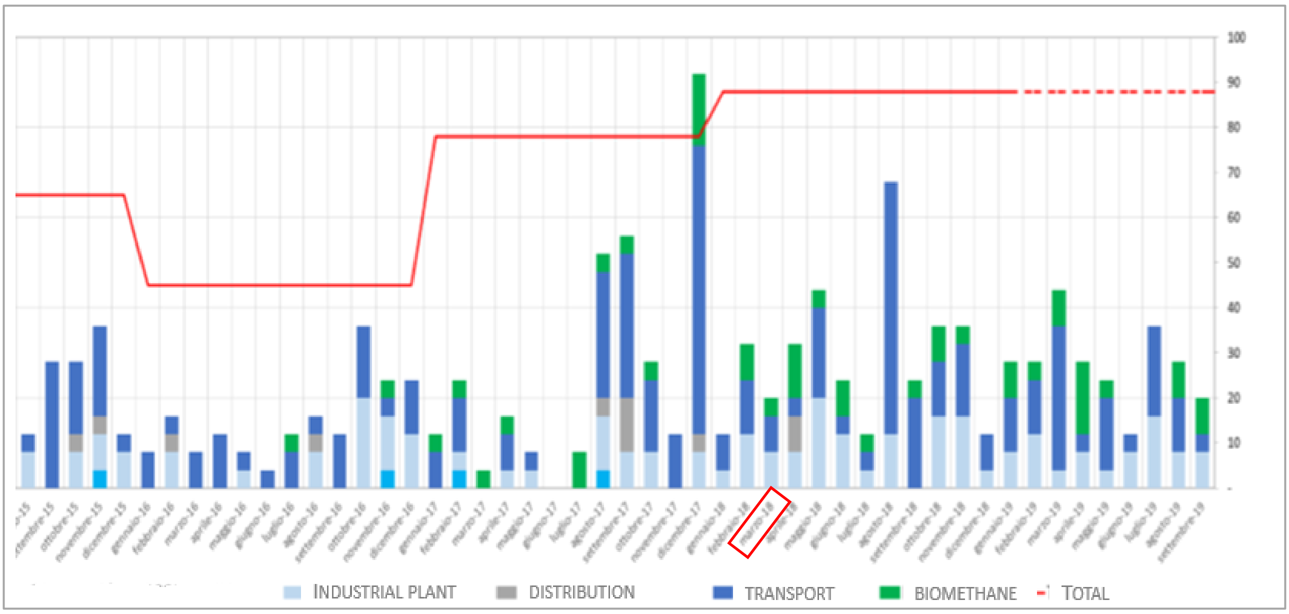


Figure 7: Trend of the requests of connection to the gas grid, Snam

Although the total emissions in Europe are decreased during the last years, the transport sector have experienced an opposite trend. For this reason, the decree stipulated in March 2018 focuses the attention on the production of renewable gas to be employed mainly in the transport sector. According to the Sustainable Development Goals, renewable fuels must be the 9% of the total, and the 10% of them have to be from advanced biofuels.

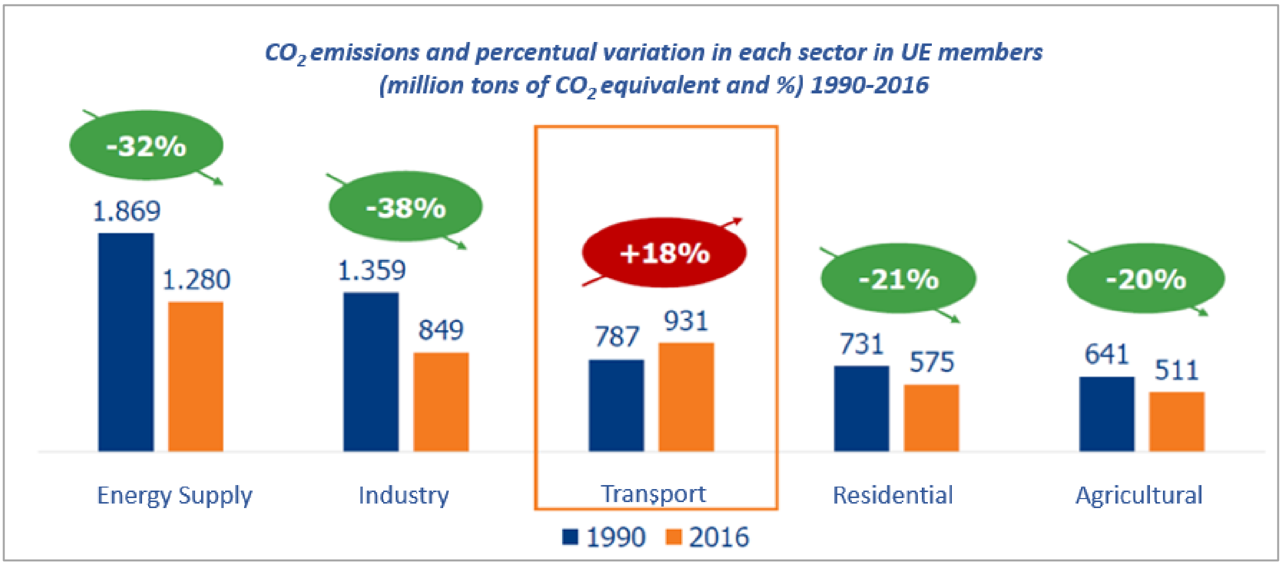


Figure 8: Trend of CO2 emissions and percentage variation for EU members, in 1990-2016, in million tons of CO2 equivalent.

Italy has imposed ambitious targets for the reduction of the emissions in the transport sector, having in mind that it is the second state in Europe for number of vehicles pro capita, after the Luxemburg.

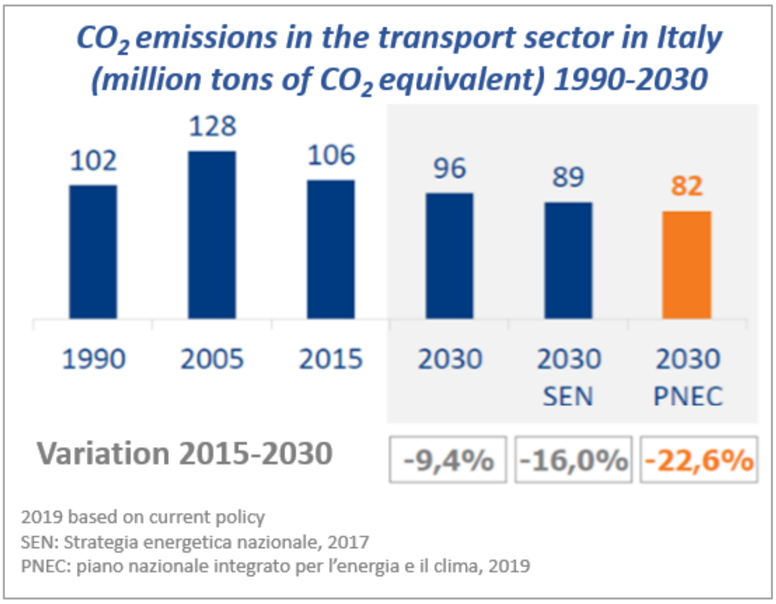


Figure 9: Forecast of the reduction of emissions in the transport sector in Italy, 1990-2030, in million tons of CO2 equivalent.

The usage of biomethane as a fuel has several advantages since it has very low emissions with respect to other fuels, cars are less noisy, and it can be mixed with natural gas in any percentage.

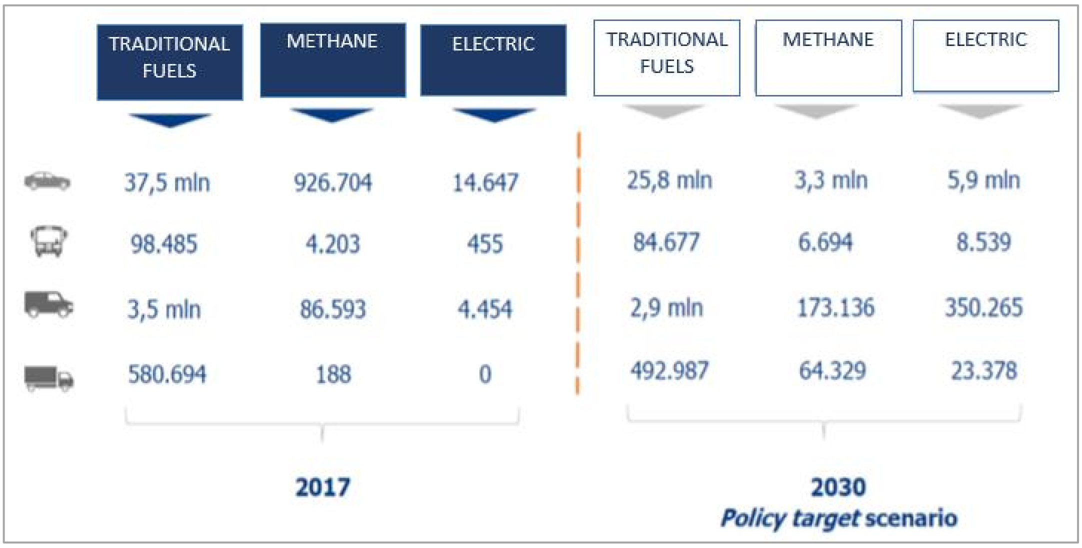


Figure 10: Development of the vehicles according to the policy target scenario

Apart from the vehicles' emissions, taking advantage of the gases produced from wastes also ensure the control and the management of substances which otherwise will be released in the atmosphere from the natural degradation of organic material. Methane has a GWP (Global Warming Potential) equal to 21÷28 (from the IPCC Climate Change, 2013) and it lasts in atmosphere for a decade, absorbing more energy than the CO_2. This means that the emissions of methane contribute to the global warming 21÷28 times more severely than the same quantity of carbon dioxide, which GWP is equal to 1.

Moreover, biomethane production also helps in the new perspective of the *circular economy*, where wastes from certain processes are considered resources for other ones. This is a good help for the agricultural factory, where also small and dislocated farms can produce biogas themselves or they can gain from the management and disposal of wastes from agricultural and animal origin.

The decentralized local production is a benefit for the reliability of fuels, free from external inconveniencies. The *safety of energy and fuel supply* and of the *economic independence* for Italy can be enhanced.

The main issues concerning renewables resources are the unpredictability and the impossibility to store them. In this case, the production of biomethane and biogas is *programmable and cumulable*. Research activities are active in developing new technologies and new paths for the storage of renewable energy, focusing on the Power-To-Gas with synthetic natural gas.

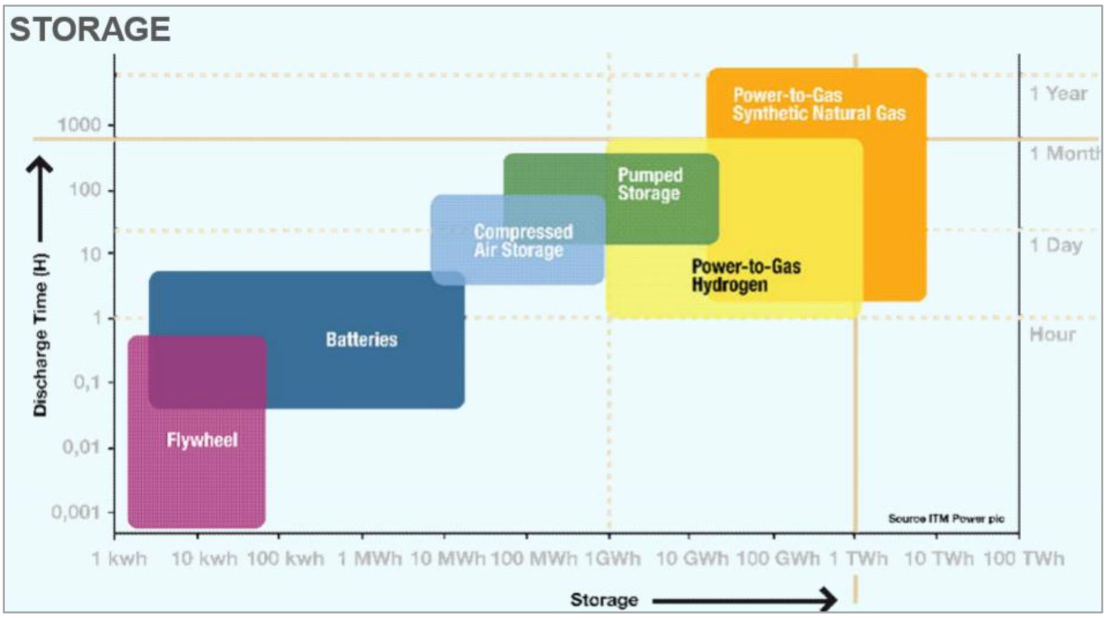


Figure 11: Development of storage technologies for RES

The **infrastructure** already available has a high capability of storage and a well-established capillarity of the grid, so the gas produced from renewable fuels can be easily brought to all the users without investing in the construction of a totally new infrastructure. Italy is particularly suitable for the introduction of biomethane in its economy since it has the most enhanced capillarity of the grid. Besides the length of the pipes grid, it is also equipped of storage directly on the grid.

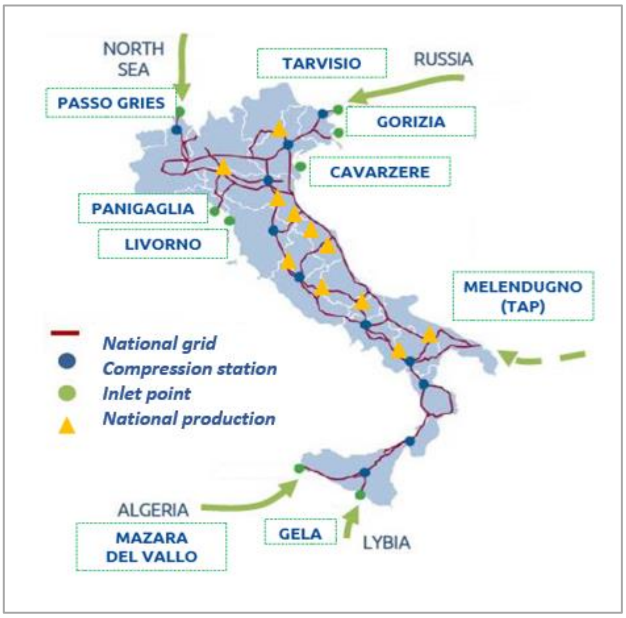


Figure 12: Snam natural gas grid

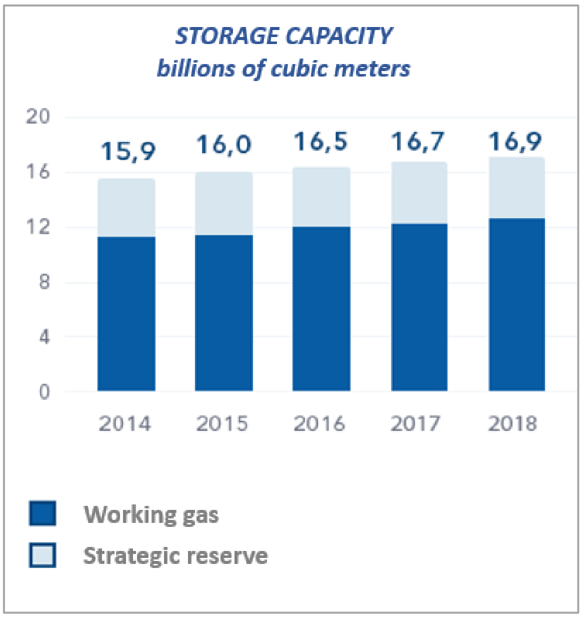


Figure 13: Storage capacity in Italy (Snam)

Due to the advantages that the production of biomethane, and since the government has recognized this opportunity establishing decrees for financial incentives, the production of biogas and its derivatives is expected to increase during the next years.

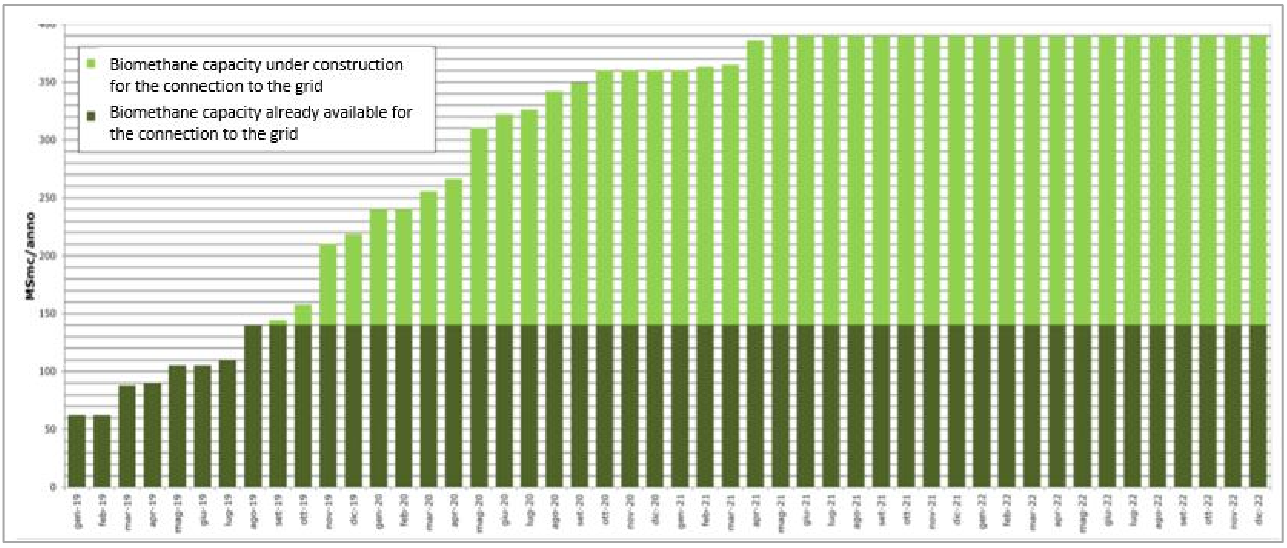


Figure 14: Capacity of connections for biomethane plants (Snam), up to 2022.

4. Policy and Financial Framework

In Italy, the biogas industry began to spread in 2008, thanks to the introduction of advantageous feed-in tariffs. They were subsequently replaced by less favourable feed-in premiums, leading to a stagnation in biogas production and derived heat and electricity since 2012.

Priorities have now shifted to biomethane production and the adoption of the ***March 2018 Biomethane decree*** is finally giving a strong boost to Italy's biomethane production, especially concerning the transport sector, supporting biomethane as a biofuel for green mobility.

Since the actual scenario guarantees a long-term role of biogas and biomethane, there is the strong necessity to be supported by full policy alignment, and thus a cost-efficient development of these fuels.

In the following part some of the main policies are described, with a particular attention to the ones concerning OFMSW and the advanced biomethane in the terms adopted in the plant managed by Asja Ambiente Italia, studied in the following chapters.

4.1 Policy on waste management

The waste management is a delicate procedure since it deals with material deriving from several matrices, different among each other, that can be dangerous in some cases or if treated in an erroneous way.

So, each plant dealing with waste treatment must be subjected to a strictly authorization process.

The European Union settled a directive to legislate waste management: *Directive 2008/98/EC.* It sets the basic concepts and definitions, such as definition of waste, recycling and recovery. It explains when waste ceases to be a waste and becomes a secondary raw material (so called end-of-waste criteria), and how to distinguish between waste and sub-products. The Directive lays down some basic waste management principles: it requires that waste has to be managed without endangering human health and harming the environment, and in particular without risk to water, air, soil, plants or animals, without causing a nuisance through noise or odours, and without adversely affecting the countryside or places of special interest.

The Directive requires that Member States adopt waste management plans and waste prevention programmes.

Italy responded to the directive, imposing legislation and requiring authorization for plants which deal with waste treatment.

Depending on the dimension, on the capacity and on the finalization of the plant, a different authorization is required. The most common are:

- *Unified authorization based on the Dlgs (legislative decree) 152/06*

Once approved, it is in force for ten years, it can be modified after five years, and it can be renovated. It identifies the conditions required to ensure the compliance of the principles of the article 178 and it includes at least the following elements:

  - Types and quantities of wastes that can be treated
  - Technical requirements for site compatibility, equipment used, types and quantities of wastes and how to verify, monitor and control the waste
  - The plant's compliance with the approved project

- The precautionary and safety measures to be taken
- The localization of the plant
- The method of each operation, provisions relating to the closure and subsequent interventions
- Financial guarantees
- Expiration date authorization and limits for the emission in the atmosphere in case of thermal treatment processes, also considering energy recovery.

- *Simplified procedure coming from art. 214 and 216 of the Dlgs 152/06*

Some recovery activities for non-dangerous (*DM February 1998*) and dangerous wastes (*DM 12 June 2002, n 161*) can get into operation after having performed a communication to the responsible territorial authority. The communication has to be renewed after five years or in case of substantial modification.

- *Ambiental Unified Authorization (AUA)*

It has been designed as a simplistic tool that includes several environmental standards required for a plant construction and operation.

- *Ambiental Integrated Authorization (AIA)*

It is applied to each installation, that can impact with emissions and pollution, and to each manager, which handles the installation and the operation of the plant. It is necessary for installations dealing with activities listed in the attachment VIII of the Dlgs 152/06, including waste management (category 5).

- *Evaluation of environmental impact (VIA)*

The process which includes the development and report of the environmental impact study by the proposer, the steps of consultations, the evaluation of the environmental impact study, any additional information provided by the proposer and consultations. The aim of the VIA is to assess environmental impacts to protect human health, to contribute a better environment which leads to better quality of life, to maintain species and to conserve ecosystems as resources. The VIA is not always necessary: to evaluate if it has to be provided, a screening procedure is previously done.

Concerning once again the Dlgs 152/06, which indeed includes all the specifications for the activities that can have an environmental impact, the attachment C lists the operation for waste recovery for electrical energy production (R1) and for composting and recovery of the organic substances not used as solvents (R3).

Another important classification is the CER, European classification of wastes, which identifies uniquely the wastes treated with a six-digit code.

4.2 Policy on upgrading biogas, in Italy

Upgrading the biogas is now completely recognized as a real possibility to promote the progress based on the exploitation of renewable sources and on the circular economy.

The UNI 16723-2 is the technical norm which sets quality specifications for biomethane to be used as a fuel for automotive vehicle engines and to be injected in natural gas network.

Table 2: Quality specifications of biomethane

Parameter	Unit	Limit Values	
		Min	Max
Higher Heating Value	MJ/Sm^3	34.95	45.28
Woobe index	MJ/Sm^3	47.31	52.33
Total volatile silicon (as Si)	mg_{Si}/m^3		0,3
Relative density	-	0.555	0.7
Carbon Dioxide	% mol/mol	-	2.5
Hydrogen	% mol/mol	-	2
Hydrocarbon dew point temperature (from 0.1 to 7 MPa absolute pressure)	°C	-	-2 (as in EN 16726)
Oxygen	% mol/mol	-	1
Hydrogen sulphide + Carbonyl sulphide (as sulphur)	mg/m^3	-	5 (as in EN 16726)
S total (including odorization)	mg_S/m^3		30
Methane Number	Index	65 (as in EN 16726)	
Compressor oil Dust Impurities	An amount that does not render the fuel unacceptable for use in end user application.		
Amine	mg/m^3		10
Water Dew Point *Classes are given to allow for climate dependent limits to be adopter nationally.*	Class A Class B Class C	-10°C at 20 000 kPa -20°C at 20 000 kPa -30°C at 20 000 kPa	

The Italian government published the legislative decree *Dlgs 28/2011* where the tools, mechanism, incentives and institutional and legal framework have been defined, introducing for the first time the term "biomethane". The art. 21specifically talks about the definition of biomethane. The art. 33 deals with biofuels for mobility in general, establishing that the injection of a certain quantity of advanced biomethane is equal to the injection of the double of the same quantity in case of injection of any other biofuel not advanced, concerning financial and legal requisites.

The market of the biomethane didn't take hold so a new decree gave the necessary boost for this technology: *March 2018 Ministerial Decree*. A recap of the main topics and mechanism is reported below.

4.2.1 Ministerial Decree of the 2 of March 2018

The ministerial decree is divided in 14 articles giving a complete framework for the biomethane production plant and for the feed-in tariffs. In particular, the Article 6 of the Decree incentivises producers of advanced biomethane. The biomethane is classified as "advanced" if it derives from specific raw materials, listed is the attachment number 3 point c of the decree of October 2014: “Organic waste as defined in the article 183, subparagraph 1, letter d), coming from the household collection and subjected to the recycling referred to in article 183, subparagraph 1, letter p), of the decree of the 3 of April 2006, n. 152.”

The decree, and its applicative procedures, gives the useful definitions, governs the operative procedures for the qualification release and the assignation of the financial incentives in favour of the biomethane and others advanced biofuels Productors.

The substances took into consideration in the Decree are:

- Biomethane injected in the natural gas grid without a specific usage destination
- Biomethane injected in the natural gas grid with transport sector destination
- Advanced biomethane injected in the natural gas grid and destinated to the transport sector
- Advanced fuels different from biomethane and intended for the transport sector
- Conversion of existing biogas plant.

The regulation for the injection in the natural gas grid is controlled by ARERA, which establishes that:

- The network operator has to accept the biomethane to be injected, excluding the process of odorization, if it responds to the technical specifications and other requirements.
- The biomethane productor guarantees that the biomethane to be injected respects the quality specifications, pressure and capacity constraints and assures that it can be treated to add smell.

The European Directives 2009/28/CE and 2009/30/CE introduced the concept of *sustainability* as a necessary condition for biofuels to have access to incentives, as well as to be counted towards the achievement of mandatory national targets directives themselves. The European Community has set standards for sustainable production of biofuels and bioliquids. Operators can demonstrate compliance with sustainability requirements by obtaining a certification of compliance that ensures the reliability of sustainability criteria, biofuel production chain and environmental and social information.

Figure 15: Symbol of methane fuel dispenser in Italy

The incentives are given to the production facilities that falls within the maximum annual production, referring to the individual plant and the single year of production of 150,000 tonnes, in cases of production of advanced biofuels other than biomethane, or 220,913,107.5 Sm^3, in cases of advanced biomethane production. The GSE also publishes annually, and updates semi-annually, an information newsletter with the list of facilities eligible for the requirements of the Decree with the indication of the type of materials used, the location and capacity production.

A *CIC* (Certificates of Input in Consumption) is the financial fees and it attests the injection of:

- 10 Gigacalories of non-advanced biofuel, including biomethane.
- 5 Gigacalories of advanced biofuel, including advanced biomethane.

The trade is regulated by the GSE. There are several types of contracts between GSE and the Productors. In the case interesting the study, the contract is the one requesting the withdrawal of the biomethane from GSE and the consequent attribution of the CIC. Considering the case of advanced biomethane only, the GSE gives to the Productor a value equal to the average prices weighted on the quantities, registered in the month of divestment on the natural gas market, reduced of 5% to take into consideration the costs of transport. The value of the corresponding CIC is giving each certificate a value of 375.00 €. Therefore, the price of the CIC, defined by the date of entry into operation, remains unchanged throughout the incentive period. It is a fixed value, while for non-advanced biomethane it changes due to natural gas market. This incentive mechanism is valid for 10 years from the entrance in operation of the plant.

The gain for the advanced biomethane Productor is indeed determined by the selling of the biomethane itself (that can be sold independently or withdrawn by the GSE) and by the value of the CICs.

The actors of the decree are mainly the productors and the *Obliged Subjects*. From 2018, the Obliged Subjects must fulfil an obligation fee through the introduction into consumption of advanced biofuels, proportionally to the energetic potential of the oil and gasoil introduced into consumption. In addition, the obligation must be fulfilled for 75% with advanced biomethane and the remaining 25% with other advanced biofuels.

Figure 16: Biofuel

Table 3: Increasing percentage of biofuels to be injected from Obliged Subjects

Year of release for consumption	Obligation percentage (both for advanced and non-advanced biofuel)	Obligation percentage (only for advanced biofuel)
2015	5,0%	-
2016	5,5%	-
2017	6,5%	-
2018	7,0%	0,6%
2019	8,0%	0,8%
2020	9,0%	0,9%
2021	9,0%	1,5%
2022	9,0%	1.85%

In order to manage the fulfilment of the obligation, the GSE gives the CIC to the Obliged Subjects that put sustainable biofuels into consumption.

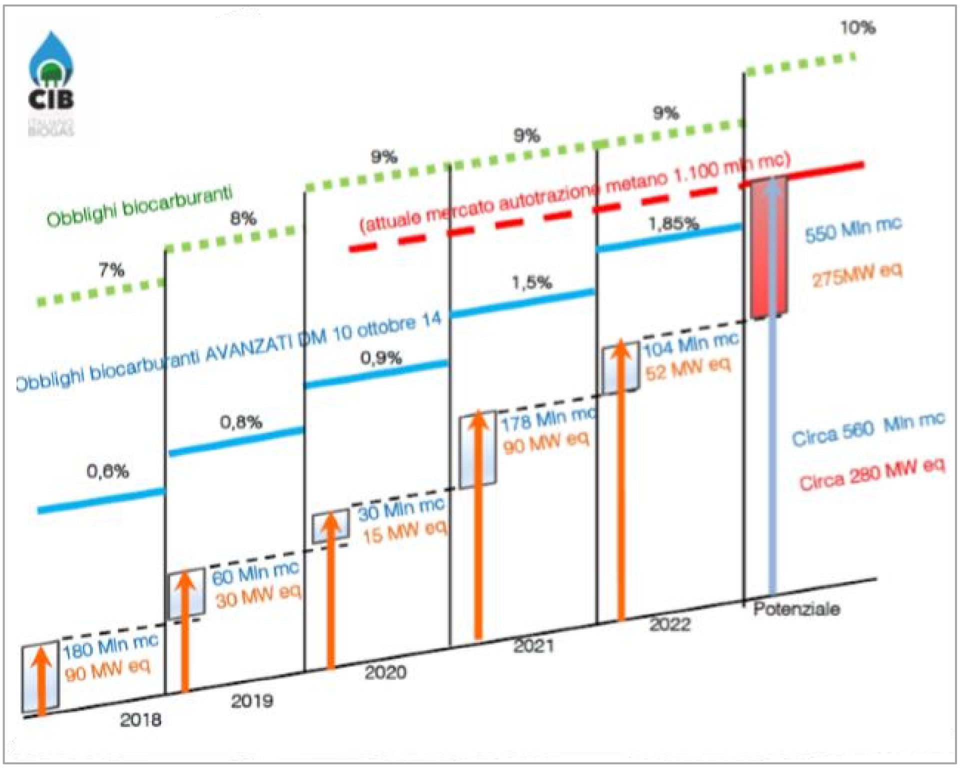


Figure 17: Representation of the injection of biofuels with the directive limits

For the introduction of biomethane transport, instead, the only parties that can obtain the CIC are the producers qualified under the Decree and not the Obliged Subjects who put it in consumption.

For biomethane production plants, both new and reconverted, the Decree sets a maximum limit of production, allowed to be incentivized, of 1.1 billion Sm^3 per year, considering both the biomethane and the advanced biomethane. In order to monitor the achievement of this limit, the GSE publishes and keeps up to date on its institutional website a counter of the production incentivised through the mechanisms provided by the Decree. When the 90% of the limit is reached, the GSE publishes a notice on its institutional website. From the date of publication of the notice, biomethane production plants that enter in operation within the next 12 months will be eligible for the incentive mechanisms provided by the Decree (Articles 5 and 6) except for the maximum limit of 1.1 billion of standard cubic meters per year.

Up to November 2019, the quantity of incentivized biomethane was equal to about 39 million standard cubic meters (4% of the maximum limit). In the same period, the GSE withdrew from the incentivized plants (biomethane and advanced biomethane) approximately 14.7 million standard cubic meters, for a value of over 2.8 million euros. The higher level of production and the maximum limit of 1.1 billion of standard cubic meters is still far from the actual framework.

INCENTIVAZIONE ASSOCIATA ALLA PRODUZIONE (ULTIMO MESE):	STIMA QUANTITÀ MASSIMA ANNUA RITIRABILE BIOMETANO AVANZATO:
5.377 CIC	388.107 CIC

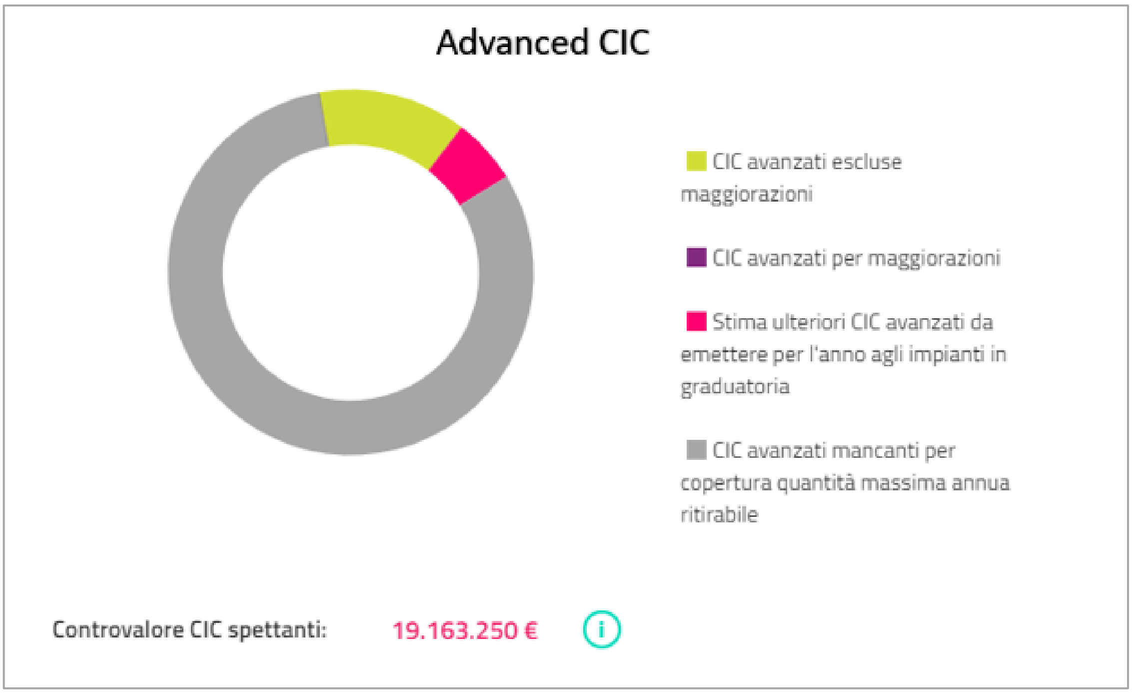


Figure 18: CIC already emitted with respect to the total capacity, November 2019

Example

An example is provided: introduction into consumption by grid for the transport sector without physical withdrawing.

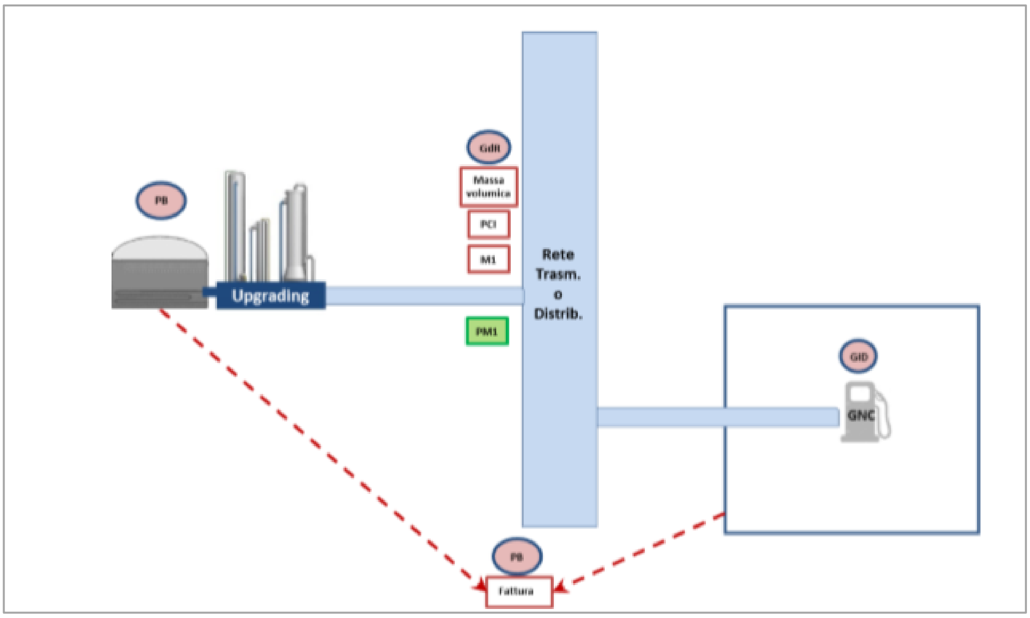


Figure 19: Scheme of the involved points of production and injection

The quantity allowed to be incentivized is calculated with the formula:

$$Ei_n = \min(M1_n; Fattura_n) * PCI_n$$

where

- Ei_n is the energy allowed to be incentivised in the month n;
- $M1_n$ is the quantity of biomethane produced in the month n;
- $Fattura_n$ is the quantity of biomethane valuable in the bills that has been effectively sold for transport sector
- PCI_n is the low heating value of the biomethane calculated with an average ponderation of the value registered in the month n.

The corresponding value of the CIC for advanced biomethane is calculated with the formula:

$$CIC_{advanced\ biomethane} = \frac{Ei_n}{5} + \sum_{p=1}^{P} M\ CIC\ distr_n^P + \sum_{p=1}^{L} M\ CIC\ liq_n^P$$

5. Upgrading technologies and infrastructures

The focus of this chapter is on the upgrading technologies for biogas, considering a mid-scale application, and on the currently available methods for transport and storage of biomethane.

The technologies for upgrading systems that are commercially available and in operation today are amine scrubbers, water scrubbers, PSA units, organic scrubbers and membrane units.

The scrubbing technologies all perform well and have similar costs of investment and operation. The simplicity and reliability of the water scrubber has made these as the preferred choice in many applications, but the high purity and the very low methane slip from amine scrubbers are important characteristics as well. Regarding to PSA and membrane, the investment cost is about the same as for the scrubbers.

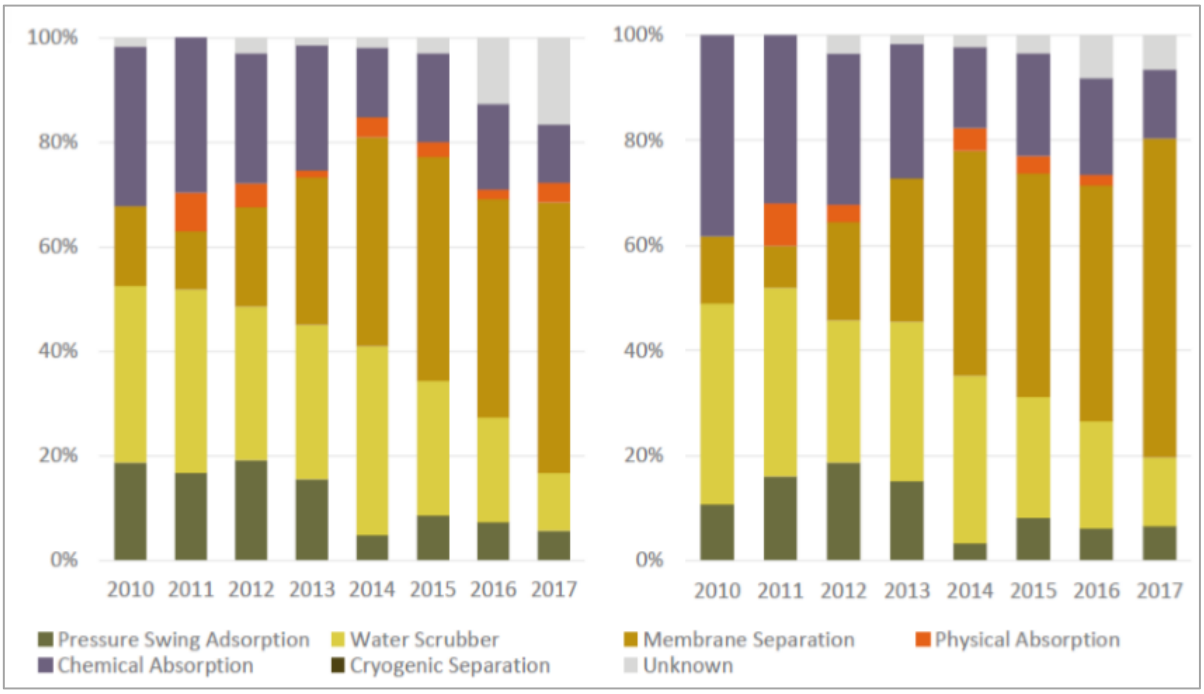


Figure 20: Development of existing and new plants and the respective upgrading techniques used on a total worldwide (left) and total European (right) scale. (Source: DMT - Environmental technology, 2018)

5.1 Description of the available upgrading technologies

5.1.1 Amine Scrubbing

The principle of this technology is to use a reagent that chemically binds to the CO_2 molecule, removing it from the gas. This process is performed using a water solution of amines (molecules with carbon and nitrogen), with the reaction product being either in the molecular or ion form. The most common amine solution available today is a mixture of MDES and piperazine (PZ) termed activated MDEA (aMDEA).

The technology consists of an absorber that removes the carbon dioxide from the biogas and a stripper that separates the carbon dioxide from the amine solution.

The driving force of the absorption may be mainly ascribed to the level of carbon dioxide in the gas as there is a surplus of amine in the system.

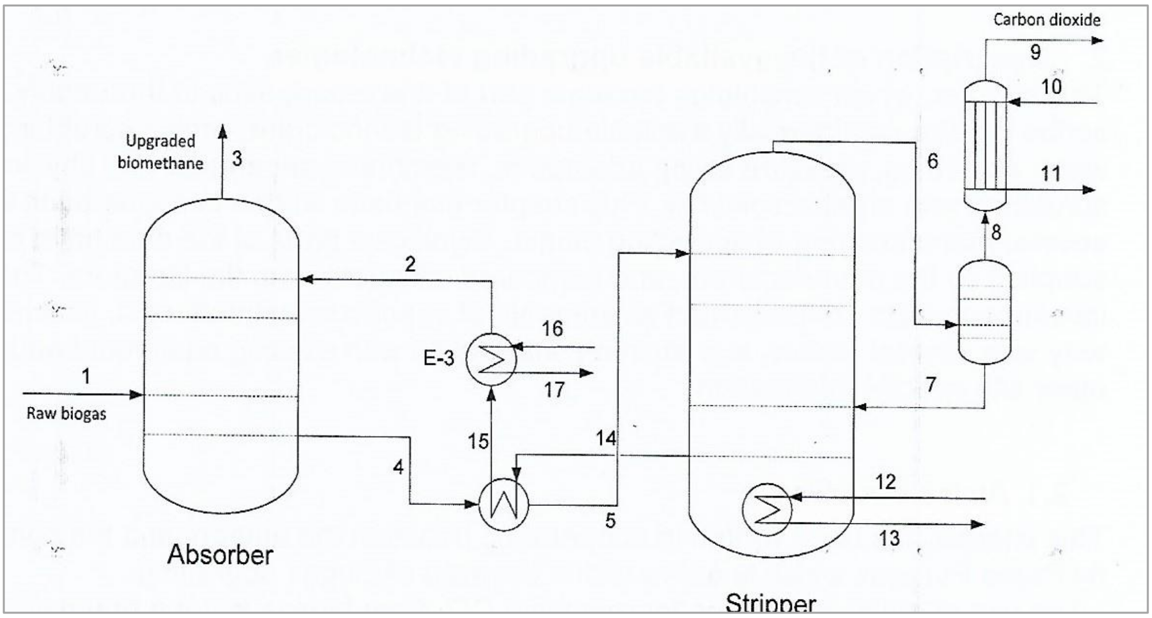


Figure 21: Amine scrubber process

The inlet stream enters the absorber from the bottom (1). In the absorber, the raw biogas flows through the amine solution. The carbon dioxide (and H_2S) part of the biogas reacts with the amine and is transferred from the gas to the liquid phase. This is an exothermic reaction that brings the solution from an inlet temperature of 20-40°C to 45-65°C. The absorption process is favoured by low temperatures from a thermodynamic standpoint but by higher temperatures from a kinetic standpoint. So, a good compromise is to be reached. The operating pressure of the absorber is 1-2 bar. The amine is fed in significant excess to the expected carbon dioxide content to avoid equilibrium constraints of the reaction. The product stream (3) exits in the top and contains mainly methane. The liquid exiting the absorber is preheated using the stripper exit stream (14) in the first heat exchanger. The liquid (5) then arrives to the top of the stripper column. Inside the stripper column, the liquid enters in a flash box where any carbon dioxide released in the first heat exchanger is removed. The liquid is then distributed and passed through a packing material where it is in contact with steam and carbon dioxide released further down in the stripper column. The bottom part of the stripper column is equipped with a reboiler in which heat is added (120-150°C) and part of the amine solution is boiled. The stripper pressure is 1.5 - 3 bar. The heat (12) supplied to the reboiler maybe hot water/oil or steam. The mixture of the release the carbon dioxide (and H_2S) and steam (6) exits the stripper column in the top and it is cooled in a condenser. The condensate (mainly steam but with traces of amine) is brought back to the stripper (7).

There is usually gas sweetening (H_2S removal) upstream of the system to avoid the smell and material issues downstream. The product gas will also have to be dried before being used.

The energy consumption for a specific application is around 0.12-0.14 $kWh/Nm^3_{raw\ biogas}$ for electricity and 0.55 $kWh/Nm^3_{raw\ biogas}$ of heat, to regenerate the amine.

5.1.2 Membrane separation

A membrane is a dense filter that can separate the components in a gas or a liquid down to the molecular level. In the biogas upgrading case, the membrane retains most of the methane while most of the carbon dioxide permeate through the membrane. During this separation, also water vapor, hydrogen and a part of the oxygen are removed from the biomethane. Their permeation rate mainly depends on the size of the molecules and on the hydrophilicity.

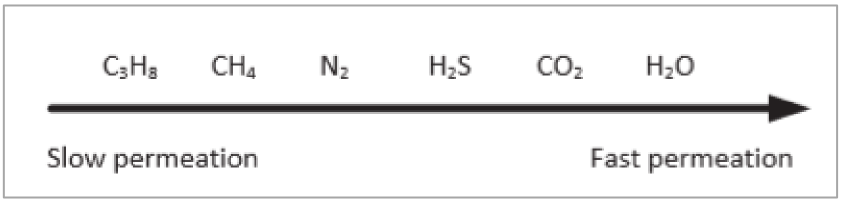


Figure 22: Relative permeation rate of different molecules through a membrane produced from a glassy polymer

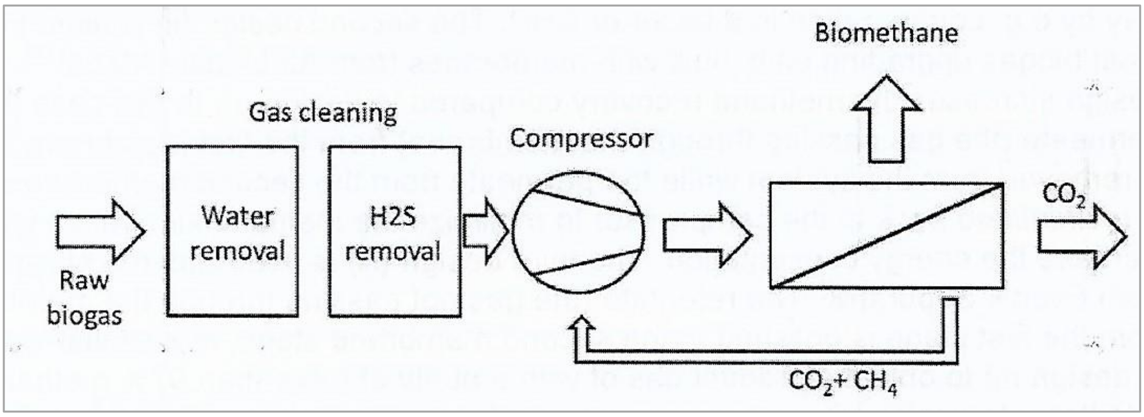
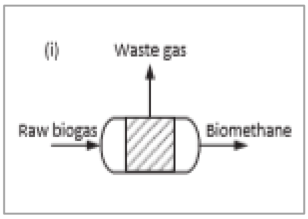


Figure 23: Design of a biogas upgrading unit with membranes

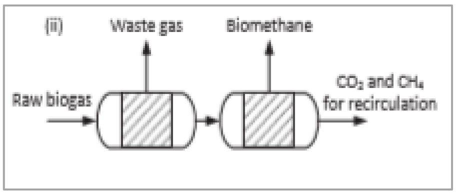
The raw biogas is normally cleaned before compression to remove water and hydrogen sulphide. In cases where ammonia, siloxanes and volatile organic carbons are expected in significant concentrations, these components are also commonly removed before the biogas upgrading. The water is removed to prevent condensation during compression and hydrogen sulphide is removed since it will not be sufficiently separated by the membranes. The water is commonly removed by cooling and condensation while hydrogen sulphide commonly is removed with activated carbon.

After that, the biogas is compressed to 6-20 bar, depending on the site specifications and on the manufacturer of the upgrading unit. Since oil lubricated compressors are commonly used, it is important to have an efficient oil separation after compression, also useful for removing the oil naturally occurring in the biogas.

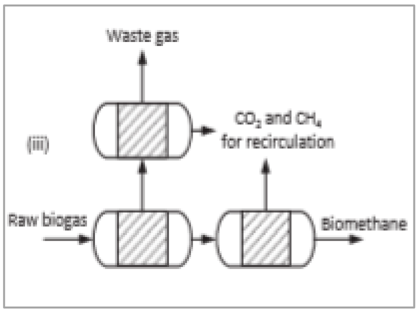
The membrane separation stage is usually designed in three different ways:



1) With no internal circulation of the biogas and lower energy consumption for the compression, but higher losses of methane. In this case it is important to use membranes with high selectively in order to minimize the methane losses.
2) The permeate from the first membrane stage is recirculated back to the compressor to minimize the methane slip which will increase the energy consumption.



3) The gas not passing through the membrane in the first stage is polished in the second membrane stage to obtain a product with a purity higher than the 97%. In this design, also the permeate from the first stage is polished in a third membrane stage to minimize the CH_4 concentration in the off-gas and the volume of gas circulated back to the compressor.



In a membrane unit, the main part of the remaining water after compression is separated from the biomethane together with the carbon dioxide, so a gas dryer is commonly not needed to further decrease the dew point.

Estimated life of the membranes is around 5-10 years. The energy consumption for a specific application (0.20-0.30 $kWh/Nm^3_{raw\ biogas}$) will depend on several parameters such as the methane slip, the required carbon dioxide removal, the installed membrane area and the applied pressure.

Figure 24: Membrane technology (TPI) in Foligno plant, by Asja Ambiente Italia S.p.A.

5.1.3 Water scrubbing

A water scrubber is a physical scrubber that uses the fact that the carbon dioxide has much higher solubility than methane in water. Carbon dioxide is separated from the raw biogas and dissolved in the absorption column using high pressure, normally 6-10 bar. The carbon dioxide is then released from the water again in the desorption column, by addition of air at atmospheric pressure.

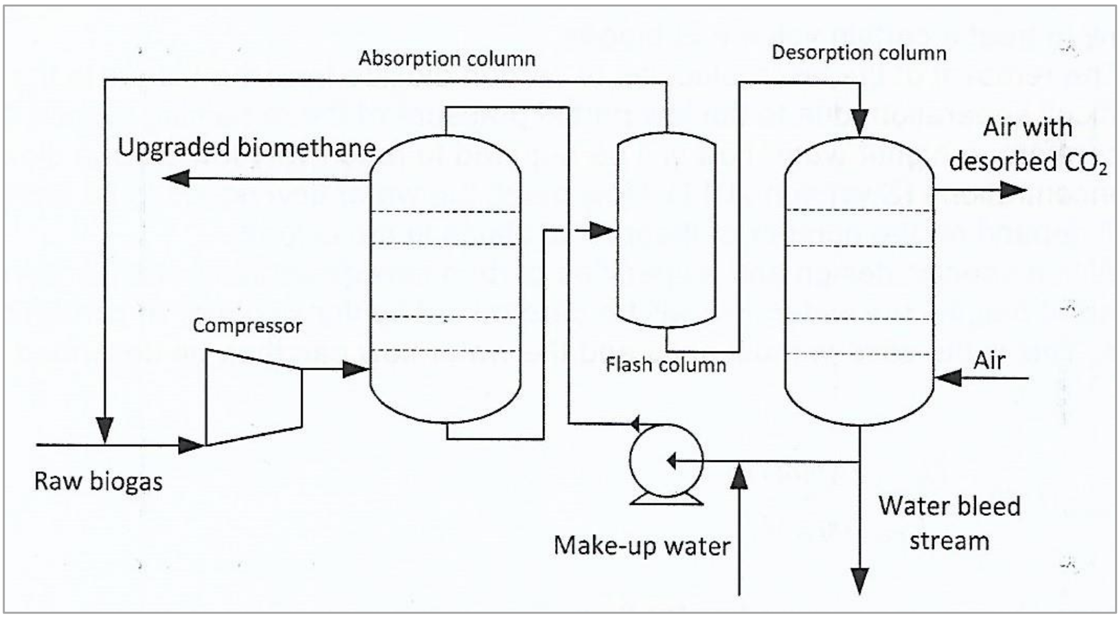


Figure 25: Water scrubber

The absorption of carbon dioxide and methane into water is described by Henry's law, which establishes the relation between the partial pressure of a gas and the concentration of the gas in a liquid in contact with the gas.

$$C_A(M) = K_H\left(\frac{M}{atm}\right) * p_a(atm)$$

The amount of water needed to remove a certain amount of carbon dioxide depends on the design of the column, the required carbon dioxide concentration in the upgraded biogas and the solubility of carbon dioxide in a certain volume of water determined by the pressure and the temperature. The removal of the last molecules of carbon dioxide from the biogas is the most difficult separation due to the low partial pressure of the remaining carbon dioxide, therefore a higher water flow will be required.

$$Q_{water}\left(\frac{l}{h}\right) = \frac{Q_{CO2}(g)\left(\frac{mol}{h}\right)}{C_{CO2}\,(aq)(M)}$$

The raw biogas has a temperature of 40°C when arriving to the upgrading plant. The pressure is increased to around 6-10 bar before it enters the absorption column. Then, only 5% of water content will remain. The pressurized biogas is injected to into the bottom of the absorption column and water is injected to the top of the column. Water and gas have a counter flow to minimize the energy consumption as well as the methane loss. The absorption column is filled with random packing. To avoid releasing the methane that is absorbed by the water in the absorption column, the water is transported into a flash column where the pressure is decreased to around 2.5-3.5 bar. After removing most of the methane from the water in the fresh column, the carbon dioxide is released from the water, which enters from the top of the desorption column, while air enters at the bottom. The required water flow depends on temperature and pressure.

Water scrubbing is the upgrading method on the market today that is the least sensitive to impurities. Although, due to the presence of microorganisms in the water scrubber, the random packing has to be cleaned before the unit can be started again.

The energy consumption is spent for compression, around 0.10-0.15 $kWh/Nm^3_{raw\ biogas}$ in modern applications operating at pressures around 6-8 bar, in the pumps, depending on the volume of water and on the efficiency of the pump and on the inlet and outlet pressure, and for by the cooling system, usually around 0.01-0.05 kWh/Nm^3.

5.1.4 Organic Physical scrubbing

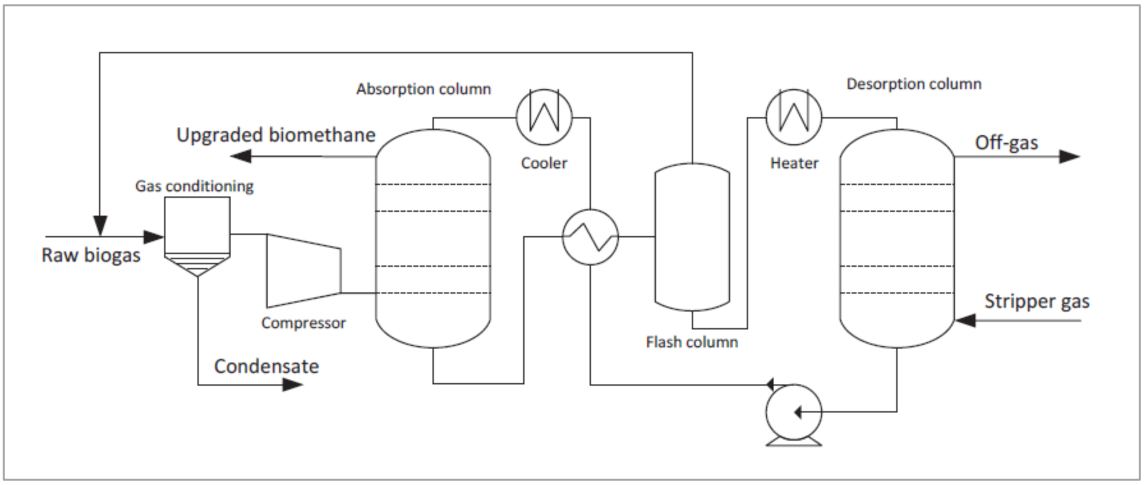


Figure 26: Flow diagram of a typical organic physical scrubbing

In organic and physical scrubbing, the carbon dioxide in the biogas is absorbed in an organic solvent. The absorption is described by Henry's law, in a way similar to the water scrubbing one. Due to the higher salinity of carbon dioxide in the solvent, the volume of solvent that must be recirculated in the system decreases significantly compared to water scrubber.

The process is designed in a similar way as a water scrubber with two main differences: the diameter of the columns is smaller since lower flow of the organic solvent is required, and the organic solvent has to be heated before desorption and cooled before absorption. The biogas is compressed to 7-8 bar and then cooled before it is injected into the bottom of the absorption column at around 20°C. The carbon dioxide is absorbed through the organic solvent and the upgraded biogas is dried before it is delivered to the gas grid or the fuelling station.

The organic solvent that is leaving the bottom of the absorption column is the heat exchanged with the organic solvent that will be injected to the top of the column. Thereafter, the organic solvent is injected into the flash column where the pressure is decreased. The main part of the dissolved methane is released in circulated back to the compressor.

To regenerate the solvent, it is further heated to reach around the 40 degrees.

The consumptions needed for the process are fuel and activated carbon required for the removal of hydrogen sulphide. The energy consumption to upgrade biogas with an organic physical scrubber is similar to that of a water scrubber and the same components (compressor, cooler and feed pump) are the main energy consumers. Compared to the water scrubber, the feed pump consumes less energy in an organic physical scrubber due to the lower flow rate. Just as for the water scrubber, the energy consumption will depend on the size of the unit, but not on the methane concentration in the raw biogas.

5.1.5 Pressure swing adsorption

Pressure swing adsorption is a dry method used to separate gases via physical properties.

In a PSA unit, an adsorbent material is subjected to pressure changes to selectively adsorb and desorb CO_2.

The raw biogas is compressed to an elevated pressure (4-10 bar) and then fed into an adsorption column where an adsorbent material retains the carbon dioxide but not the methane. When the column material is saturated with carbon dioxide, the pressure is released, and the carbon dioxide can be desorbed and led into an off-gas stream. For a continuous production, several columns are needed as they will be closed and opened consecutively. PSA unit characteristics include feeding pressure, purging pressure, adsorbent, cycle time and column interconnectedness among other things.

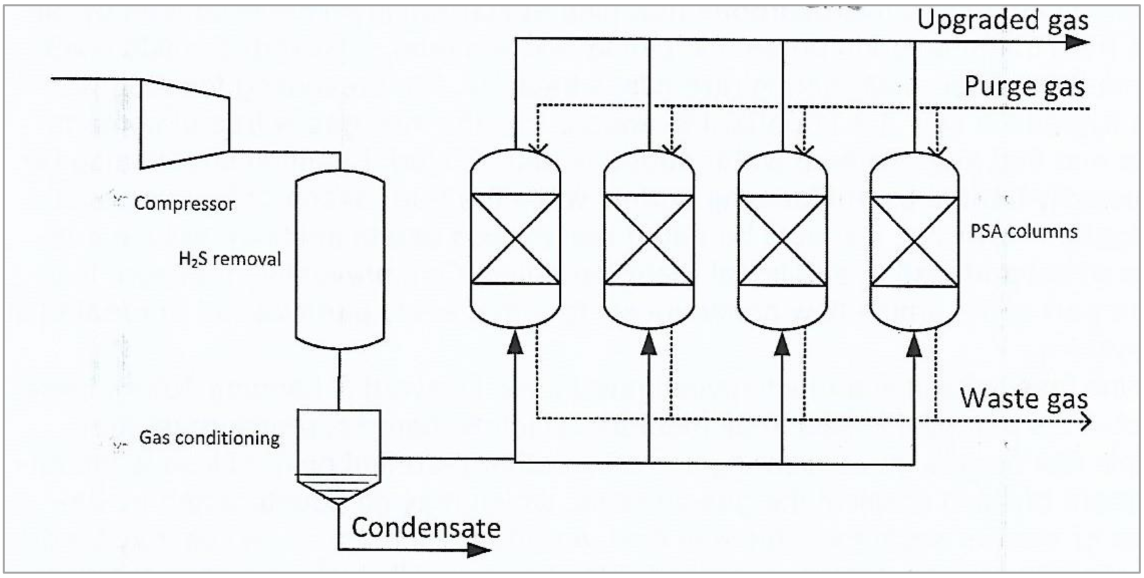


Figure 27: Process diagram of PSA

The process can be from two to ten minutes long and it principally consists of the four phases:

1. Pressurization
2. Feed
3. Blowdown
4. Purge

During the feed phase, the column is fed with raw biogas. The carbon dioxide is adsorbed on the bed material while the methane flows through the column. When the bed is saturated with carbon dioxide the feed is closed and the blowdown phase is initiated. The pressure is decreased considerably to desorb the carbon dioxide from the adsorbent and the carbon dioxide rich gas is pumped out of the column. Some methane is lost with the desorbed carbon dioxide. At the lowest column pressure, the purge is initiated. Upgraded gas is blown through the column to empty it from all the carbon dioxide that has desorbed from the column bed. The column is now regenerated and can be re-pressurized, either with the raw gas or with upgraded gas, and the cycle is complete.

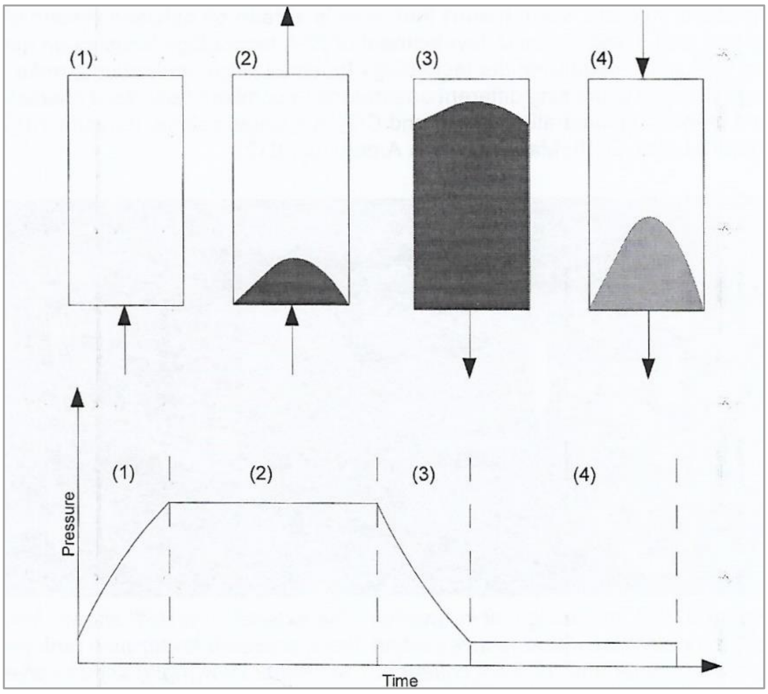


Figure 28: Four phases and pressure profile of the cycle

As the cycle consists of four phases, a common design includes four columns. One of the columns is always engaged in adsorption while the other three are in different phases of regeneration. To reduce the methane loss from the process, the columns are usually interconnected so that the existing gas flow during a blow down is used to pressurize another column in a pressure equalization phase, which also reduces the energy consumption of the process.

Using several columns there are many ways of modifying the process cycle to increase the yield of methane from raw biogas to upgraded gas, reduce the loss and increase the energy efficiency of the process up to 98% methane purity.

The choice of adsorbent, the bed material which selectively adsorbs carbon dioxide from there raw gas stream, is crucial for the function of the PSA unit. The adsorbent is a porous solid with a wide contact area in order to maximize the contact with the gas.

Absorbents materials are divided in equilibrium absorbents, which have the capacity to adsorb much more carbon dioxide than methane, and kinetic absorbents, which have micropores where the small carbon dioxide molecules can penetrate faster than the hydrocarbons which thus pass the column bed unretained. Those materials commonly are activated carbons, natural and synthetic zeolite, silica gel and carbon molecular sieves. A new type of adsorbent material is the metal organic frameworks (MOFs). Carbon molecular sieves (CMS) are one of the most employed materials.

The material selected should at least satisfy one of two criteria:

1. Have a higher selectivity to CO_2: this gas should be more “attached” to the surface of the material than CH_4; in most solids CO_2 can create stronger bonds with surface groups than CH_4. This kind of materials will be termed as equilibrium-based adsorbents since its main selectivity is due to differences of interaction forces between CO_2 and CH_4 with and the surface.
2. The pores of the adsorbent can be adjusted in such a way that CO_2 can easily penetrate their structure while larger CH_4 molecules have size limitations to diffuse through them. These

materials will be termed as kinetic adsorbents since its main selectivity is due to diffusion constrains

There is a correlation between the gas adsorption and pressure.

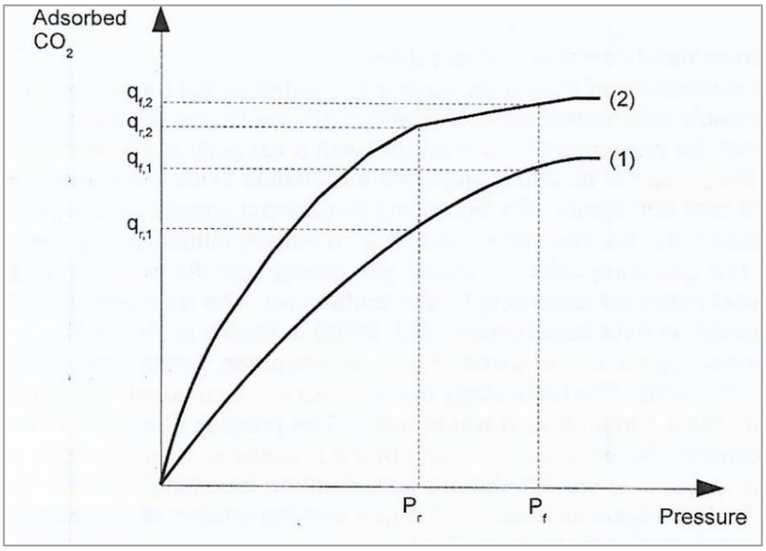


Figure 29: Two generic adsorbent isotherms showing the partial pressure of CO2 in the gas streams at feed pressures and regeneration pressure

Isotherms show the equilibrium level of adsorption at a given pressure. During the process, the raw biogas is fed into the column at the pressure P_{feed}, at which the adsorbents can retain a given amount of carbon dioxide, q_{feed1} and q_{feed2}. Δq thus equals the amount of carbon dioxide that has been separated from the gas stream during this process cycle. Although the adsorbent (2) has the capacity to adsorb much more carbon dioxide at pressure P_f, it is obvious that adsorbent (1) is a better choice for this process ad Δq_1 is much larger than Δq_2.

Also, the presence of contaminants is an important issue for the selection of the material. Apart from CH_4 and CO_2, other gases present in biogas are H_2S and H_2O. In almost all adsorbents, H_2S is irreversibly adsorbed, reason why it has to be removed before the PSA process.

PSA technology does not demand a lot of resources which makes it suitable for many applications. The technology is dry: it does not consume any water and does not create a contaminated wastewater. The process also does not require any heat. However, the electricity demand of the process is significant (0.15-0.3 $kWh/Nm^3_{raw\ biogas}$) due to the relatively high pressure used in the process. Further, a cooling machine may be needed for the de-moisturization of the gas and the cooling of the main compressor, if no external cooling water is available. Using a filter with activated carbon to separate H_2S before the PSA columns will include the consumption of activated carbon for this separation.

5.1.6 Comparison

Basically, the scrubbing technologies all perform well and have similar performances. The technologies described are now compared by means of some key performance indicators.

Table 4: Key Performance Indices

Tech. / KPI	Gas purity – capability to remove CO_2	Consumes	Methane slip
PSA	98 - 99 %	0.2 - 0.3 kWh/Nm^3	1.8 – 2 %
Water scrubbing	98 %	0.23 - 0.3 kWh/Nm^3	1 %
Organic physical scrubbing	98 %	0.21 - 0.23 kWh/Nm^3	1.5 %
Amine wash	99.8 %	0.12 - 0.14 kWh/Nm^3	0.1 %
Membranes	98 %	0.2 - 0.25 kWh/Nm^3	0.5 %

The investment cost is an important KPI. The amine scrubber is slightly higher in investment cost in the lower end of the spectra and the membrane technology is slightly lower in investment cost in the lower to mid-scale range. The investment costs start to converge at the higher throughputs.

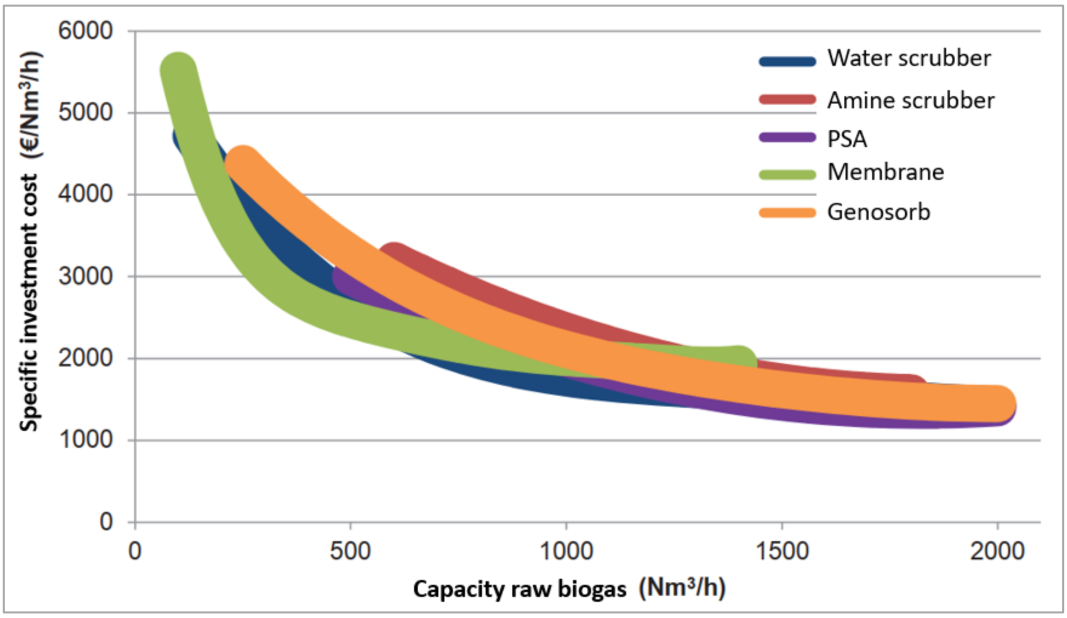


Figure 30: The specific investment cost of water scrubbers, amine scrubbers, PSA units and membrane units as a function of raw biogas

The upgraded biomethane can be used for different applications, requiring different gas pressure. The upgrading technologies operate at different pressure, making a proper comparison of the energy demand for specific applications. Feeding upgraded biomethane into the gas distribution grid at 5 bar can be done directly from the pressurized upgrading systems such as water scrubbers and PSA units, whereas the gas from an amine scrubber must be pressurized after the upgrading. The natural gas transmission grid is operated at 70 bar and vehicle fuel is handled at about 250 bar, which requires further compression of the gas from all technologies. The energy needed for this compression does however differ significantly as the first compression steps (1-10 bar) are the most expensive, in terms of energy. The energy needed to compress a gas depends on the volume of gas that shall be compressed, the inlet temperature of the gas, the ratio of specific heats (c_p/c_v) for the gas, inlet and outlet pressure and the efficiency of the compressor. The efficiency of the compressor is usually rather constant for various loads and, furthermore, variations of inlet pressure and inlet temperature are usually rather small and not affecting the overall energy consumption significantly. Thus, the values presented below are also valid for the raw biogas compression.

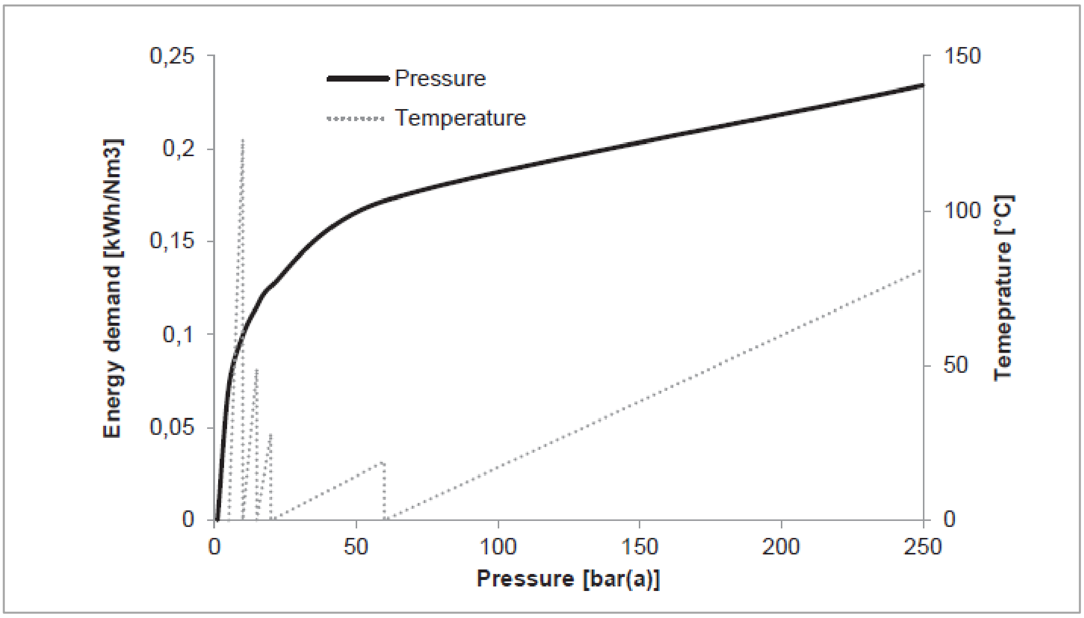


Figure 31: Energy demand for compression of biomethane between different pressure levels. The inlet gas is to be cooled before each compression

5.2 Transportation and storage of the biomethane

One of the main advantages of the bio-methane production is that it can exploit the technologies already available and consolidated for the methane of fossil origin, both concerning transportation and storage. This is a huge contribution to prevent further emissions in the environment due to new construction activities and it is a good opportunity to save budget.

Moreover, in the last years several ways to transport and to distribute biomethane are improving, due to the increasing environmental, industrial, geographical, economical requests. The technologies available today is:

- Compression (Bio-CNG, Compressed biomethane) for transport on the road and in pipes;
- Liquefaction (Bio-LNG, liquefied biomethane) for transport on the road and on boat;
- High pressure and high capacity pipes, both underground and undersea;
- Conversion in liquid hydrocarbons (GTL, Gas To Liquids);
- Electric generation directly on the well (GTW, Gas To Wire).

The first two are the main diffused techniques and the most consolidated ones thanks to the precedent usage for the methane.

5.2.1 Compression

The biomethane compression is the most used method to transport and to store it.

It has two principal advantages:

- Increase in density: for a given control volume, increasing the pressure means a higher quantity stored in that volume;
- Increase in specific energy: as a direct consequence of the increase in density, a fixed control volume and an increase in pressure leads to a higher specific energy stored.

So, a smaller tank can enclose the same density and the same energy with respect to a bigger one, with advantages in terms of space, both in static and dynamic storage and transport. It is also an improvement for vehicles powered by this fuel, since compression can guarantee longer autonomy. Furthermore, concerning transport in pipes, the increase of pressure can provide the useful energy to cover long distances maintaining at the intermediate station the required level of pressure.

The *storage* of the compressed biomethane exploits the same technologies used from the fossil natural gas. The main problems that the storage technologies intrinsically carry are the great economic costs, for energy consumption and for the tanks, and the natural risk of dealing with high quantity of inflammable fluid under pressure.

Apart from the traditional methodologies, some new applications are spreading for natural gas storage, for medium-high quantities and in vehicles:

- Compressed methane underground, which exploits former wells, from gas-oil extraction, and caves geomorphologically suitable;
- Storage in porous materials, beneficial especially in the vehicle sector, exploiting the properties of some materials of easy availability (such as active carbons) for the storage of gaseous fuel. They work as a sponge, revealing the fuel when heated. The main advantage is that they have a high volumetric energy density, with pressures between 0 bar and 100 bar, with respect to ordinary tanks.

The *transport* is afforded by two technologies: pipes and tank-trucks, special trailers with specific storage tanks.

Transport in pipes remains the main used method of transport. It is divided in importation and production grid, primary transmission, secondary transmission, local transport, distribution and connections. The first one and the fourth are usually at 5-12 barg since they are locally distributed, while the second and the third have to cover long distances so they need higher pressure such as 60 barg. The dispatching at the final users is at 0.5 barg.

Transport by truck is used for localities not served from pipes. The trucks have to respect the international norm for transportation of dangerous substances (ADR). Due to the high consumption of fuel for the transfer of the trucks, this method is usually used for short distances or for emergency.

5.2.2 Liquefaction

Liquefaction is the second method currently strongly improved, having a high potential to cover long distances as a bio-LNG (bio liquefied natural gas). The liquefaction consists in the cooling of the biomethane below his point of condensation, at -162 °C, by exploiting the properties of gasses such as nitrogen.

The balance of an LNG plant consists in:

- Pre-treatment with impurities extraction and drying
- Precooling of the fluid
- Fractionation of components of the gas mixture with higher molar mass
- Liquefaction
- Measurements and injection into the storage.

The main advantages for dealing with liquefied biomethane are physically the same as those for compressed biomethane, but with a higher impact: bio-LNG occupies about 600 times less space than the same quantity of bio-CH_4 not compressed, corresponding to a volume 2,4 lower than the one occupied by compressed biomethane at 250 bar. So, bio-LNG contains much more specific energy than the not compressed bio-CH_4 in the same volume.

Although, higher efficiency always brings higher costs and difficulties in the process. Indeed, the liquefaction is considered only if other alternatives are not available.

The *storage* of bio-LNG faces an important thermic challenge due to the necessity to constantly take the material at -162 °C. Special cryogenic containers are used in dynamic and static storage. The tank is constituted by two layers, eliminating the contact between each type of surface and avoiding convection and conduction. In order to reduce also the radiation exchange, a coat of reflective material is placed on the external walls of the container.

The transport is mainly provided by trucks, supplied with special cryogenic containers, and by LNG ships, depending on the distance that has to be covered.

The LNG ships can transport around 65.000 tons of liquefied gas. Such measures can classify them as the biggest ships constructed for non-military purpose.

One of the issues of the LNG consists also in the necessity of re-gasification plants ones the ship arrives at destination.

Regarding Italy, the LNG infrastructure can account on 45 stations, mainly in the North of Italy, and about 3000 LNG trucks.

To recall the *DM 2 March 2018*, for the creation of new liquefaction plants, the 20% additional CIC is recognized. The increase is a function of the quantity of biomethane produced and liquefied by the new plant and it is proportional to the financial participation of each producer.

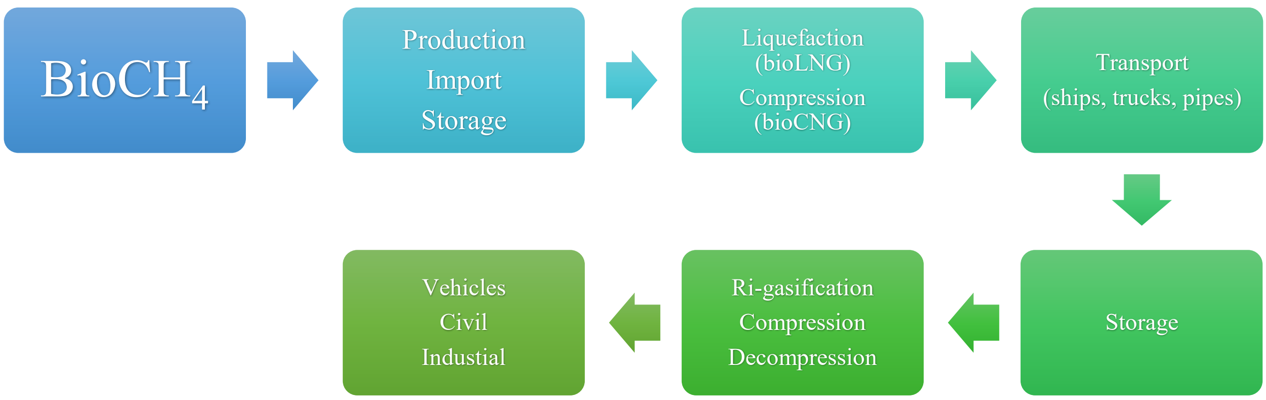


Figure 32: Total biomethane supply chain

6. Analysis of a productive upgrading plant – Foligno plant

This chapter is focused on the description of the plant situated in Foligno (PG) and managed by Asja Ambiente Italia S.p.A.

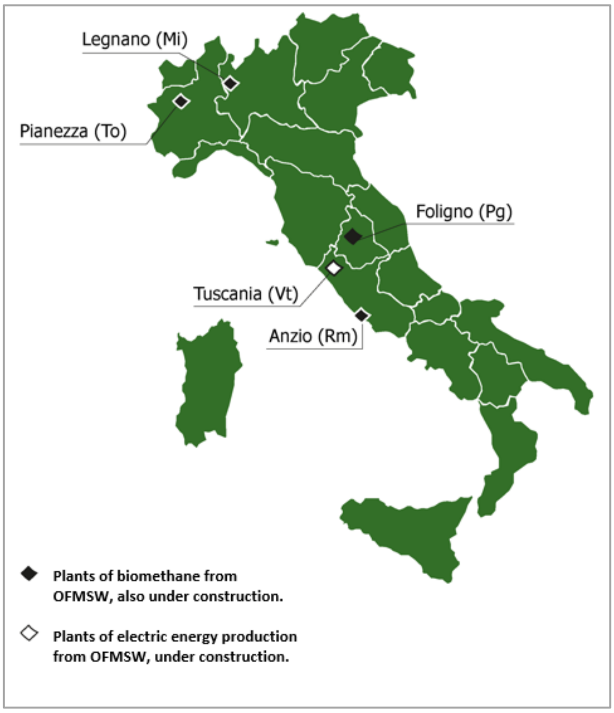


Figure 33: Plants for upgrading biogas from OFMSW, managed by Asja Ambiente Italia S.p.A.

The considered plant entered in operation in May 2018 with the composting part, while it has produced and injected in the grid its first Sm^3 of biomethane in March 2019.

The aim of the plant is to upgrade the biogas obtained from the anaerobic digestion of the organic fraction wastes, coming from the municipalities. The obtained biomethane is intended to be injected in the national grid.

The plant is situated in Foligno, loc. Casone. The choice of the location derives from the opportunity to exploit the nearby existing plant of waste treatment and depuration of wastewater.

Figure 34:Site of the plant

The biomethane plant is composed of:

- Unit of anaerobic digestion, where the degradation of the organic substance occurs with the consequent production of biogas and compost.
- Unit of purification and upgrading of the biogas, where it is collected and depurated in order to obtain biomethane.
- Unit of injection of the biomethane in the grid.

6.1 Authorization roadmap

The complex in Foligno is catalogued in the activities described in the *attachment VIII part II* of the *Dlgs 152/2006* as an installation which recovers and disposes non dangerous wastes, with a capacity higher than 75 ton/day. Integrated Ambiental Authorization (AIA) request was submitted for its construction and operation which ended with the approval from the Region Umbria.

Before the AIA procedure, the screening for the VIA has been provided, as a plant of disposal and recovery of non-dangerous waste, with a total capacity of more than 10 t/day, concluded with the assumption that the VIA evaluation wasn't necessary.

The simplified procedure actuated for the construction and the operation of the plant is done according to the *Dlgs 28/2011*.

The wastes treated in the plant are both the organic fraction of wastes from municipalities, with the certification CER 20 01 08, and the sub-products of lignocellulose matrix.

In according to the attachment C of the *Dlgs 152/2006*, the treatment of the biomethane is included in the R3 activities: recycling of organic substances which aren't used as solvent, also considering the composting and other biological transformations.

For the biomethane plant only, the *AU* (Unified Authorization) has been provided.

Figure 35: The entrance of the plant

6.2 General Plant Description

The plant is composed of two different parts, independent among one another concerning the functional aim:

- Section for *biomethane production*, where production of biogas occurs and where it is then purified and transformed in biomethane for the injection in the gas pipes. It is further divided in:
  - Section of anaerobic digestion, where the degradation of the organic substance occurs and where there is the consequence production of biogas.
  - Section of energetic conversion, concerning the dehumidification process, the upgrading process and the connection with the gas grid.
- Section for *compost production*: intended for the aerobic stabilization of wastes to produce a mixed compost, in accordance with the Dlgs 75/2010.

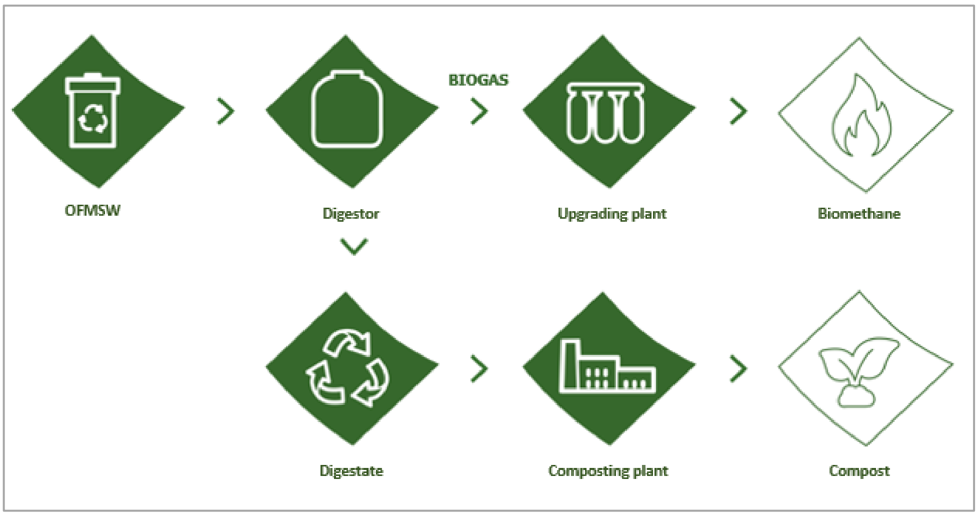


Figure 36: Scheme of the process

The quantity of wastes collected are forecasted as 53.500 ton/y overall, from organic and green wastes.

The predicted quantity of biogas production is 6.400.00 Nm^3/anno, while in the upgrading complex the forecast is of 4.370.000 Sm^3 of biomethane, corresponding to 499 Sm^3/h.

Table 5: Process timing

PHASE	TIME
OFSMW storage	Max 3 days
Green Waste storage	Max 6 months
Anaerobic digestion	21 days
Composting	59 days

6.2.1 Biogas production

The process treats not dangerous wastes collected from municipalities and sub-products from agriculture. Such wastes are listed, overall considered as OFMSW, in the attachment 3, part A, of the Ministerial Decree of the 2 of March 2018, which catalogues the matrices that returns advanced biomethane.

Table 6: CER codes for wastes treated in the plant

CER COD.	DESCRIPTION
200108	Biodegradable wastes from kitchen and canteen
190604	Digestate from anaerobic treatment of wastes from municipalities
190606	Digestate from anaerobic treatment of wastes of animal or vegetal origin

During the start-up of the digester or during anomalies, also digestate can be used as an injected material.

The unit meant for the biogas production comprehends the anaerobic digestion, while the aim of the composting process is to transform the OFMSW and the green waste (mowing), exiting from the digestors, into compost, exploiting mechanical and biological processes.

The plant has been realized to work with two different approaches:

1) Combined process of digestion and composting
2) Process of composting

The difference in the processes is the presence of the anaerobic digestion part, which can be skipped in the rare case of major maintenance.

Table 7: Each process to each part of the plant

PLANT ZONE	TREATMENT PHASE
Pre-treatment zone	Pre-treatment
Digestion zone	Digestion
Mixing zone	Mixing
Bio cells zone	Static process in bio cells
Intermediate screening zone	Intermediate screening
Maturation zone	Maturation
Final screening zone	Final screening
Upgrading zone	Cleaning and upgrading

The various stages of the processing of the input material are:

- *Pre-treatment*: OFMSW is brought to the shredder. The shredded material is then screened: the fraction of under screened material continues the process, while the over screened material goes into the bio separator where the organic fraction is separated from the inorganic one. The inorganic part exits the cycle, while the organic part is reinjected in the cycle and the total organic fraction goes to the digestive process and to the composting process.
- *Digestion*: the organic material is injected in the biodigester for the biological process of microbial decomposition and biogas formation. This stage takes about 21 days, at the end of which most of the digestate is sent to the mixing phase, while a small portion is reinjected in the digester. The biogas produced is collected by a pipe.
- *Mixing*: in this phase, the digested product is mixed with the mowing.
- *Static process in the bio cells*: the mixed material is conducted into the bio cells, that are tunnels with forced ventilation in which the aerobic digestion takes place. In particular, the aim of the static process is to stabilize the material and it takes around 14 days.
- *Intermediate screening*: the matter with a diameter lower than 40 mm continues the process, while the other one is reinjected into the mixer.
- *Maturation*: for around 45 days the material is left in this phase to maturate. the ripening compost is turned over on a regular basis to favour stabilization.
- *Final screening*: the material characterized by a diameter lower than 10 mm is the compost, the final product. The over screened material can be disposed, taken back to the mixer or brought back to the begin of the entire process.

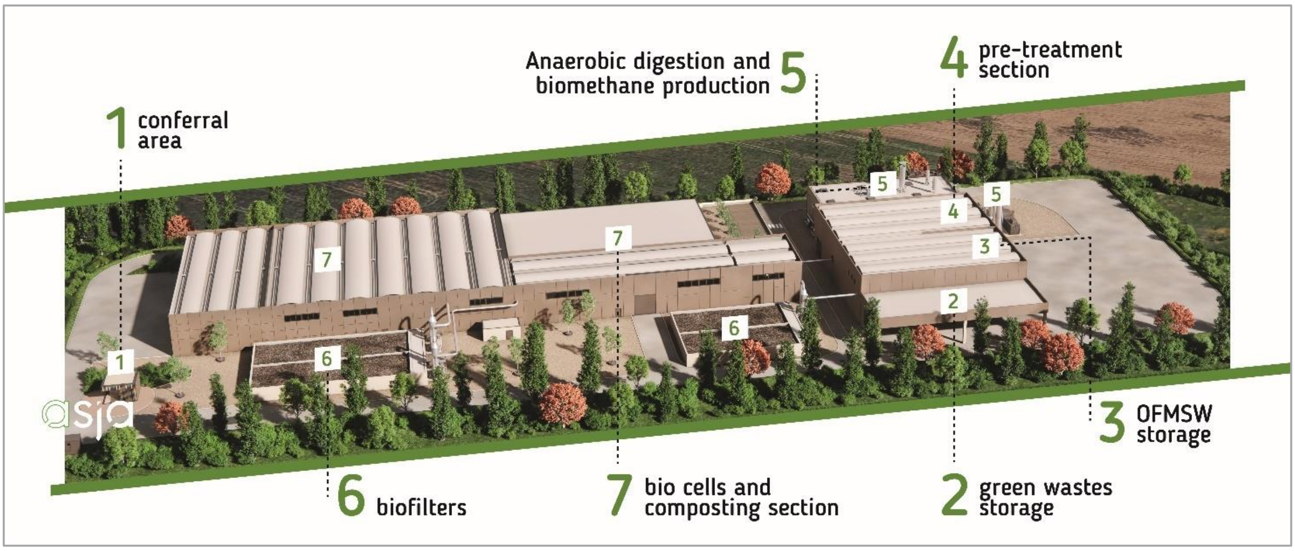


Figure 37: Map of the plant

The entire plant is equipped with an air ventilation system to contain smells and emissions. The polluted air is then washed through the scrubber and brought to the biofilter, which has the aim to trap odorous particles and release water vapor.

6.2.2 Biogas upgrading

The unit meant to upgrade the biogas produced from the anaerobic digestion of the OSW has the aim to separate the carbon dioxide and other compounds, such as the H_2S, from the raw biogas in order to obtain a biomethane rich as much as possible of CH_4 (purity of 95-98%).

Figure 38: Upgrading section in the Foligno plant

The technology used for the upgrading is a membrane separation process, designed to treat all the biogas produced from the digester, corresponding to a maximum of 900 Nm^3/h.

The plant section dedicated to the upgrading is composed of four unity:

- pre-treatment of the biogas.
- biogas compression.
- biogas upgrading.
- emergency torch.

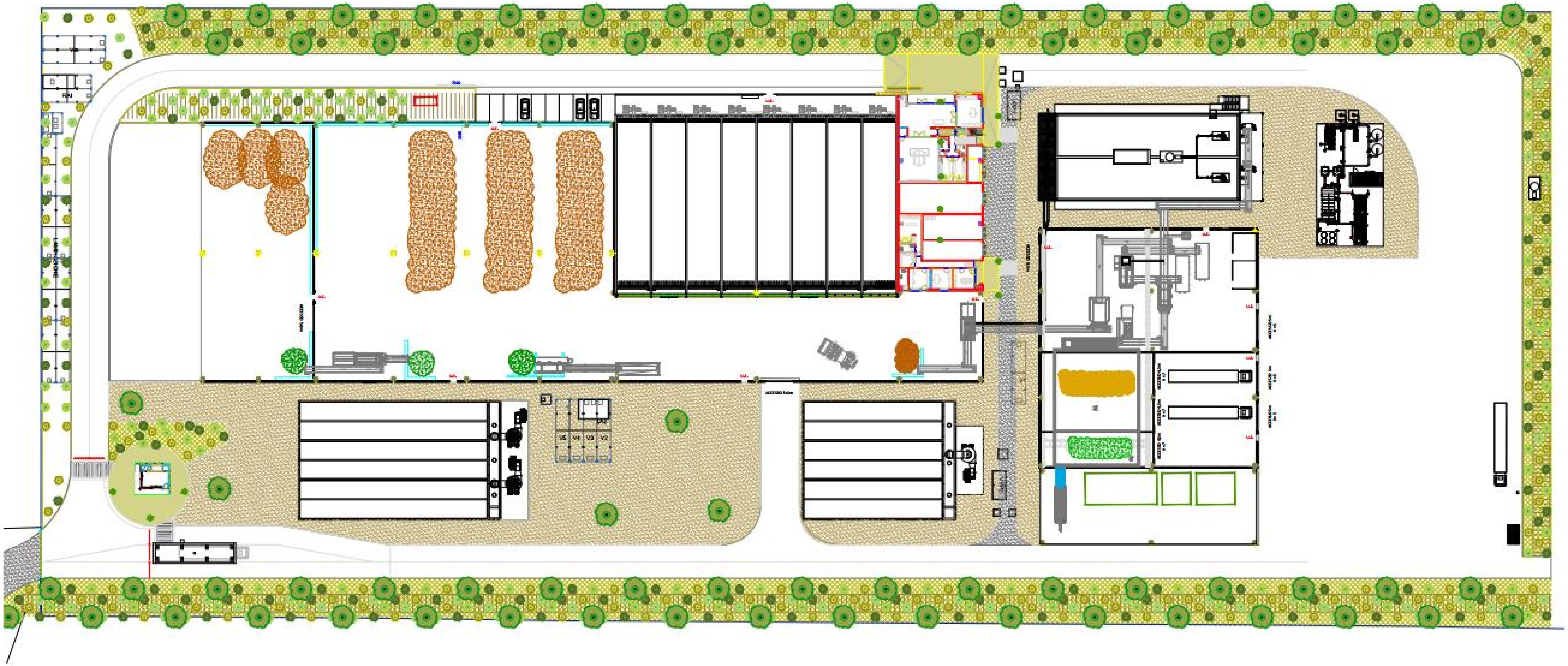


Figure 39: Layout of the plant

6.3 Section of receiving, storage and pre-treatment of the OFMSW

The pre-treatment of the organic waste material collected from municipalities consists in:

- Reduction of the dimension of the material (through shredding)
- Separation of the organic material from the inorganic (through screening and bio-separator)

The overall waste, both the organic and the green wastes, are collected and transported to the plant by trucks. They are temporarily arranged in large pits. The huge material, which can hinder the process, is manually removed beforehand.

In the pits for the storage of the organic wastes coming from municipalities, a pump is installed in order to collect the leachate into a tank for the disposal or to bring it to the bio-digestion process.

6.3.1 Pre-treatment of the OFMSW: the shredder and the sieve

The OFMSW is drawn directly from the grab bucket and brought to the primary shredder, which provides the shredding and crushing of the material.

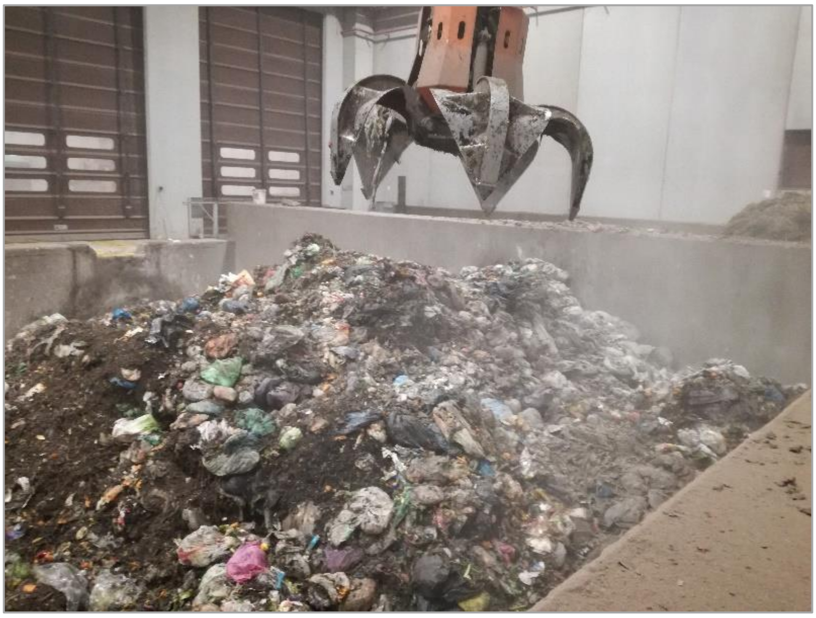


Figure 40: Grab bucket collecting from the pit

The OFMSW is usually collected from the municipalities contained into plastic bags, which are opened by means of the shredder.

The primary shredder is a shredder with a slow running. The material to be processed is deposited into the hopper of the shredder. Inside the machine, the crushing is carried out and the material exits from the machine toward the end of the shredder and it is discarded through an evacuator tape. The entire structure is covered with insulating materials from an acoustic point of view. The smashing roller, constitutes of 17 teeth, presses the material to be shredded over the comb counter-knife, hydraulically controlled. In case of overload, the comb recedes to get rid of useless objects to avoid damage, then it returns automatically to its working position via the hydraulic control system. The shredding system includes a mobile smashing roller that allows adjustment of the size of the shredded material. The comb tips are made of stainless steel.

Figure 41: Primary shredder

Before the screening phase, a magnetic separator cleans the waste flow from metallic objects and aluminium. Then, series of conveyor belts lead the treated material to the discs sieve (also called star screening), for the screening phase, which separates the thin fraction (under screened material with a diameter smaller than 60 mm) from the bigger fraction (over screened material with a diameter bigger than 60 mm). The machine is a tough steel construction with a distribution of parallel axes, each one with discs equally spaced from one another in order to realize a fixed light. The shafts are driven by electric motors. In the lower part there are some deflectors to guide the screened material.

Figure 42: Discs sieve for the screening procedure

Depending on the process to be carried out (direct composting of the material or digestion and composting), the under screened material is conducted by conveyor belt to the loading hopper for the mixing phase or to the digesters.

6.3.2 Under screened material: the bio-separator

The under screened material reaches the bio-separator through a series of conveyor belt. The bio-separator divides the organic substance from the inorganic.

Figure 43: Vertical shaft inside the bio-separator

The feeding auger has the task of gradually pushing forward the material towards the squeezing part. The squeezing assembly is composed of a shaft arranged vertically, which, rotating at 800 revolutions per minute, can separate the organic fraction from the packaging. The separation occurs through 20 blades mounted on the shaft. The centrifugal motion allows the organic material to be pushed against a grid provided with holes of 2 cm. The upward motion allows the packaging to exit from above through the auger for the extraction of the dry fraction. An additional auger directly connected to bio-separator reinsert the organic material inside the loop.

During the treatment it is possible to add a part of liquids, obtaining different levels of the dilution of the material in relation of the quality and quantity of the moisture in the inlet material.

The unrecovered inorganic part exits the loop and it is then lead to the disposal.

6.3.3 Air treatment: scrubbers and bio-filter

The entire structure, that contains the pre-treatment stage, is equipped with a depressurization system and air capture to limit odours and emissions.

The drawn air is conducted to the scrubber in which the pollution, contained in the air, is absorbed by appropriate chemical reagent at a low concentration.

The scrubber operates a transfer of pollutants, in a gaseous state, from a gaseous fluid to a condensed fluid, the washing liquid. The washing fluid is water with addition of an antagonist substance absorbing the ammonia component from the air in counterflow. The enriched water is delivered through a spray system with nozzles and then it is recirculated by washing pumps. The scrubber is equipped with a dosing system of chemical reagents (H_2SO_4 at 60%).

Subsequently, the air is introduced from the bottom through the biofilter and then emitted into the atmosphere.

Figure 44: Scrubbers

Biofiltration is a purification technique, with the aim to purify the stream of air from odorous organic molecules in exhausted air extracted from confined spaces. The air filtering happens through microbiologically activated biomass. The abatement effect is based on adsorption of odorous molecules on the surface colonized by the bacterial flora of the organic matrix of the filtered material. The contact is facilitated by the presence of a liquid film on the filtering biomass that, apart from being a necessary condition for life, it allows the solution of odorous molecules and thus their neutralization. The filtering layer should combine a good biodegradability with a good porosity to air. The obtained reduction of contaminants is up to 95-99%.

Figure 45: Biofilter

6.4 Unit of anaerobic digestion

The unit of anaerobic digestion is composed of:

- anaerobic digester
- feeding line to the digester and discharge lines for the digestate
- heating plat for the digester (boiler and distribution line)
- emergency torch for the biogas.

6.4.1 Anaerobic digestion: a semi-dry process

The digester is the main component of the section and it is constituted of two reactors. The digestion is performed with a semi-dry process. Each digester is a plug and flow reactor, working in continuous with a temperature higher than 50°C with a residential time of 21 days. In the fermentation chamber, entirely coated with watertight steel, all the four phases of digestion take places.

Table 8: Digester specifications

Characteristic	**Description**
Process	Semi-dry Plug&Flow
Number of modules	2
Nominal volume	1.300 m^3
Effective volume	2.600 m^3
Capacity of organic mix	40.000 t/y
Residence time	21 days
Temperature	>50°C

The dry process allows the material to pass from inlet to the outlet of the digester in a stable plug flow, avoiding the mixing of the input material with the already treated material, thus avoiding short circuits of material not treated in output to the digester. The retention time defined allows to sanitize the material, by eliminating for example pathogenic organisms and seeds of plants, and it allows optimum decomposition of the organic material with relative conspicuous production of biogas. Inside each reactor there is a mechanical system is for mixing the biomass inside the chamber, consisting of a single horizontal axis agitator. This system guarantees the correct agitation of the digester inside the module and prevents the formation of incrustations and sediments on the bottom and the formation of a crust on the surface, which will hinder the contact between the liquid part and the part of the biogas formation.

Figure 46: Digesters

The two reactors, each with a useful volume of 1.300 m^3, work in parallel and they are designed to be in communication among each other, with a bypass for each eventuality, to transfer the digestate from a digester to the other.

The volume is intended as the effective volume for the material to be digested, not as the effective geometric volume.

The biogas is accumulated in the upper part of the digester, while in the bottom part the digested material can sediment. A portion of the digested material is brought into recirculation to inoculate the input material of the digester.

The digester is continuously alimented by a cochlea, while the digestate is collected with pumps. The recirculation of the digestate is internal: the material is collected from the bottom of the digester to be reinjected in the top by means of a dedicated pipe inside the digester itself.

It is overall intended as a completely closed system, where the cochlea is fixed to the internal part with an angle of 45° downwards, completely immersed in the digested pulp in order to avoid the infiltration of oxygen or the leak of biogas. The material entering in the digester pushes the material towards the exit. The feed and discharge of the digestate are fully automatic and controlled by a monitoring system.

To optimize the process, each module is equipped with a heating system inside the fermentation chamber, directly in contact with the mass, crossed from heated water alimented by the hydraulic circuit connected to the heating system. The heating system is constituted by a boiler alimented by methane from the grid.

The volumetric capacity of the digester is limited, and it determines the input quantitative (t/day) and the biogas production (Nm^3/d), depending among each other.

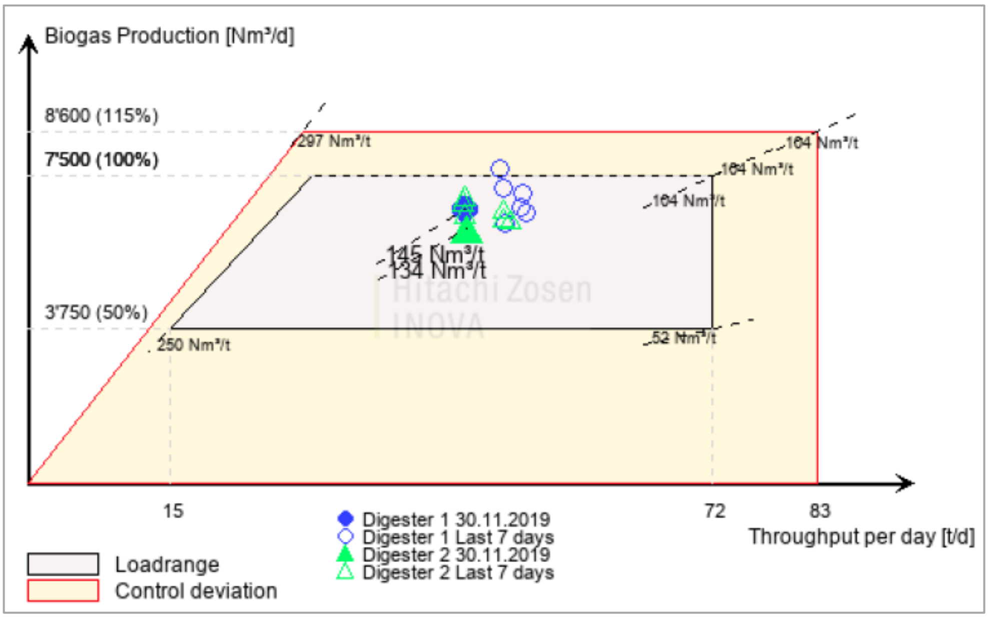


Figure 47: Level of the digesters

The material inside the digester has the consistency of a puree. The level of maximum storage capacity of the digester is 70%, the remaining 30% is for the collection area for the biogas. If the level reaches the 85%, the cochlea is shut down. If the level goes below the 70%, the disposal line is closed.

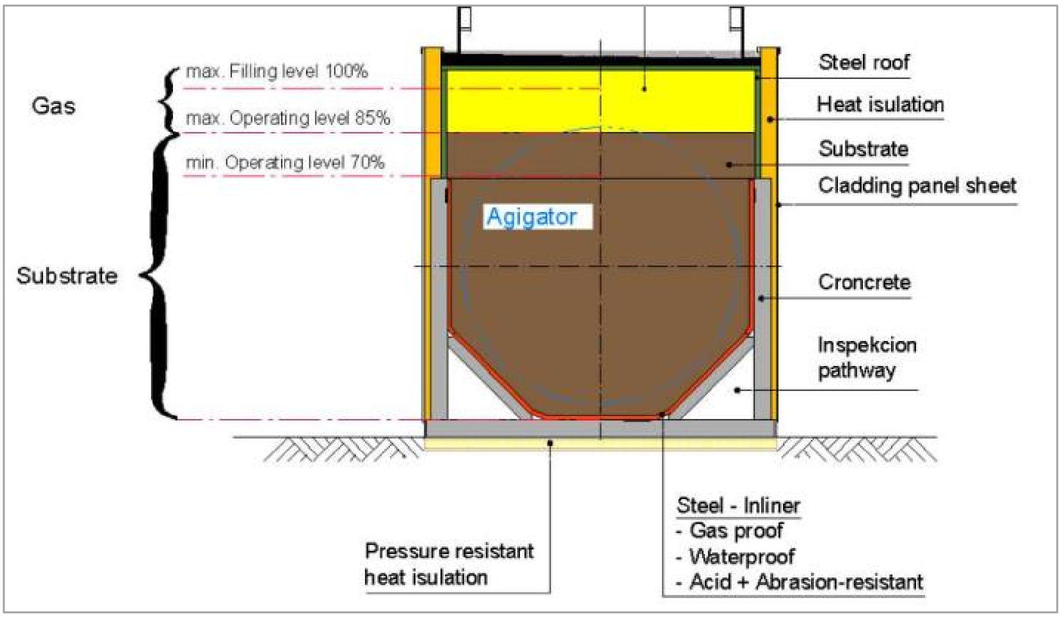


Figure 48: Levels of the digester

The biogas situated on the top of the biomass is collected naturally with a pipe system, which avoid creating explosive gas-air mix, and brings it to the next step.

6.4.2 Safety system: the torch

Installed on the top cover of the digester, there is an emergency torch. It is a biogas combustion torch, fully automatic, for the combustion of gas in case of surplus produced by the anaerobic fermentation process or in case of plant shut down for maintenance or in case of failures. It enters in function as the pressure of the gas increases up to the first stage of the pressure sensor, which is 40mbar. The sensor will check if there isn't a flame inside of the pipe of combustion. The ignition system is then supplied, and the valve of the propane gas supply pipe is opened. A propane gas flame is created. At this point, the biogas is allowed to flow, it turns on and burns independently. The flame is detected by the sensor in the combustion pipe and consequently the gas duct is interrupted, and the biogas continues to burn without the propane gas support.

As safety systems, a pressure relief valve and a rupture disc enter in function of the pressure inside the digester reaches 100 mbar.

Figure 49: Emergency torch

6.5 Unit of mixing phase

During the mixing phase, the material is shredded and blended. Subsequently, it is conducted, by means of wheel loader, to the bio cells system.

The unit is composed by the hopper, mixer and conveyor belts. The feed hopper is an input feeder with conveyor chain with a capacity of 12 m^3. The loading speed is customizable, depending on the plant requirements. From the hopper, the organic material and the green part will reach the mixer, which has the task of blend and homogenize biological organic fractions. The mixer, by means of three counter-rotating augers equipped with teeth with speed control, is able to shred and mix the biological organic fractions in few minutes, even if there are wooden structures resistant or difficult to treat. The load capacity is 15 m^3.

Figure 50: Green wastes (mowing)

6.6 Unit of static process in bio cells

The biological treatment provides a static process in bio cells where the organic matrices are igenized and stabilized. That process is called "active composting time", where the processes curated by the more fermentable microorganism are more rapid and intense. This step needs high temperature and a good quantity of oxygen for the biochemical reactions.

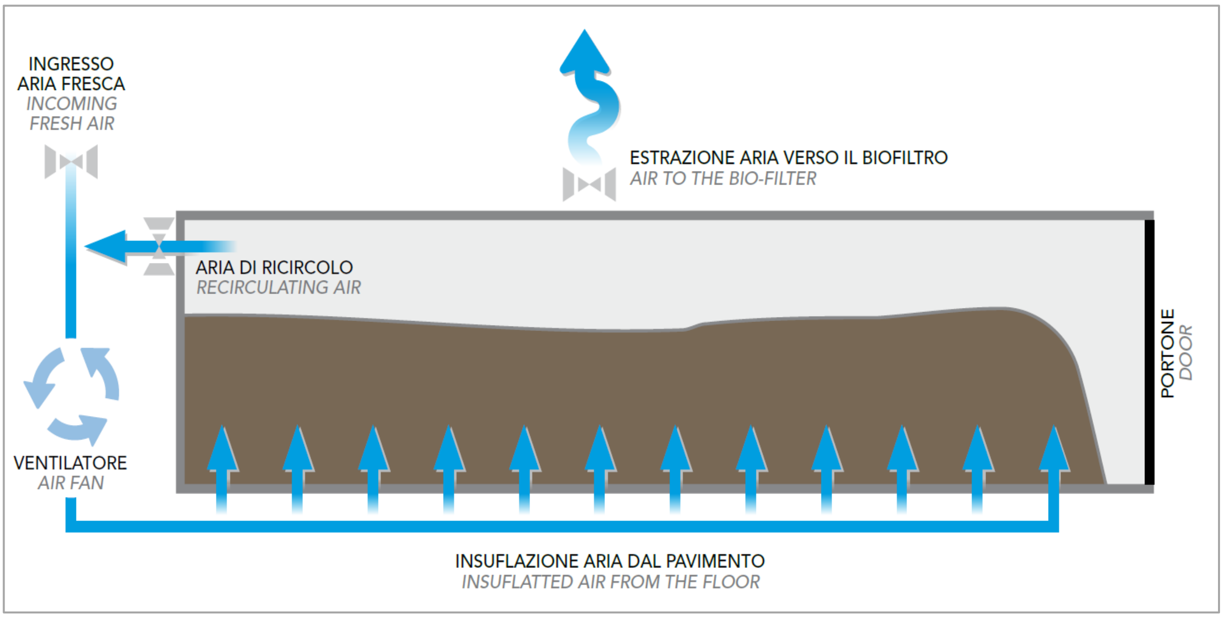


Figure 51: Bio cell scheme

The bio oxidation in bio cells presents various vantages:

- More rapid biochemical reactions
- Avoid creating anaerobic mechanism, responsible of odorous emissions
- The developed energy heats the organic material, causing sterilization
- The structure is particularly efficient and flexible thanks to the automatic operative system in real time.

The excess of heat produced needs to be drained.

The floor is equipped with an air insufflation system process, while in the ceil there are nozzles which sprinkle water on compost.

Figure 52: Breathed floor in bio cell

6.7 Units of screening and maturation phase

6.7.1 Intermediate screening stage

After the treatment in bio cells, the material is picked up with the wheel loader and deposited on the hopper. Then, it reaches the disc sieve, where the material is divided in the thin fraction out of the coarse material. The thin fraction is intended for the maturation, while the over screened material is recirculated and brought directly to the mixer.

6.7.2 Maturation phase

In the maturation phase, the under screened material coming from the sieve is carried out, by means of a wheel loader, in a suitable place for the maturation, in which remains for a determined period.

6.7.3 Final screening stage

After the maturation treatment, the material is taken, with the wheel loader, and deposited on the trommel screen. This separates the compost, with diameter lower than 10 mm, from the over screened material, with diameter higher than 10 mm. The compost is the final product of the plant, while the above screened is recirculated into the mixer or at the beginning of the cycle or it is sobered.

Figure 53: Compost before the final screening

6.8 Unit of upgrading biogas

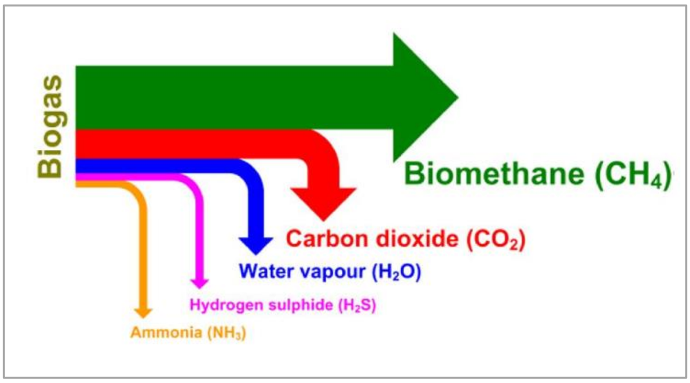


Figure 54: Fluxes

The biogas flux is subjected to purification and to upgrading.

6.8.1 Pre-treatment of the biogas stream

First, it is washed from the ammonia content and then it is sent to a heat exchanger to be cooled down, in order to reduce the moisture content.

Then, the biogas is sent to the pre-treatment section where it is purified from the H_2S and the VOC (volatile organic compound).

The pre-treatment section is so overall composed of:

- washing tower for ammonia and soluble impurities removal with a direct cooling of the gas.
- active carbons for the removal of H_2S.
- active carbons for the removal of the VOC.

Figure 56: Washing tower for ammonia reduction

Figure 55: Activated carbon for VOC removal

Figure 57: Activated carbon for H_2S removal

The washing water used in the first step is previously cooled down to 7°C with glycolic water and then is collected in the bottom and then reinjected on the top. It decreases the quantity of NH_3 from 10 ppm to 5 ppm.

Later, the flux of cleaned biogas is compressed up to a maximum of 16 bar, which is the pressure range useful for the membrane separation. The flux of compressed biogas is furthermore treated to be separated from the water content and to be purified from the content of oil with an active carbon filtering system.

Table 9: Inlet biogas characteristic, before any purification step

Inlet BIOGAS	Value	Unit	
Temperature	50-55	°C	
Pressure	1.5	kPa(g)	
Flow rate	900	Nm^3/h	
Composition	CO_2 dry gas	34,5	%V/V
	N_2 dry gas	0,85	%V/V
	O_2 dry gas	0,085	%V/V
	CH_4 dry gas	49	%V/V
	H_2S	254	ppm
	NH_3	127	ppm
	VOC	<10	mg/Nm^3
	Water	15	%V/V

6.8.2 Membrane upgrading technology

The flux reaches the membrane for the separation of the CO_2: it is a multi-stadium process where the first and the second stadium bring the purity of methane up to 97%, while the third one recovers the permeate from the first stadium and takes it back to the compression system. The CO_2 produced from the process is released in the atmosphere with the flux called "off gas", which contains a very small percentage of methane losses (< 0.5%).

Table 10: Composition and physical state of the biogas and utilities entering the first step

Utilities	Unit	Minimum	Maximum
Air			
Pressure	bar	5.5	7
Temperature	°C	5	40
Pressure dew point	°C	-	-10
Quality	-	Oil free	-
Water			
Temperature	°C	10	20
Flow rate	l/h	1400	2000

Inlet biogas	
Temperature Range	16 °C
Maximum dew point inlet biogas	20°C less than the temperature of the inlet biogas
Inlet pressure min/max	20 kPa(g)
Flow rate	900 Nm^3/h

Composition	Project values	
CO_2 dry gas	40,2	% V/V
N_2 dry gas	0,99	% V/V
O_2 dry gas	0	% V/V
CH_4 dry gas	57,3	% V/V
H_2S	0,088	ppm
NH_3	0,665	ppm
VOC	< 5	ppm
Water	1,3	%V/V

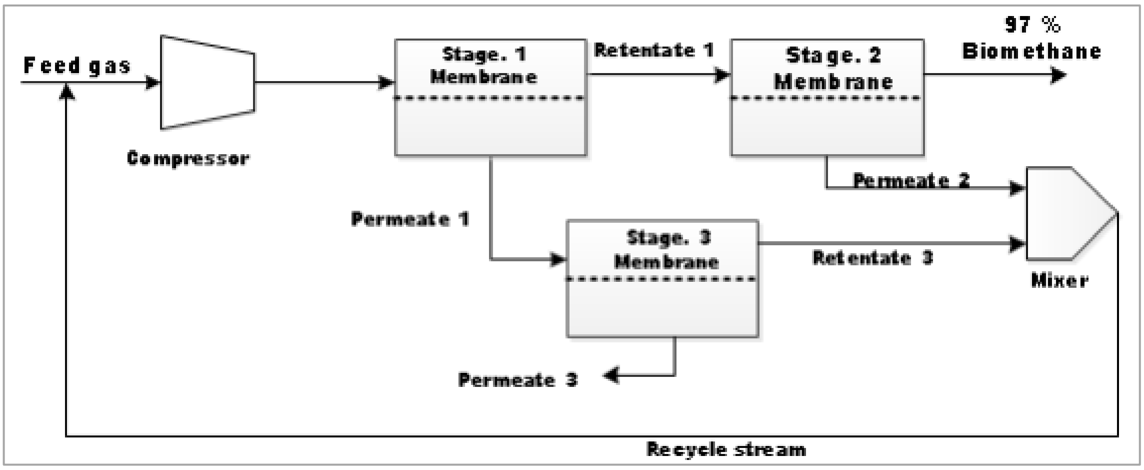


Figure 58: Three stage membrane process

The heart of the upgrading process is composed of three stadia of membranes constituted of multiple modules. The membrane is an interface between two phases, and it promotes the penetration of one with respect to the other one. The higher affinity of the molecules of CO_2 with the polyamide grid permits the quicker diffusion of them with respect to the methane. The input biogas is separated into two fluxes: the permeate rich in CO_2 and the retentate rich in CH_4. The flux is naturally dehumidified since the water passes through the membrane, as the CO_2.

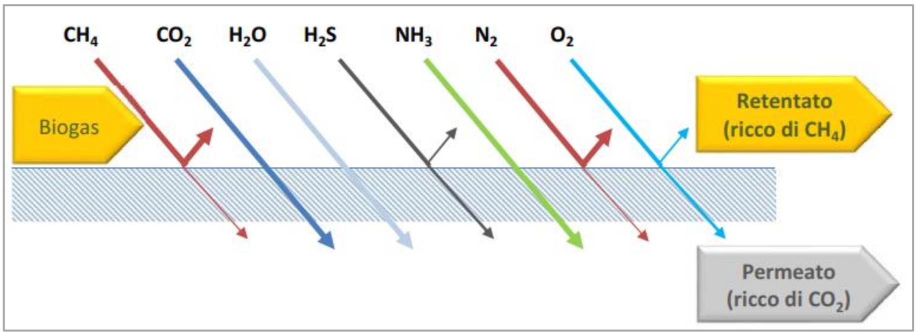


Figure 59: Membrane operation description

Each module of the membrane in constituted of fiber in a tube-shaped capsule made of steel.

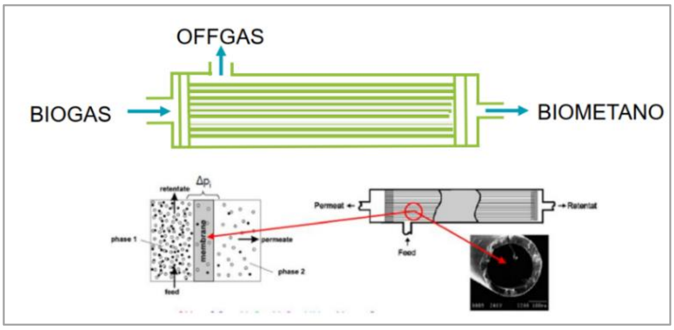


Figure 61: Internal structure of the membrane

Figure 60: Skid of the membrane

The passage in the first membrane produces a retentate rich in methane and a permeate rich in CO_2. With the second stadium, the retentate is further purified from CO_2 obtaining biomethane. The permeate of the first stadium, rich in CO_2 but still with some CH4, is sent to the third stadium which creates a permeate of pure CO_2.

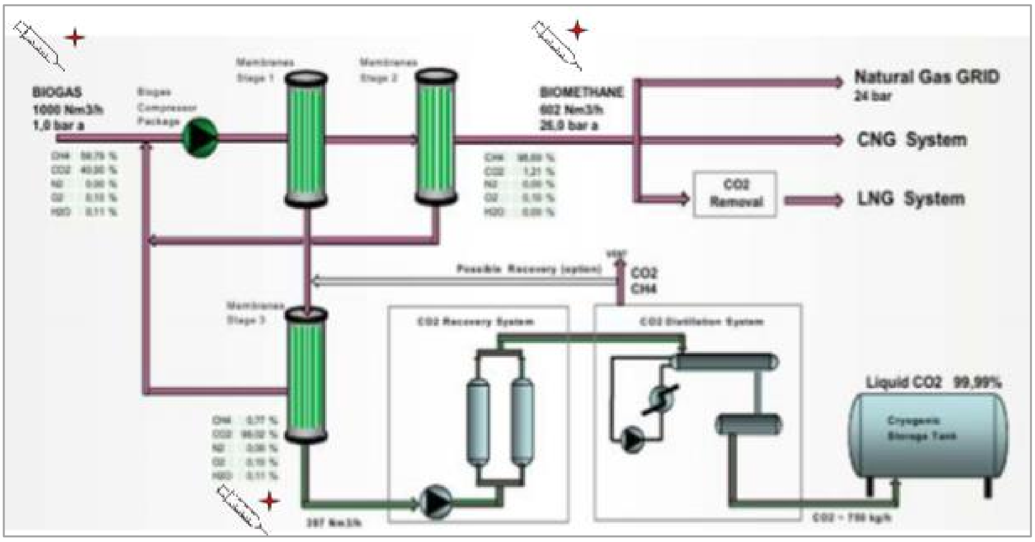


Figure 62: Three stage membrane process

The system is designed for the automatic procedure which guarantees the quality of the biomethane and of the off gas in atmosphere.

Both the flow rate and the purity of the final products, biomethane and flux rich in CO_2, depends on several factors:

- CH_4/CO_2 ratio of the inlet biogas
- Flow rate biogas
- Membrane configuration of the three steps of the system
- Age of the membrane

The plant is designed to produce a retentate with < 3% of CO_2 and a minimum heating value of 34.95 MJ/Sm^3, while the permeate with a concentration of CO_2 higher than the 98%.

The concentration of pollution in the inlet gas, such as VOC's, H_2S and NH_3, are monitored every day, with the heating value of the produced biomethane. Moreover, every three days, the dewpoint of the inlet biogas and the recalibration of the CH_4 detector is checked.

In case of biomethane not conforming the quality for injection in the grid, the flux is taken back to the top of the upgrading process, to be further processed.

Table 11: Specifications of the produced biomethane

BIOMETHANE	Value		Unit
Temperature	30		°C
Pressure	15		bar(g)
Flow rate	540		Nm3/h
Composition	CO_2	0.5	%V/V
	N_2	<1	%V/V
	H_2O	Dry	
	CH_4	>97,5	%V/V

Table 12: Specifications of the produced off gas

OFF GAS	Value		Unit
Temperature	25		°C
Pressure	0.1		bar(g)
Flow rate	360		Nm3/h
Composition	CO_2	>98	%V/V
	CH_4	<1	%V/V

As a safety procedure in case of malfunctioning of stops, it is installed a high temperature torch.

Figure 63: Safety torch

6.9 Destination of the biomethane

As the natural gas from fossil origin, the biomethane in intended to be:

- used as vehicle fuel.
- injected in the grid.
- transported and stocked for the subsequent production of energy also in location far away from the site of production.

Figure 64: Pipe for biomethane

The infrastructures able to receive the biomethane for the distribution are managed from the society *Valle Umbra Servizi S.p.A.*

For the connection of the new cabin with the gas grid already existing, the section was completed with a dedicated pipeline.

The biomethane is analysed and it is injected in the grid whenever it has the right specifications. The part resulting out of specification is reinjected on the top of the upgrading process.

For the connection between the upgrading section and the section of delivery and measurement a gas line has been realized with an underground pipe made of steel. For the recirculation of the biomethane non-compliant with the specification of the injection into the grid, a gas line has been installed underground connecting the section of delivery and measurement with the upgrading plant.

The part of the plant used for the grid connection is constituted of two parts:

- plant of delivery and measurement
- plant of receive and injection

The plant of delivery and measurement is meant for the monitoring of the physical characteristics of pressure and temperature of the biomethane. It's equipped with a three-way valve for the recirculation of the biomethane not qualified to be injected in the grid, a measurement for the energetic content, a measurement of volumes, flow rate and software for data elaborations.

The plant of receive and injections is composed by hardware and software for data elaboration, section of biomethane filtration, system of pressure regulation for the injection of the grid, system of odorization of the biomethane and the infrastructures for the injection.

Table 13: Specification for biomethane to be injected into the grid

Parameter	Unit	Limit Values Min	Max
Higher Heating Value	MJ/Sm^3	34.95	45.28
Woobe index	MJ/Sm^3	47.31	52.33
Total volatile silicon (as Si)	mg_{Si}/m^3		0,3
Relative density	-	0.555	0.7
Carbon Dioxide	% mol/mol	-	2.5
Hydrogen	% mol/mol	-	2
Hydrocarbon dew point temperature (from 0.1 to 7 MPa absolute pressure)	°C	-	-2 (as in EN 16726)
Oxygen	% mol/mol	-	1
Hydrogen sulphide + Carbonyl sulphide (as sulphur)	mg/m^3	-	5 (as in EN 16726)
S total (including odorization)	mg_S/m^3		30
Methane Number	Index	65 (as in EN 16726)	
Compressor oil	An amount that does not render the fuel unacceptable for use in		
Dust Impurities	end user application.		
Amine	mg/m3		10
Water Dew Point	Class A	-10°C at 20 000 kPa	
Classes are given to allow for climate dependent limits to be adopter nationally.	Class B	-20°C at 20 000 kPa	
	Class C	-30°C at 20 000 kPa	

<u>*6.9.1 Cabin of measurement and delivery*</u>

The cabin of measurement and delivery is the responsible of the check of conformity of the produced biomethane in order to inject it into the gas grid.

The specifications are strictly normed concerning several decrees, including:

- Ministerial decrees April 2008, technical rule for the project, construction, operation and control of distribution systems and direct lines of natural gas with a density not exceeding 0.8
- UNI 9167: collecting facilities, first reduction and measurement of natural gas

The cabin will be composed of two confined spaces, in which are installed:

- Section of gas inlet, gas analysis and three-way valve
- Filtering
- Measurement
- Gas outlet

- Control system

Several analysers are installed for the detection of the limits settled by norms:

- Gas chromatograph for carbon dioxide, nitrogen and oxygen
- Analyser with UV technology for H_2S
- System for water dew point analysis
- Oxygen transmitter with thermo paramagnetic technology

Figure 67: Gas chromatograph

Figure 65: H2S analyser

Figure 66: Analyser for water dew point

Apart from the specification of certain compound limits, also physical properties have to be respected, such as temperature, pressure and flow rate, listed in the table below:

Table 14: Physical specification for inlet in the gas grid

Outlet flowrate	499	Sm^3/h
Inlet pressure min/max	from 6 to 16	bar g
Inlet temperature min/max	from -10 to +60	°C
Outlet pressure min/max	from 40 to 70	bar g
Outlet temperature min/max	from 5 to 30	°C
CPI gas pipeline	70	bar g

6.10 Mass balance

The following section is dedicated to the mass balance of the plant, expected under normal operating conditions.

The OFMSW enters the plant, it is duly treated and then mixed with ad adequate amount of structuring material coming from mowing and green wastes. The mixture is sent to the digester for anaerobic stabilization and the production of biogas destined to be purified into biomethane through the upgrading process.

Table 15: Total quantities in mass balance

Total OFMSW	40.000	ton/year
Total Green	13.500	ton/year
Total Biogas	5.840.000	Nm^3/year
Total over screened D40	22.000	ton/year
Total over screened D10	2.430	ton/year
Total over screened	24.430	ton/year
	25.500	ton/year
Process losses	55,52%	%

The mass balance is constructed under several hypothesis coming from the operation experience of the plant using real operational data.

The inlet stream of OFMSW is taken as 40.000 tons per year, which is the value used in the project of the plant. In real operation, the value changes in accordance to the quantity collected from municipalities and it goes from 35.000 up to 40.000 tons per year.

The inlet stream of green wastes is authorized as 13.500 tons per year. This quantity is settled as a constant quantity since it is subjected to the authorization.

The incoming waste flow is deposited in a pit, where the grapple of the crave collects it. In the pit there is a sedimentation of the percolation water (leachate), for an amount of 7 t/day, that has to be disposed properly.

After the primary shredder, a magnetic separator collects the metallic fraction of the wastes. Metallic objects are useless for the digestion process and they can harm the various machines and components. The fraction of collected metallics is around the 0.3% of the total incoming waste flow.

The screening phase chooses the fraction of the flow that is idoneal to be injected in the digester (under screened) and the fraction that has to be furthermore processed and cleaned (over screened). The bio separator then recovers the organic part from the over screened material and returns the fraction of material that cannot be used in the composting process. This material is about the 13% of the total incoming waste flow, but it strongly depends on the nature of the incoming municipal solid waste and on the accuracy of the recycling made by the municipalities where the rubbish is collected, parameter that obviously can’t be controlled previously. The disposal costs for such material is relevant and can represent an issue in the plant due to the high OPEX.

The bio separator washes the over screened material and it requires an amount of water, taken from the grid, of about 2.600 t/y. Part of the water and the recovered organic are injected into the digester.

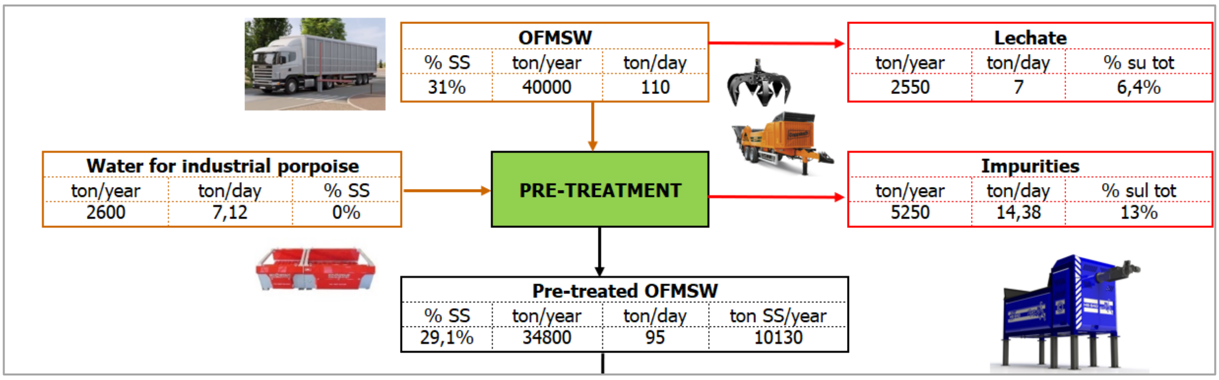


Figure 68: Pre-treatment mass balance

The percentage of solid material entering in the digester is a constantly controlled parameter since it is important for the yield of the process, that is the parameter that influence the quantity of biogas sent to the upgrading process. The value of this percentage is 35%. About the 15% of it derives from two incoming flows: the structuring green wastes, which contribute with the 8%, and the over screened material coming from the final screening stage, which contribute with the remaining 7%.

After the digestion process, the products are the biogas and the digestate. The biogas yield is 160 Nm^3/t with a content of 52% of CH_4.The digestate is furthermore processed to become compost.

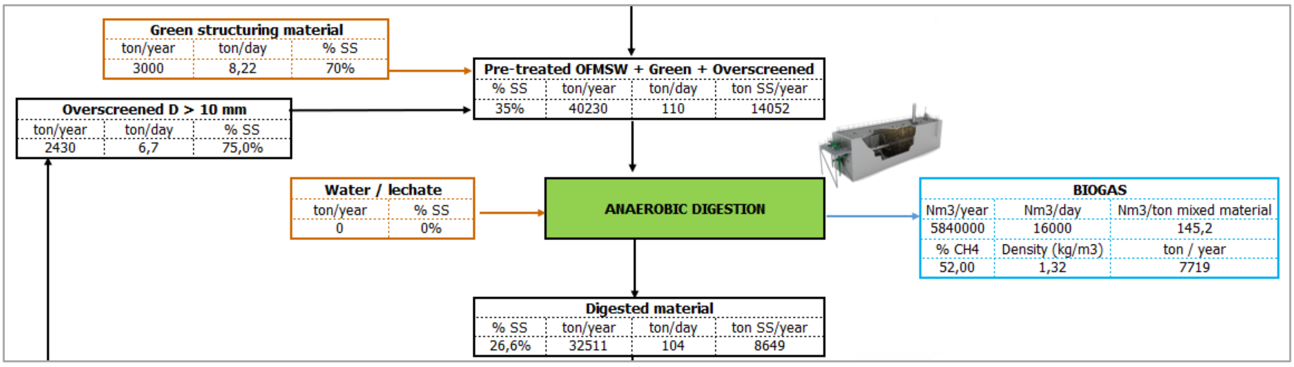


Figure 69: Digestion mass balance

In the mixer, the digestate is properly mixed with structuring material in a percentage useful to guarantee a good compostable material, which is 50% of digestate ad 50% of structuring. The added material comes from the inlet flow of green wastes and from the over screened of the intermediate screening process.

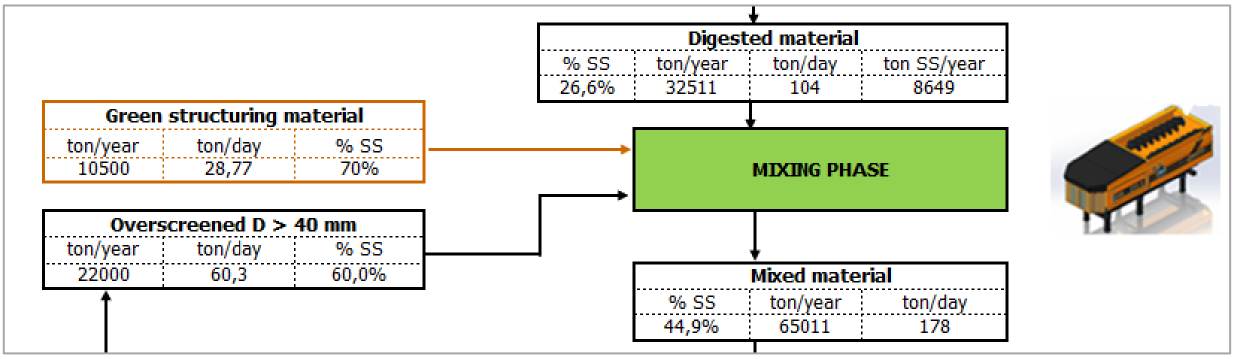


Figure 70: Mixing phase mass balance

The mixed material enters the bio cells, which are characterized by a 30% of process losses. The mixed material, decreased of the quantity of the losses, is subjected to the intermediate screening with a yield of over screen equal to 45 - 50%.

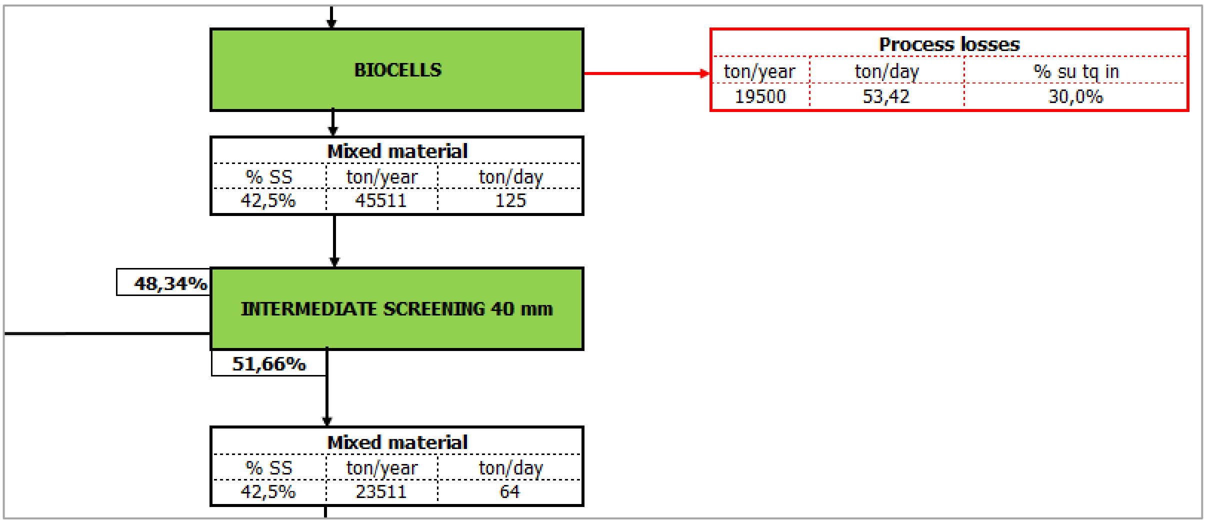


Figure 71: Composting mass balance

Also, the maturation is characterized by process losses, in the amount of 6.000 ton/year. The final screening returns over screened material, with a yield of the 13 - 14%, and compost, which is the final product.

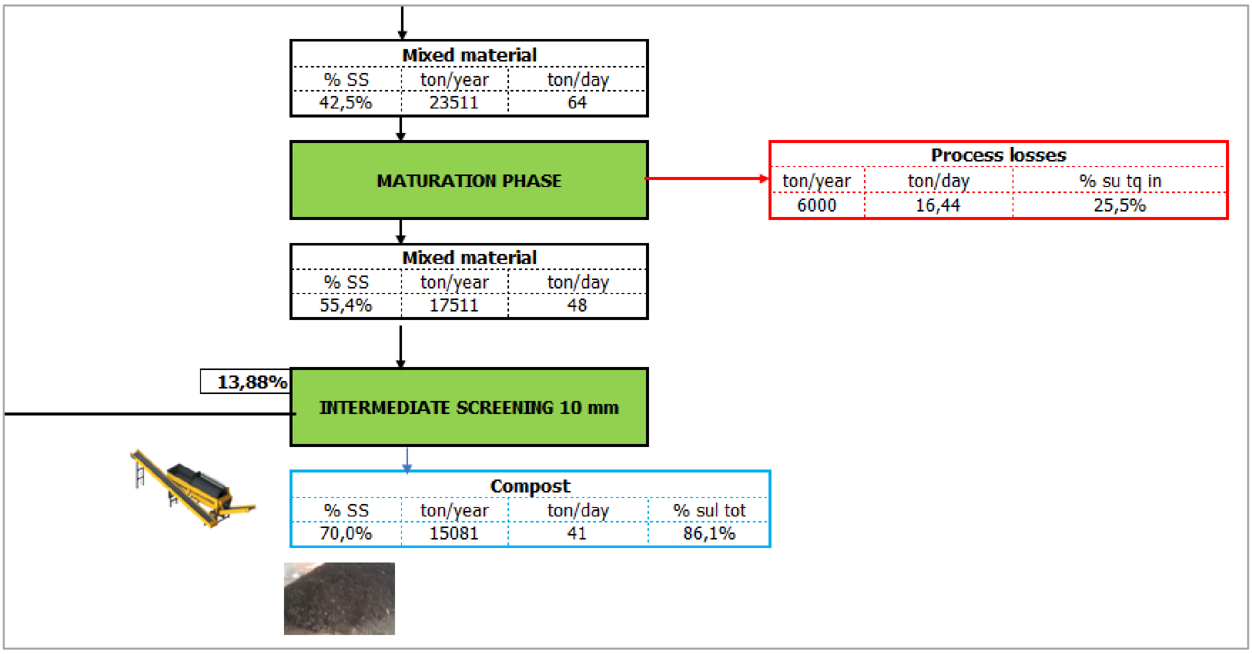


Figure 72: Composting mass balance

Regarding the upgrading part, the incoming biogas is considered as 900 Nm^3/h from the dimensioning of the plant. During the upgrading process, the biogas flow goes under three steps of purification: ammonia removal, H_2S removal and VOC removal. The removed quantities are very small, since the impurities are present in a small percentage. The cleaned biogas enters into the compressor and then into the membrane. The products are the biomethane and the off gas.

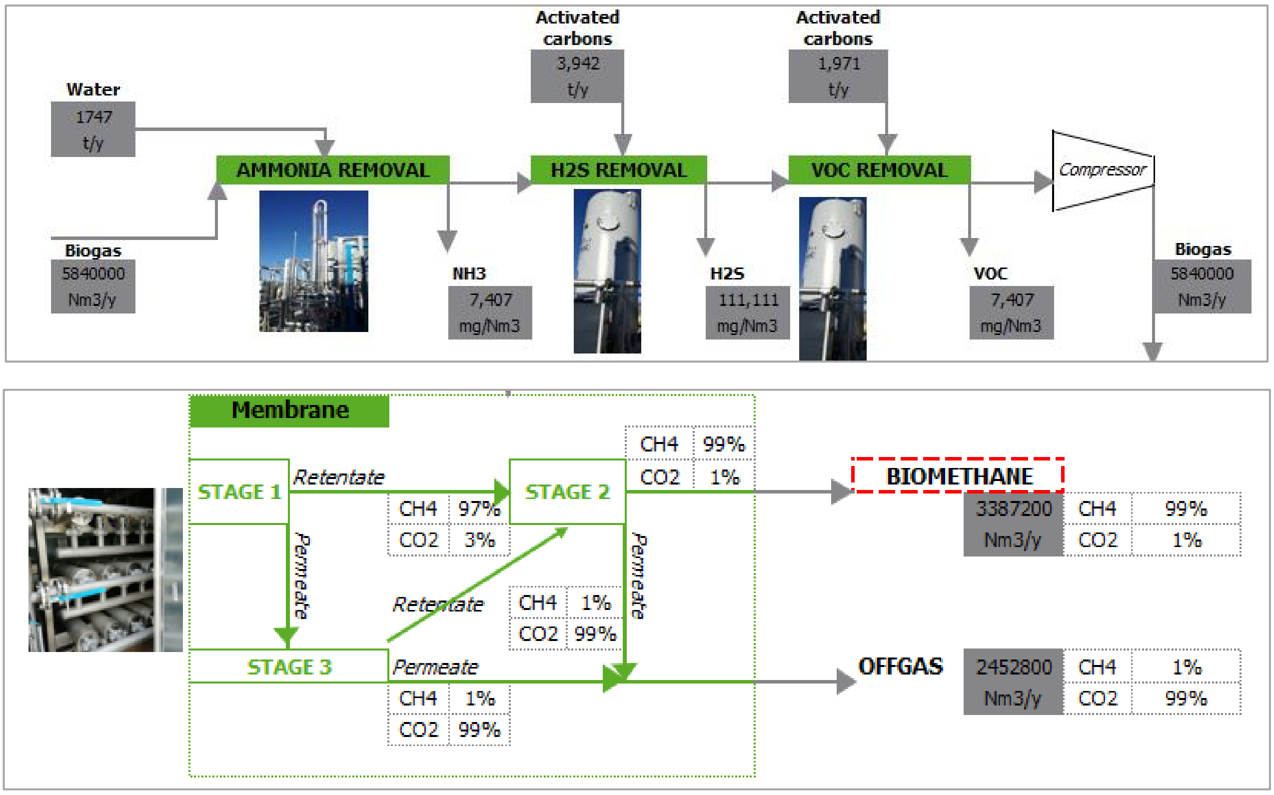
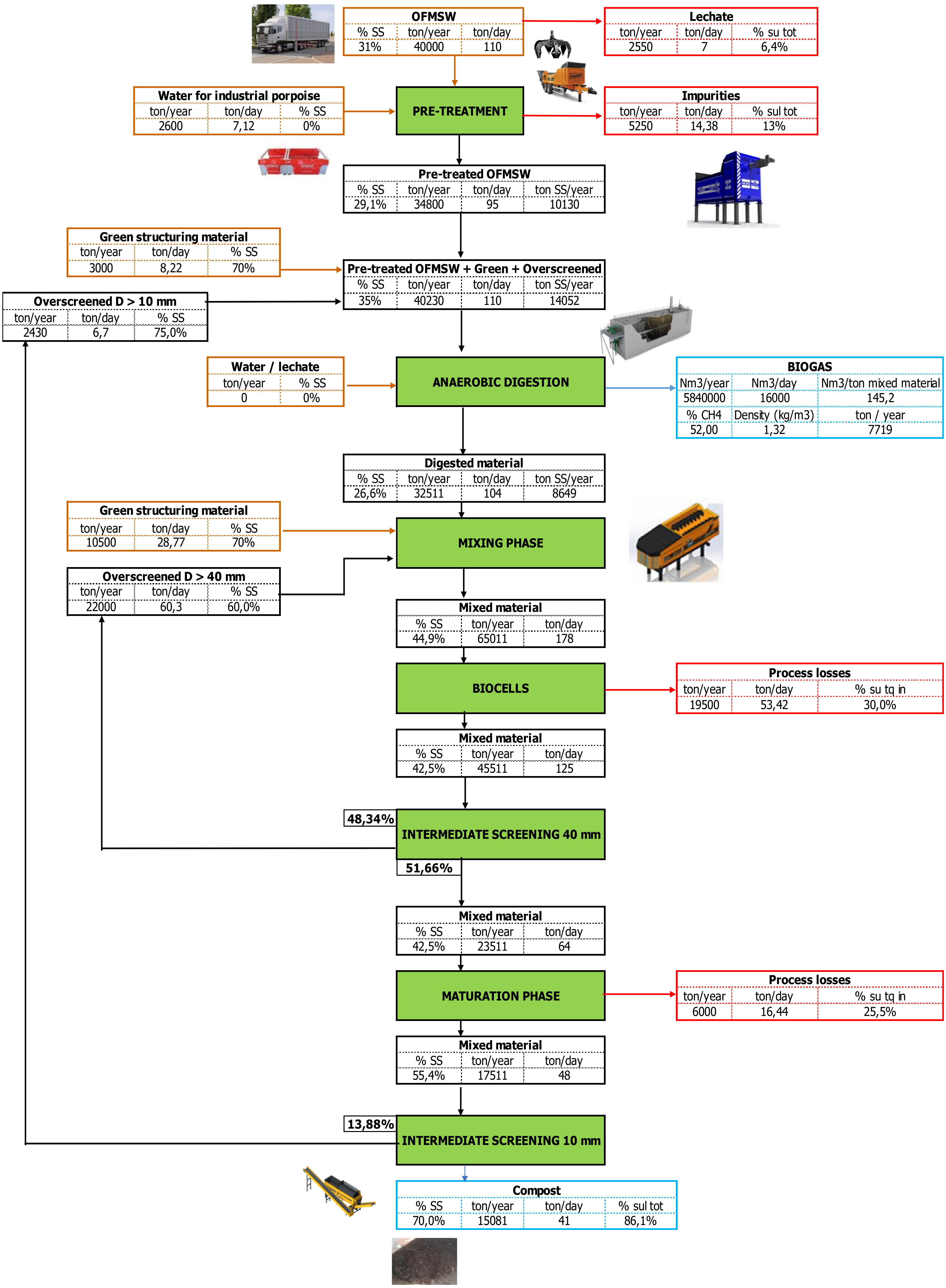


Figure 73: Upgrading mass balance


OFMSW
% SS 31% | ton/year 40000 | ton/day 110
Lechate
ton/year 2550 | ton/day 7 | % su tot 6,4%
Water for industrial porpoise
ton/year 2600 | ton/day 7,12 | % SS 0%
PRE-TREATMENT
Impurities
ton/year 5250 | ton/day 14,38 | % sul tot 13%
Pre-treated OFMSW
% SS 29,1% | ton/year 34800 | ton/day 95 | ton SS/year 10130
Green structuring material
ton/year 3000 | ton/day 8,22 | % SS 70%
Pre-treated OFMSW + Green + Overscreened
% SS 35% | ton/year 40230 | ton/day 110 | ton SS/year 14052
Overscreened D > 10 mm
ton/year 2430 | ton/day 6,7 | % SS 75,0%
Water / lechate
ton/year 0 | % SS 0%
ANAEROBIC DIGESTION
BIOGAS
Nm3/year 5840000 | Nm3/day 16000 | Nm3/ton mixed material 145,2
% CH4 52,00 | Density (kg/m3) 1,32 | ton / year 7719
Digested material
% SS 26,6% | ton/year 32511 | ton/day 104 | ton SS/year 8649
Green structuring material
ton/year 10500 | ton/day 28,77 | % SS 70%
MIXING PHASE
Overscreened D > 40 mm
ton/year 22000 | ton/day 60,3 | % SS 60,0%
Mixed material
% SS 44,9% | ton/year 65011 | ton/day 178
BIOCELLS
Process losses
ton/year 19500 | ton/day 53,42 | % su tq in 30,0%
Mixed material
% SS 42,5% | ton/year 45511 | ton/day 125
48,34%
INTERMEDIATE SCREENING 40 mm
51,66%
Mixed material
% SS 42,5% | ton/year 23511 | ton/day 64
MATURATION PHASE
Process losses
ton/year 6000 | ton/day 16,44 | % su tq in 25,5%
Mixed material
% SS 55,4% | ton/year 17511 | ton/day 48
13,88%
INTERMEDIATE SCREENING 10 mm
Compost
% SS 70,0% | ton/year 15081 | ton/day 41 | % sul tot 86,1%

6.11 Energy balance

The plant requires thermal energy for the management of the biological process and electrical energy for the supply of all machinery.

The thermal energy, necessary for the anaerobic digestion plant section, is exploited to guarantee an optimal temperature regime for the metabolic activities of the bacteria responsible of the degradation of the organic substance.

Electrical power is used for the mechanical and electromechanical components installed in each of the different plant sections, the control devices, auxiliary services as well as the general services of the entire productive plant.

The data for the estimation of the **electrical consumption** in the entire plant have been collected directly from the exercise of the plant.

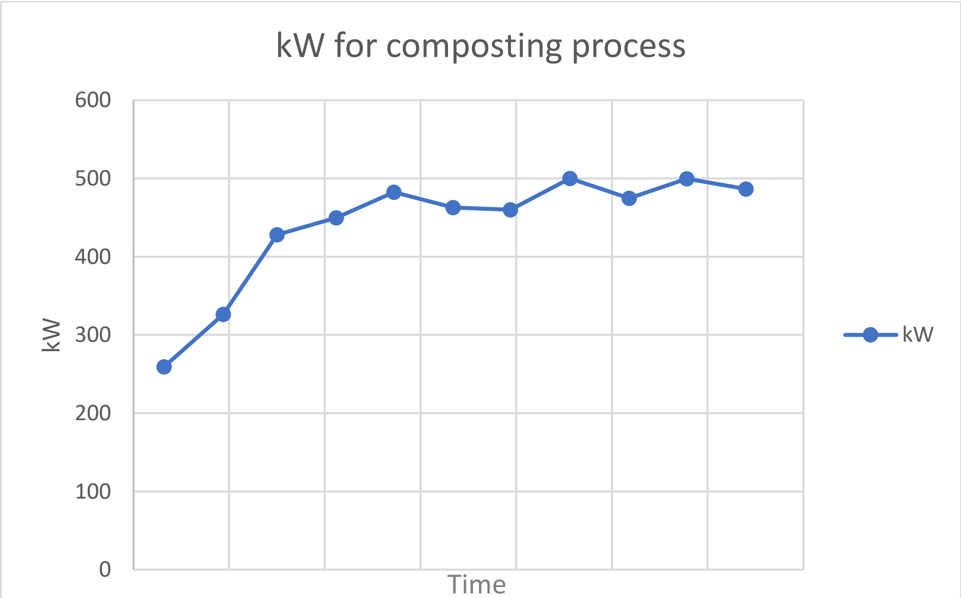


*Figure 74: kW used in the composting process, evaluated over the total hour of the month calculated as 24h*days in each month*

The behaviour represented in the graph is due to the initial ramp up of the plant. The trend became consistent when the upgrading plant entered in operation.

The highest electrical energy requirement comes from the upgrading section and from the section of compost production, since a ventilating system is always in function.

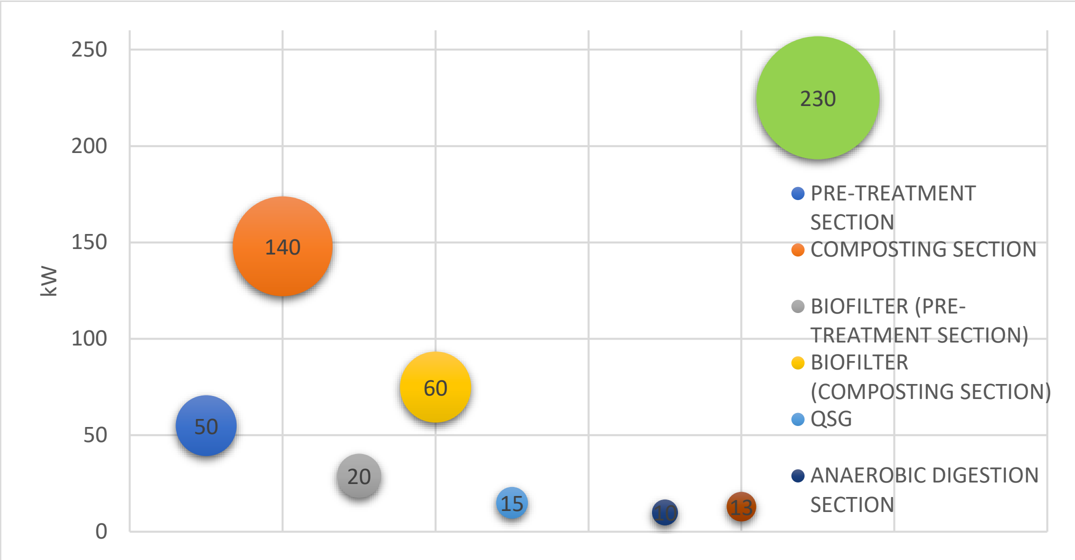


Figure 75: Electrical energy consumption in the various sections (kW)

Regarding the heat consumption, the only process that requires it is the anaerobic digestion. The heat is provided by a boiler alimented by fuel.

Table 16: Thermal requirement for the anaerobic digestion

Parameter	Value
Thermal power	150-384 kW_t
Flowrate	36 m3/h
T in	80°C
T out	72°C

Thermal power consumption has a behaviour coherent with the changing of the season: during winter the requirement is higher to maintain the same temperature inside the digester.

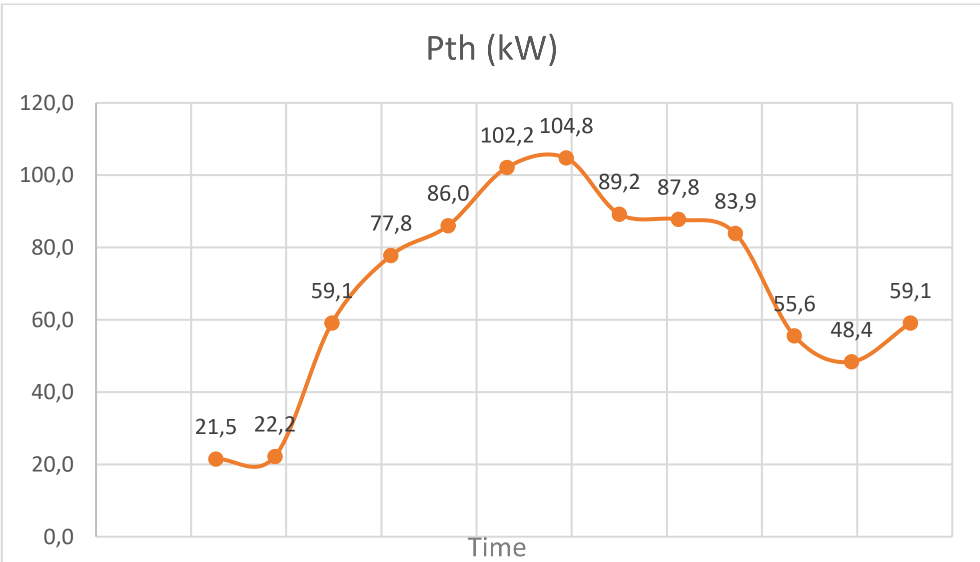


Figure 76: Thermal power required

6.12 Sustainability

The Foligno plant is part of the activities acted to reach the goals of sustainability in a framework of climate change due to the increase of pollution and greenhouse gasses in the atmosphere.

The sustainability of the plant consists in three main aspects:

- usage and recycling of wastes from municipalities that will otherwise be left into landfills, releasing harmful gases in the atmosphere and bad substances in the ground
- avoiding the usage of natural gas, which is a fossil and non-renewable fuel
- decreasing the release of CO_2 into the atmosphere: the biofuels are "carbon-neutral", which means that all the CO_2 emissions generated are balanced with the absorption of the same quantity of CO_2 by the crops where they derive.

Biofuels usually arise apprehensions regarding:

- greenhouse gasses (GHG) emissions
- loss of biodiversity due to the change in use of the soil
- social issues
- increase in the price of the food
- possible fraud for the advanced ones.

The *European Directive 2009/28/CE* reacted to those points asking certificates in which Productors of biofuels have to declare the conformity of the products with some **sustainable criteria**.

The sustainability has to be declared for the final product, for the raw materials and for the intermediate products used during the entire process (chain of custody). The statement has to assess that the soil has been used without socio-environmental impacts, for the biofuels coming from crops.

6.12.1 GHG avoided emissions

One of the most interesting point of discussion for the sustainability of the plant is the greenhouse gasses emissions. The Directives imposes that the emissions of GHGs to produce and to use the biofuel has to be lower that a reference value with respect to the GHGs emissions generated from the usage of the reference fossil fuel. Each member of every step of the supply chain, which comprehends raw material procurement, processing and transport and distribution of the final product, has to assess the value of the greenhouse gasses associated to the products and expressed in terms of gCO_{2eq}/kg of product.

$$E = eec + el + ep + etd + eu - esca - eccs - eccr - eee$$

where:

E is the total emission deriving from the usage of the biofuel.

eec is the emission deriving from the procurement of the raw material.

el is annual emission due to the change of usage of the soil, in terms of carbon storage

ep is the emission due to the upgrading process.

etd is the emission deriving from transport and distribution of the final product.

eu is the emission deriving from the usage of the biofuel.

esca is the emission avoided thanks to a better usage of the raw material, both deriving from agricultural activities and from wastes recycled.

eccs and eccr are the emission avoided thanks to the capture and storage of the carbon

eee is the emission avoided thanks to the surplus of electricity produced with cogeneration.

The emissions avoided are to be calculated also in terms of gCO_{2eq}/MJ to be compared with the reference values.

The saving is expressed as:

$$Saving[\%] = \frac{(E_f - \sum_i Eb_i)}{E_f} * 100$$

where:

Eb_i is the value of the emissions of each step of the process for the biofuel production, of the raw material and every intermediate product.

Ef is the reference value for the reference fossil fuel, equal to 83.8 gCO_{2eq}/MJ.

6.12.2 Sustainability procedure applied to the biomethane plant

Each month, a sustainability certification is provided, with the value of the overall biomethane produced in the month, expressed in Sm3.

The sustainability certification responds to the requirements of the DM 23 January 2017 (art. 7 comma 8).

The plant is included among those for which standard values of greenhouse gas emissions are defined in the DM 14/11/2019.

The emissions of GHGs are calculated with the previous formula and are expressed in gCO_{2eq}/MJ. The GHGs evaluation is updated every six months. The first evaluation is based on the project values, while the following ones are based on real operational data.

The reference period assumed for the evaluation is the current year (2019) with 365 days and with a biomethane injected in the grid equal to 3.712.000 Sm^3.

With an estimated production of 6.400.000 Sm^3 of biogas produced in one year, considering 58% of percentage of methane in the biogas, 3.712.000 $Sm^3_{bio\text{-}CH4}$ are produced. The density of biomethane is considered as 0.000714 t_{CH4}/Nm^3_{CH4}, obtaining 2.650,4 ton_{CH4} produced every year.

The quantity of CO_2 equivalent is calculated considering the GWP of CH_4 equal to 23 times the GWP of CO_2 (in accordance with DM 23/02/2012). Indeed, 60.958,5 tCO_{2eq} are produced, recovering them from the waste treatment.

Table 17: Conversion table

GWP CH_4	23	kg CO_{2eq}/kgCH_4
Biogas	6.400.000	Nm^3
CH_4 in biogas	58%	-
Biomethane	3.712.000	Sm^3
Density	0,000714	tCH_4/Sm^3CH_4
bio-CH4 in biogas	2.650,368	tCH_4
CO_2 equivalent	60.958,464	tCO_{2e}
PCI biomethane	9,45	kWh/Sm^3
PCI biomethane	34,02	MJ/Sm^3
kWh equivalent	35.078.400	kWh

The total emissions are calculated in according with the Directive, considering the total emissions of the process (e_p) and the emission of transport (e_{td}). For the emissions of the process, the quantity of the substance under consideration is multiplied by the emission factor of the same substance (E_f), values that comes from literature.

Table 18: Emissions for each flow

EM	*$kgCO_{2eq}$/period*	*% over the total*	*Consumption*	*Unit*	*EF*	*Unit*
Electricity consumption	552.000,00	21,0713%	1.200.000,00	kWh	0,46	kgCO2eq/kWh
Natural Gas (for e.e. self-production)	981.942,60	37,4833%	500.000,00	Sm3	55,90	t_{co2eq}/TJ
Heat Production (gasoil consumption)	268.158,33	10,2363%	100.000,00	kWh	73,58	t_{co2eq}/TJ
Process Water	1.200,00	0,0458%	4.000.000,00	kg	0,0003	$kgCO_{2eq}/kg$
Deionised Water	5,00	0,0002%	5.000,00	kg	0,001	$kgCO_{2eq}/kg$
Air Compressed	41,37	0,0016%	384,62	m^3	0,11	$kgCO_{2eq}/m^3$
Oxygen	190,89	0,0073%	300,00	Nm^3	0,64	$kgCO_{2eq}/kg\ O_2$
Fe(OH)3	3.624,50	0,1384%	5.000,00	kg	0,72	$kgCO_{2eq}/kg_{Fe(OH)3}$
NaHCO3	5.790,00	0,2210%	3.000,00	kg	1,93	$kgCO_{2eq}/kg_{NaHCO3}$
Active carbons	79.845,00	3,0479%	10.000,00	kg	7,98	$kgCO_{2eq}/kg_{\text{active carbon dry}}$
Wastewater	0,099	0%	0,30	m3	0,33	$kgCO_{2eq}/m^3$
Off gas (CH4)	279032,32	10,6514%	17.920,00	Sm3	23,00	$kgCO_{2eq}/kg\ CH_4$
Waste	447.849,30	17,0956%	4.470.000,00	kg	0,10	kgCO2eq/kg

Table 19: Saved GHG

e_p (tot process emissions)	2.619.679,41	$kgCO_{2eq}$/ref_period
e_p (specific tot process emissions)	705,73	$gCO_{2eq}/ Sm^3_{biomethane}$
e_{td} (transport emissions)	63.141,12	$kgCO_{2eq}$/ref_period
e_{td} (specific transport emissions)	17,01	$gCO_{2eq}/ Sm^3_{biomethane}$
e_t (total emissions)	2.682.820,53	$gCO_{2eq}/ Sm^3_{biomethane}$
e_t (total specific emissions)	722,74	$gCO_{2eq}/ Sm^3_{biomethane}$
Value of the reference fossil fuel	83,8	gCO_{2eq}/MJ
E_{fossil}	2.850,876	$gCO_{2eq}/ Sm^3_{biomethane}$
GHG SAVINGS		***74,65%***

From the evaluation, the calculate emissions of GHG is reduced by the 74,65% producing and using biomethane, with respect to the same quantity of natural gas in the form of fossil fuel.

7. Data from Operation

The Foligno plant, managed by Asja Ambiente Italia S.p.A., is in operation since 2018, regarding the composting plant, and since 2019, regarding the upgrading process.

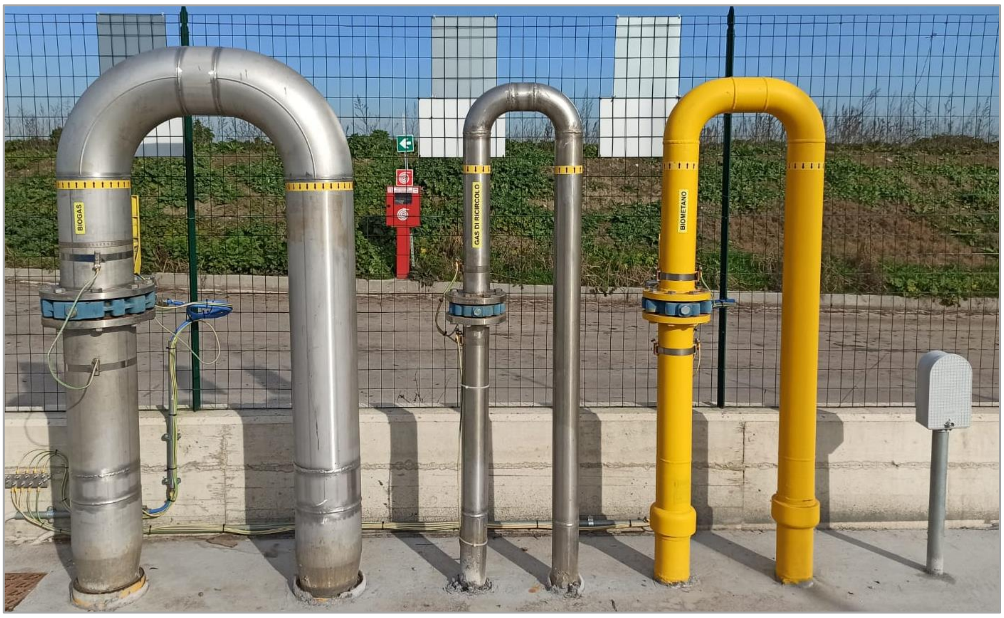


Figure 77: Piping for biogas, recirculated gas and biomethane

During the operational period, some considerations have been performed thanks to data deriving directly from the exercise of the processes involved, rather than from the literature.

In this chapter, some of those data are discussed with proper graphs. For each part of the plant (conferral, pre-treatment, digestion, maturation and upgrading) some data are to take particularly under control, as they can affect the overall process.

The entire plant route begins with the conferral of the organic fraction of municipal solid waste. It happens six days a week, excluding Sundays and festivities. In the graph below, the behaviour of the conferral reflects it. The trend shows a fluctuation in the conferral, since it comes from municipalities and the quantity is affected from the waste collection. The average value is around 100 ton/day.

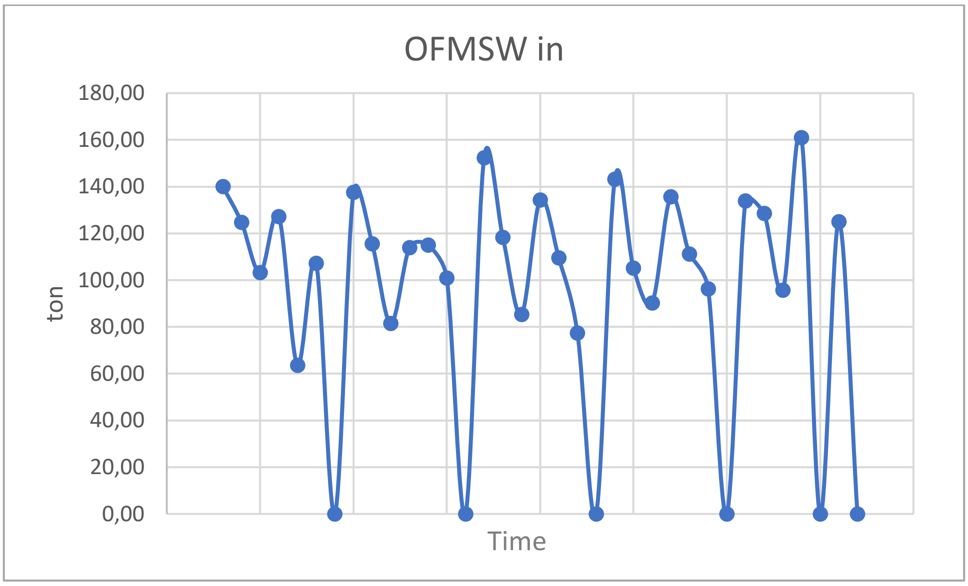


Figure 78: OFMSW conferral

The organic fraction is collected in the pit, where it is stored for at maximum 3 days and where there is production of leachate, for an average of 7 ton/day. In the graph reported, is it shown that the production of leachate is directly proportional to the conferral of the wastes.

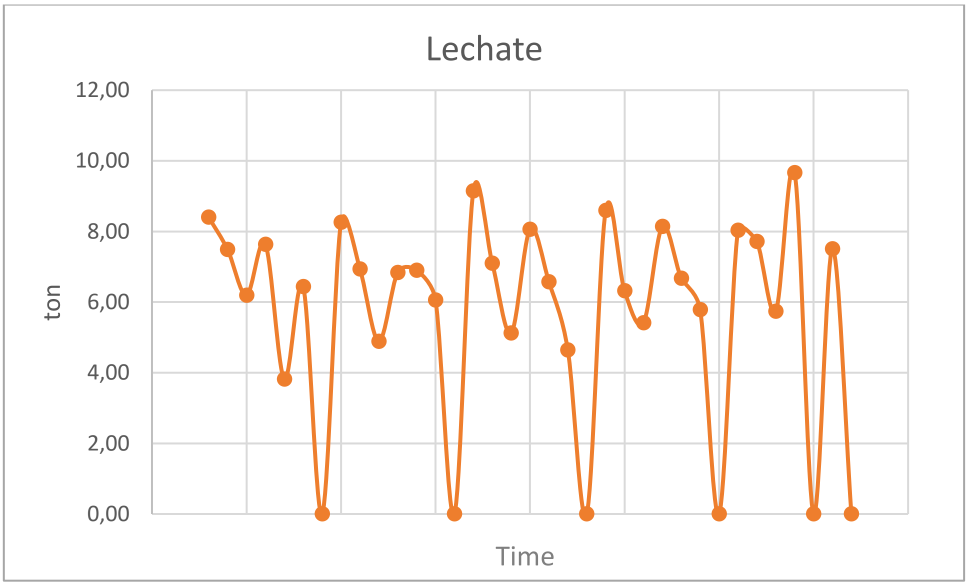


Figure 79: Leachate production trend

Once the pre-treatment is completed the mix, composed of the organic fraction, water and the structuring material (mowing + over screened from the final screening) enters in the digester. The digester needs specific parameters to perform a right anaerobic digestion and to return a good quantity of biogas and a digestate able to be composted. The trend shown in the graph below reports a stable input to the digestor, with a few exceptions caused by operational necessities.

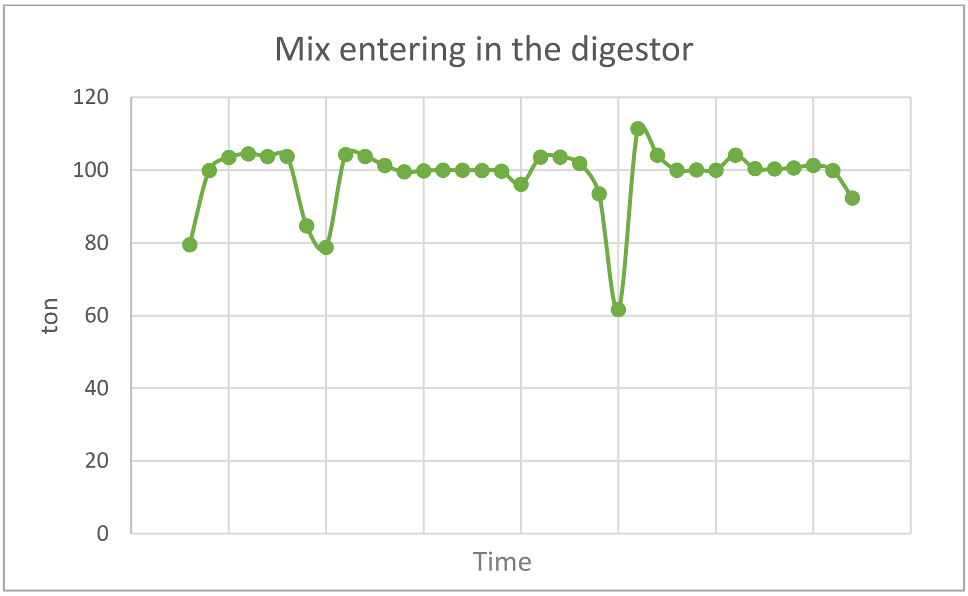


Figure 80: Mix entering in the digester

The anaerobic digestion process is constantly monitored since it is a sensitive biologic process which requires specific parameters to give the highest yield possible. The end products of the digestion, biogas and digestate, are what is sold, and they have to be as performing as possible.

An interesting parameter is the quantity of H_2S contained in the mixture in the digester, since it will influence the quantity of H_2S in the biogas. H_2S is an air pollutant responsible of damage to health and to environment, if in high quantity, and it is characterized by a strong odour.

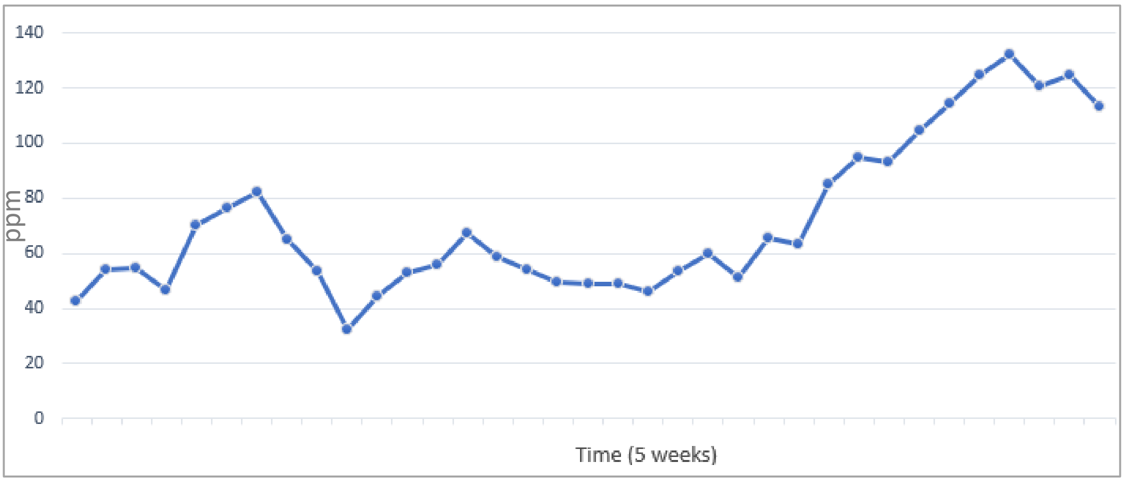


Figure 81: Trend of the quantity of H2S

The level of storage capacity of the two digesters is shown below. It is an important parameter to take into consideration. The maximum storage capacity is 70%, while the remaining 30% is for the collection area for the biogas. If the level reaches the 85%, the cochlea is shut down. If the level goes below the 70%, the disposal line is closed. If the level isn't in the right range, there might be lower space for the biogas formation on the top of the digester, or the cochlea doesn't permit the entering of new material.

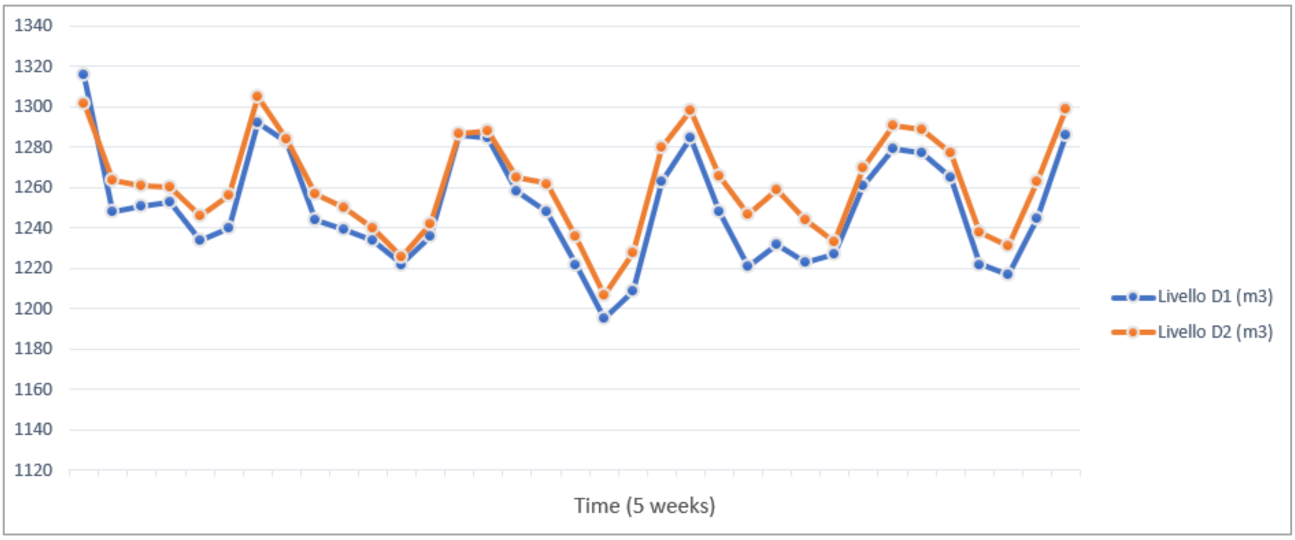


Figure 82: Trend of the level in the digester 1 and digester 2

After the anaerobic digestion, each product follows a different chain. The digestate goes into the mixing, the bio cells and the maturation phase, while the biogas goes to the upgrading and purification process.

The most interesting parameter of the composting part is the behaviour of the temperature inside the bio cells. It must remain within a certain range and it is controlled by the insufflation of a flow rate of air coming from the external environment, in a quantity directly proportional to the required fluctuations of the temperature.

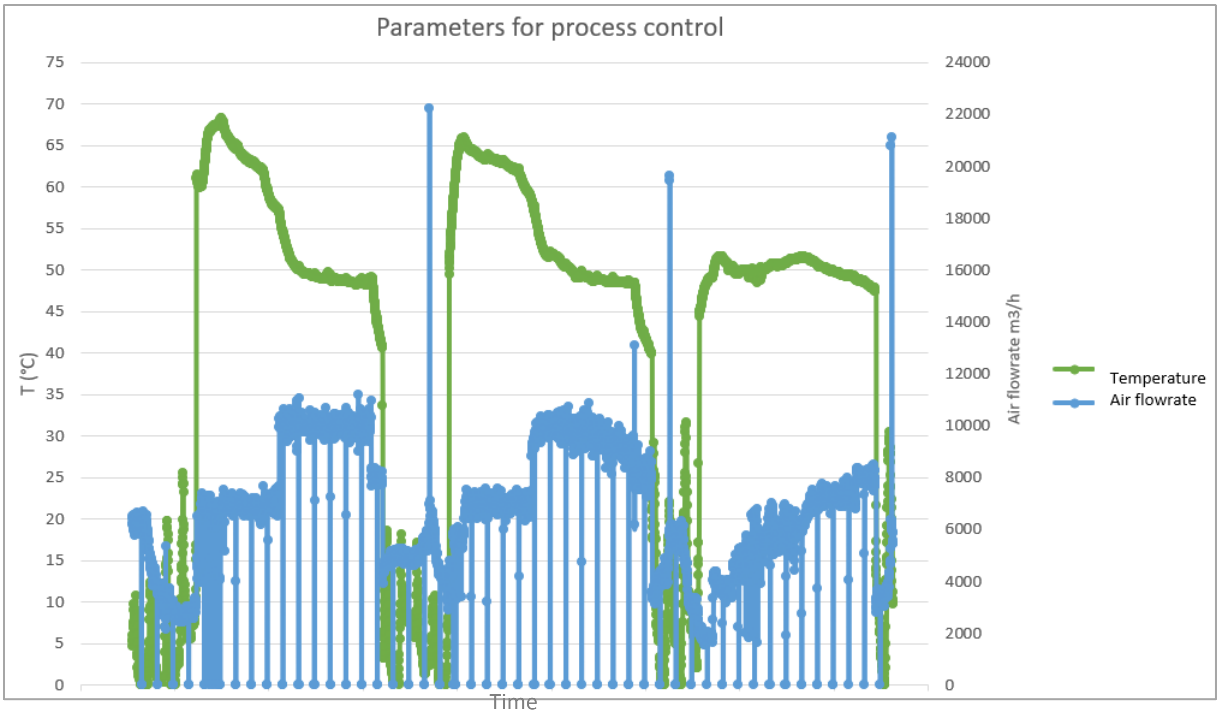


Figure 83: Relationship between temperature and air flowrate in the bio cells

The biogas goes into the upgrading part of the plant, where it is purified from ammonia and VOC and where it is separated in CO_2 and CH_4.

For the injection of the biomethane in the grid, some parameters have to be in a certain range. Those parameters are constantly controlled.

Some graphs of the main parameters are reported below.

First, the higher heating value, which is the amount of heat released by the unit mass or volume of fuel (initially at 25 °C) once it is combusted and the products have returned to a temperature of 25 °C.

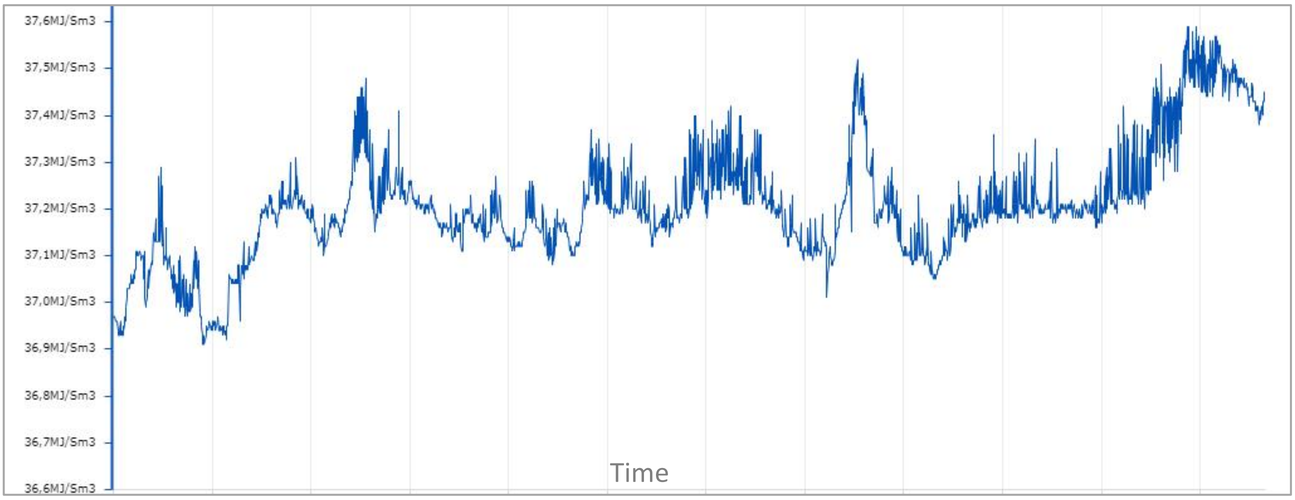


Figure 84: Trend of the Higher Heating Value of the produced biomethane

Then, the Wobbe Index, used to compare the combustion energy output of different composition fuel gases in an appliance.

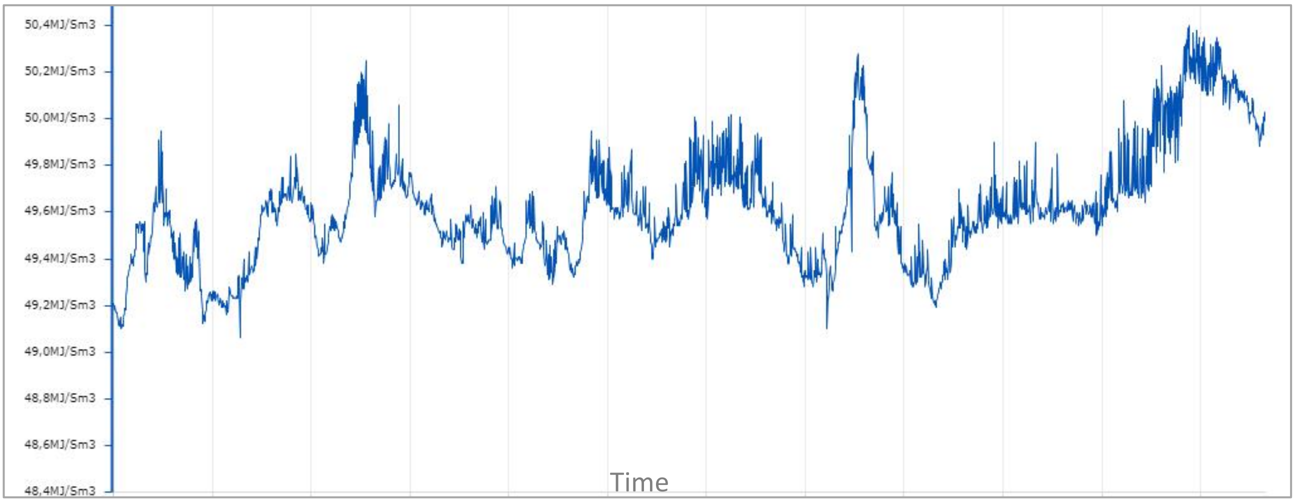


Figure 85: Trend of the Wobbe index of the produced biomethane

Even if the stream is cleaned and purified from pollutants, a small value of HS and CS still remains.

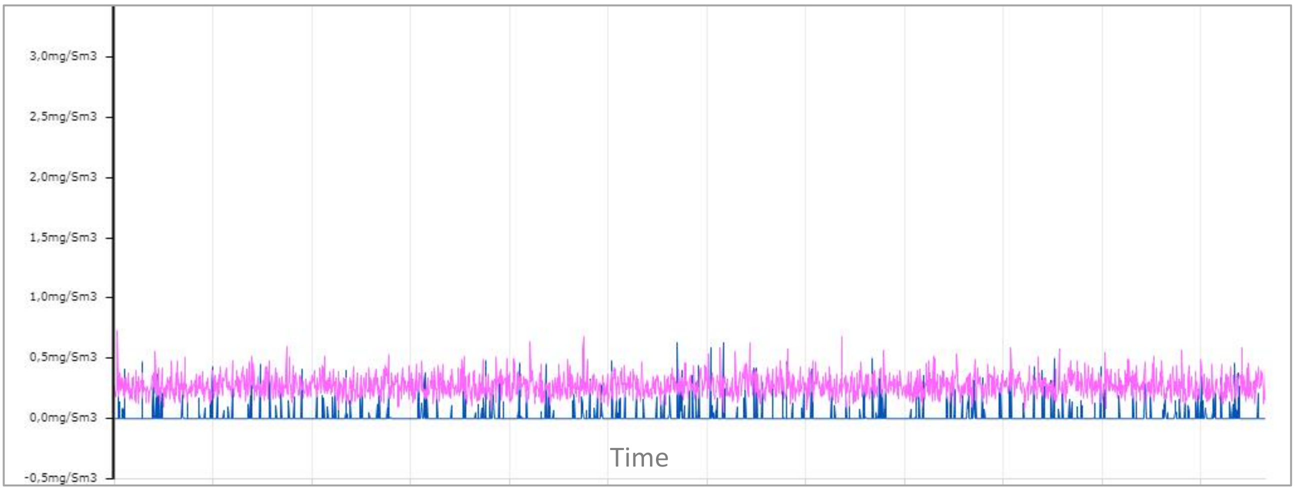


Figure 86: Trend of the quantity of CS (blue) and HS (pink) remaining in the produced biomethane

The quantity of carbon dioxide that remains in the flux injected in the grid has to be lower than 2.5 % mol/mol, imposed from legislation. It is an index of the purity of the gas.

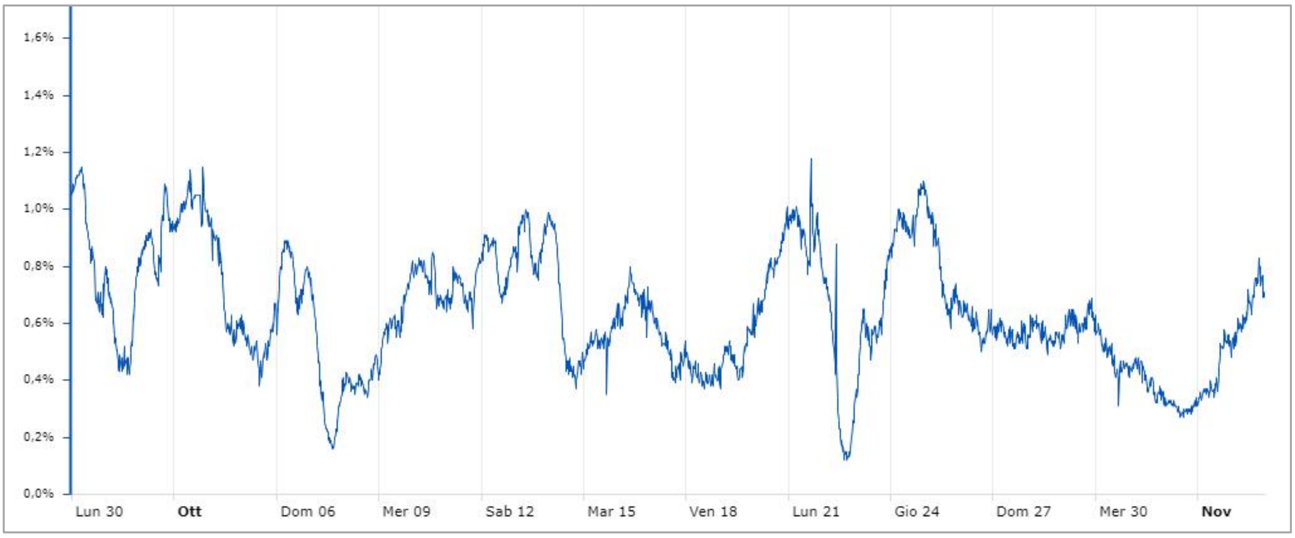


Figure 87: Trend of the CO2 remaining in the produced biomethane

8. Economic Analysis

The economic analysis for the Foligno plant has been performed by Asja Ambiente Italia S.p.A.

The plant has been constructed in the 2017. The operation of the plant began May 2018. The digestion process for biogas production began in June 2018, while the first Sm^3 of biomethane has been injected into the grid in March 2019.

The aim of the economic analysis is to evaluate the **payback time** and the **internal rate of return**.

The Payback Time (PBT) is the period of return of the total invested capital. It has to be as short as possible. It measures the time τ when negative cash flows are equal to positive cash flows.

$$-I + \sum_{t=1}^{\tau} \frac{B_t}{(1+i)^t} = 0$$

where I is the initial invested capital, B_t is the net cash flow, i is the inflation rate and t is the time in which each net cash flow is considered.

The Internal Rate of Return (IRR) is the value of i that makes the cash flow equal to the investment cost.

$$-I + \sum_{t=1}^{n} \frac{B_t}{(1+i)^t} = 0$$

It is expressed in percentage and it represent the increase of the value of the money invested after a certain period, arbitrarily chosen. It is a sort of efficiency of the plant in terms of cash flow. For example, if the IRR is equal to 10% after 10 years of plant operation, it means that the return of capital is 10% higher than the initial invested value.

The IRR, evaluated over the entire lifetime of the plant, is ***13%.***

The payback time is foreseen as 8 years. It means that from the 2026, there will be a real gain. The PBT is the time when the cumulated cash flow goes to zero.

The **cash flow** is the net amount of cash and cash-equivalents being transferred into and out of a business.

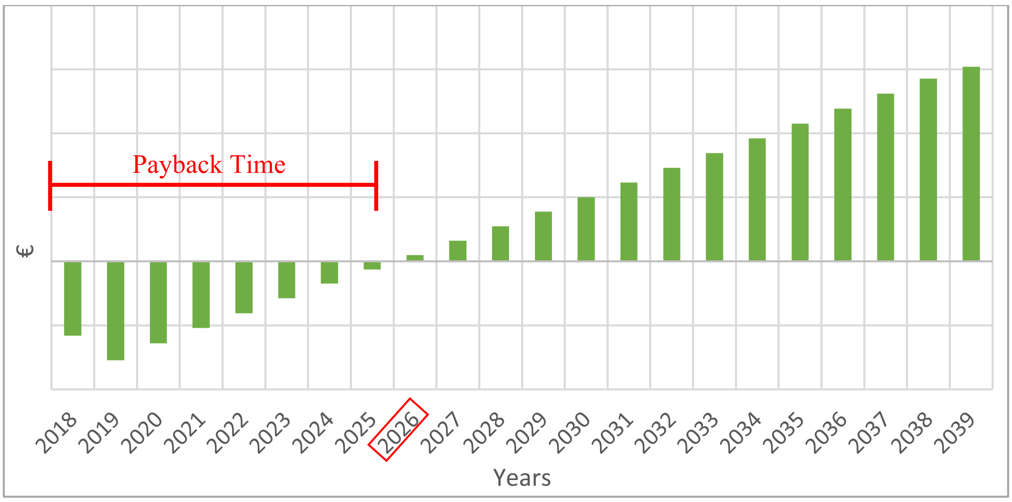


Figure 88: Cumulative cash flow

The net income is calculated as the difference between the EBIT and the taxes. The EBIT is the difference between the EBITDA and the sum of the depreciation of the initial investment and the provision for the decommissioning of the plant.

The EBITDA is the difference between incomes and outcomes.

$$EBITDA\ [€] = incomes - oucomes$$

$$EBIT\ [€] = EBITDA - (depreciation + decommissioning\ provision)$$

$$Net\ Income\ [€] = EBIT - interests - \ taxes$$

The **outcomes** of a plant are represented by CAPEX and OPEX.

8.1 CAPEX

CAPEX (capital expenditure) is the initial invested capital, which is the sum of the costs for the project phase and for the construction. The amount is usually invested during the first year of life of the plant and it is to be amortized during a certain period of operation of the plant, arbitrarily chosen.

In this case, the depreciation rate has been considered during the whole lifetime of the plant and it is determined as

$$Dep. Rate = \frac{TPC\ (€)}{20\ yr}$$

where the TPC is the total plant cost.

The total plant cost for the construction of infrastructures, civil works and for the supply of machines, instrument and tools needed for the process amount around €20 million.

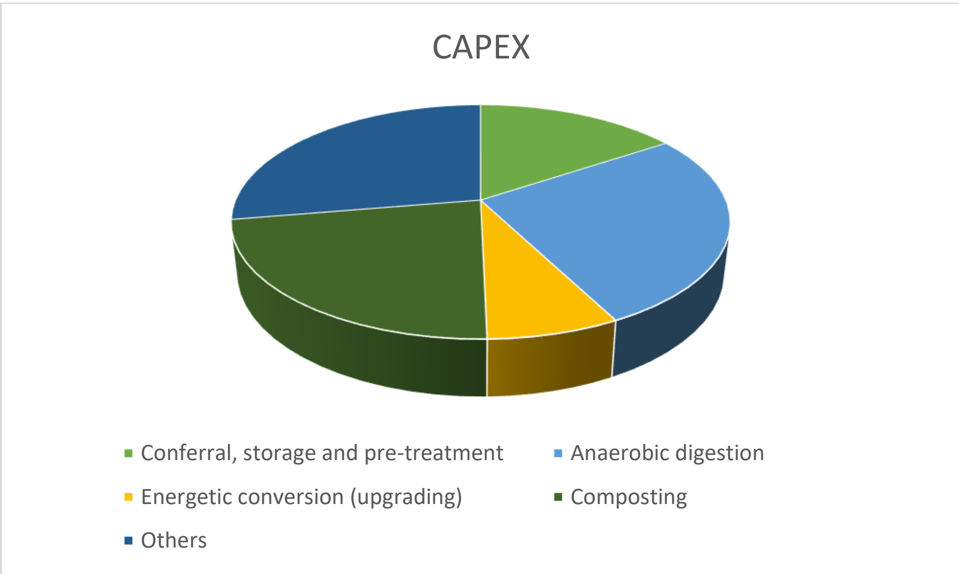


Figure 89: CAPEX costs divided by section

For the section of receiving, stock and pre-treatment of the inlet waste, the main responsible of the total price are the machines such as the screening, the bio separator and the shredder. Also, the civil works have a high impact over the total.

For the section of anaerobic digestion, the cost of the two digesters represent the whole expenditure and they are one of the most expensive CAPEX of the whole plant.

The sector of energy conversion includes the upgrading technology, which is expensive and innovative.

The composting process section has an important role over the total CAPEX, especially due to the cost of the mixer and bio cells.

Apart from the various sections, there are the costs for the electric plant and for the connection of the plant to all the existing infrastructures.

Since the initial investment for the construction of the plant is an important amount, external institutions gave funding for the implementation of the biomethane production technology.

Umbria Region gave a non-repayable fund for the composting part for a value of about €3 millions. The Region is positively involved in helping new plants that stands into the perspective of circular economy and environmental preservation.

Others funding came from banks, with a leverage up to 70-75% of the total investment cost.

8.2 OPEX

OPEX (operational expenditure) derives from operation and maintenance of the plant and it is the sum of all the costs to be spent during the operation phase.

The biogas production plant is supposed to work in continuous, while for the upgrading part the working hours are estimated as the 96% of the total. So, the capacity factor (CF) for the upgrading part is given by the ratio of the working hours over the total hours per year.

$$CF = \frac{working\ hours}{total\ hours\ per\ year} = \frac{8410}{8760} = 96\%$$

The OPEX are to be weighted over the effective working hours, which means multiply the OPEX by the CF.

The value of the incoming OFMSW used for the evaluation is 40.000 ton/year, with a percentage of wastes not treated and destined to the disposal of 12%.

In each section on the plant the costs are evaluated foreseeing fault of the machinery, according to the technical specification of each one, and labour requested from the external, in case of necessity.

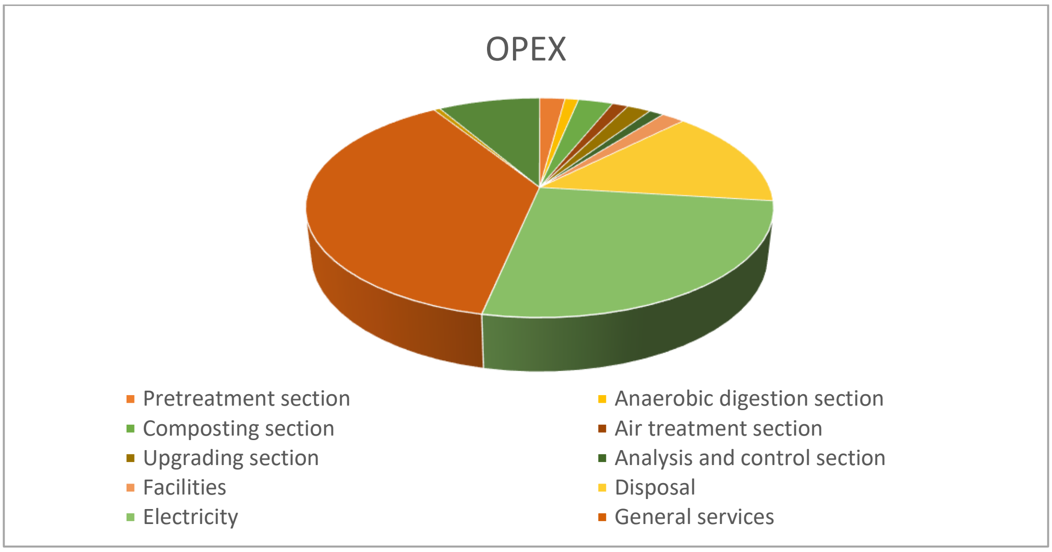


Figure 90: Total OPEX

General services comprehend the costs for telephone services, water and methane supply, GSE taxes, assurances, transports, logistic and all the costs for the everyday living of the plant.

The highest impact over the total is due to electricity purchase and general services.

OPEX also includes salaries of the operators and of the plant manager which work in the plant every day.

One of the operational costs which have a higher impact over the total OPEX is the costs for the disposal of the materials that cannot be used in the digestion process, coming mainly from the pre-treatment section.

The main part where an optimization can decrease the operational costs are the electricity purchase and the disposal. Nowadays, some improvement are taken into consideration for the future.

A fundamental part of the operational costs are the periodic analysis and all the instruments. Analysis are provided for the incoming materials, for the over screened material and for the emissions on all environmental matrix. Laws and regulations impose sever standard on the quantity and quality of the allowed emissions, so the analysis must be provided often and are to be taken into severe control.

The total value of the operative costs corresponds to an average of 70-80 € for each ton of OFMSW entering the plant.

An important parameter used to take under control the behaviour of the plant is the unit costs of management (€/Sm^3), which gives an overview on the cost to be paid every Sm^3 of biomethane produced and sold.

8.3 Incomes

The incomes of an advanced biomethane plant derives both from the GSE, which provides CICs, and from selling the biomethane at its effective market price.

The trend of the biomethane market price is analysed and planned to predict the income cash flow. It is on average 18 €/MWh.

In the case of the Foligno plant, the biomethane to be injected in the grid is collected from the GSE, which pays the market price of the biomethane minus a 5% as the transport fees.

The service life of the plant is intended to be 20 years, until March 2039. For 10 years, the CICs are assured at the fixed price of 375€, while in the following 10 years the CICs will be paid according to the market trend.

OFMSW biogas production plants can count on the income flow deriving from the conferral of the wastes, provided from the municipalities which bring them directly to the plant, including the conferral of the green wastes.

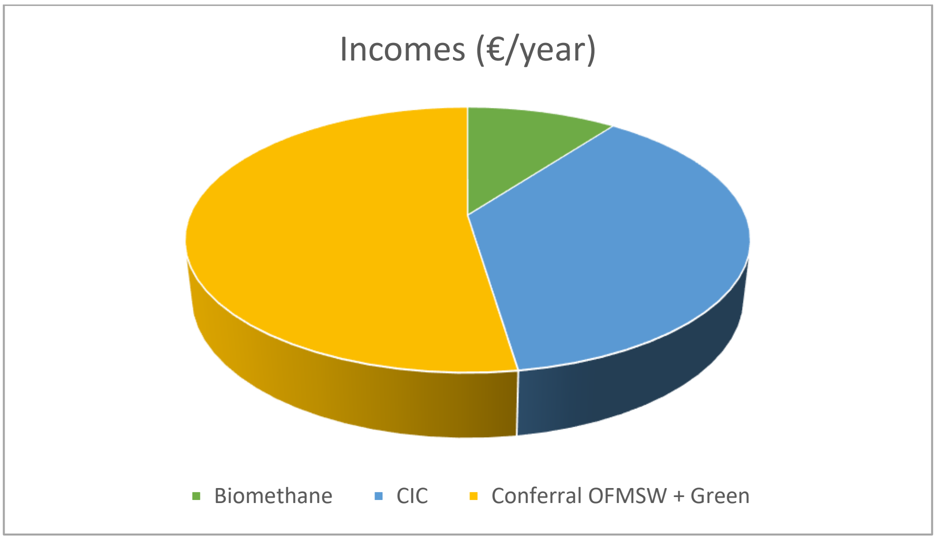


Figure 91: Incomes

During the first year, the costs are represented by the total investment, since the plant is under construction. From the second year on, the depreciation rate, incomes and operating costs have to be considered.

9. Improvement for the plant: CO_2 recovery from off gas

Biomethane and carbon dioxide are the products coming from the upgrading process. Biomethane is the final, useful and valuable product, while the carbon dioxide is collected from the membranes in the permeate and emitted as an off gas.

Currently, in the Foligno plant, the off gas is released into the atmosphere with a flowrate of 370 Sm^3/h.

The off gas is composed of a high-purity flow of CO_2. The following chapter deals with the possibilities to recuperate such flow, also recovering the remaining biomethane and enhancing the opportunities that CO_2 can give.

The possibility to recover and to stock the carbon dioxide has to be evaluated in accordance with the demand in the market.

In a world of decarbonization priority and in a frame of a biomethane production plant, the main opportunity to recover the off gas, and to avoid any methane loss, is the process of methanation, which is part of the Power-To-Gas technologies. The methanation process consists in the synthetization of CH_4 from CO_2 and H_2, which has to be produced with an electrolysis process.

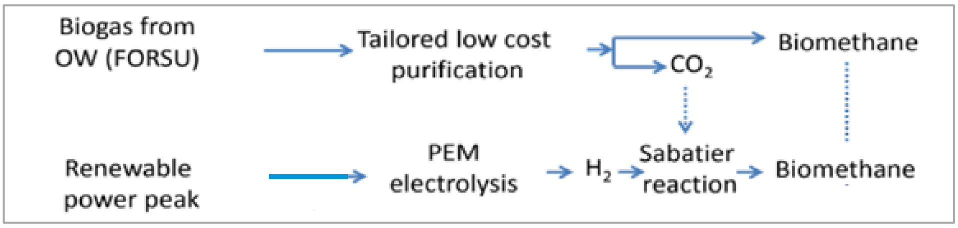


Figure 92: Fluxes scheme

Although, the process of methanation requires high capital and operational costs, so it is only in research projects and it is not commercialized for plants with a reduced capacity, as the Foligno plant. One of the main issues is the procurement of the hydrogen, which has to be purchased, increasing the plant OPEX, or produced on site, increasing both the CAPEX and the OPEX.

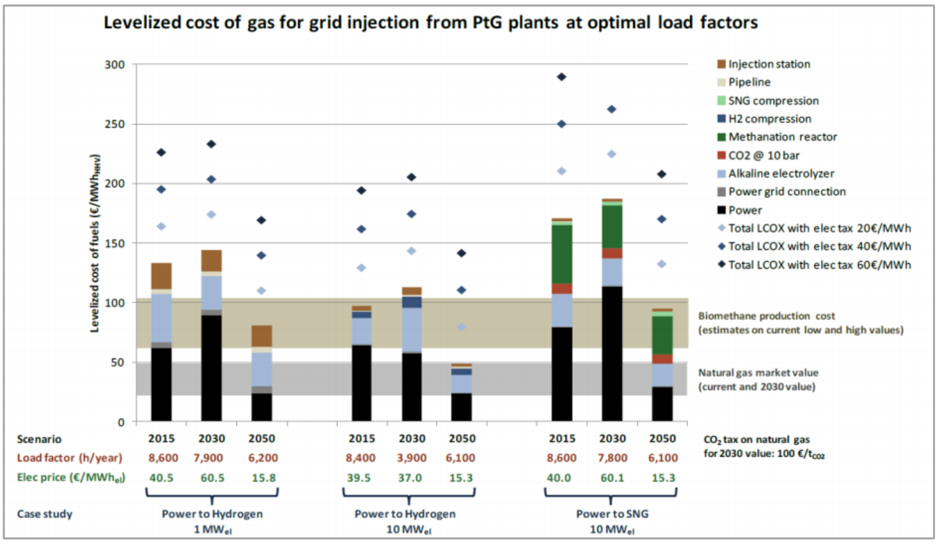


Figure 93: Levelized cost of hydrogen and methane under various scenarios

9.1 Electrolysis

The electrolysis process consists in splitting water molecules in oxygen and hydrogen by means of the transition of electrical current in an appropriate electrolyte.

It is an endothermic process which requires an energetic contribute.

$$H_2O \rightarrow H_2 + \frac{1}{2}O_2$$

$$\Delta H° = 285.84 \frac{kJ}{mol}$$

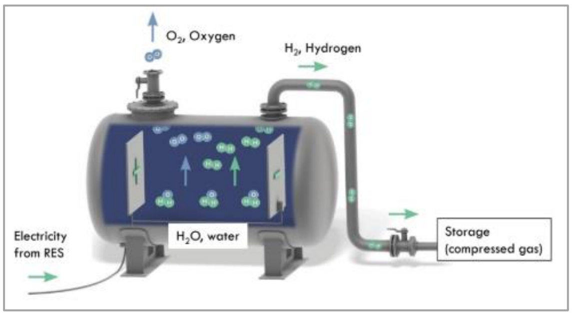


Figure 94: Electrolyser

Technologies available today are:

- Alkaline Electrolysis
- Polymer Electrolyte Membrane
- Solid Oxide Electrolysis

Table 20: Comparison of the technologies for electrolysis

	Alkaline	**PEM**	**SOEC**
State of development	Commercial	Commercial	Laboratory
Electrolyte	OH-	Nafion	ZrO_2 ceramic doped with $Y_2O_3O^{2-}$
Power consumption kWh$_e$/Nm3H2	4.5-7	4.5-7	3
Efficiency	67-70%	60-80%	90%
Investment cost €/kW$_e$	800-1000	1400-2100	>2000

9.2 Methanation

There are various catalytic and biological methods for methanation which have been developed at a demonstration scale (in the range 1 to 10 MW of electricity consumption) in recent years.

9.2.1 Biologic methanation

In this case, methanogenic microorganisms work as a biocatalyst converting CO_2 into CH_4. The process takes places in a liquid solution under the temperatures of 40 – 70 °C. Reduced temperatures can simplify the process, reducing the possibility of recirculating the excess of heat. STR or bubble reactors are the main exploited. Although, high specific volumes are required. his process is highly tolerant to the pollutant, making the clean-up process easier.

9.2.2 Catalytic methanation

It is developed in the temperature range of 300 - 400 °C, at pressures between 1 - 30 bar, by means of nickel or ruthenium base catalyst.

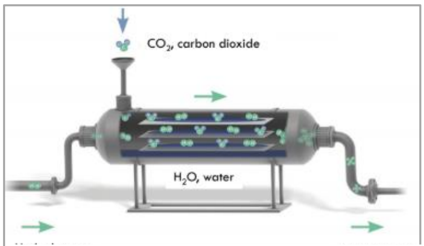


Figure 95: Methanation reactor

$$CO_2 + 4 * H_2 \rightarrow CH_4 + 2 * H_2O$$

$$\Delta H° = -165 \frac{kJ}{mol}$$

The reaction is highly exothermic. So, the temperature has to be under control. The excess of heat can be recirculated.

9.3 Applications

The carbon dioxide is used in industrial and food and beverage processes.

In the Food & Beverage Industry, it is used for sparkling beverages, for packaging food under protective gas atmosphere. It is also employed in greenhouses, used as fertilizer for enhancement of production food grade quality. The enrichment of the greenhouse atmosphere with carbon dioxide promotes this process and increases production.

Carbon dioxide is odourless and tasteless. These properties make it ideal to use it in the food industry.

The document 70/17 *"Carbon Dioxide Food and Beverages Grade, Source Qualification, Quality Standards and Verification"* of the EIGA (European Industrial Gases Association) sets the specification requirements for liquid carbon dioxide in bulk production tanks or intermediate storage tanks at the gas supplier's depots, for use in foods and beverages such as an ingredient or additive.

Table 21: Specification for the CO_2 for food and beverages applications

Component	Concentration	Component	Concentration
Assay	99.9 % v/v min	Total volatile hydrocarbons (calculated as methane)	50 ppm v/v max of which 20 ppm v/v max non-methane hydrocarbons
Moisture	20 ppm v/v max	Acetaldehyde	0.2 ppm v/v max
Ammonia	2.5 ppm v/v max	Aromatic hydrocarbon	0.02 ppm v/v max
Oxygen	30 ppm v/v max	Carbon monoxide	10 ppm v/v max
Oxides of nitrogen (NO/NO_2)	2.5 ppm v/v max each.	Methanol	10 ppm v/v max
Non-volatile residue (particulates)	10 ppm w/w max	Hydrogen cyanide	0.5 ppm v/v max
Non-volatile organic residue (oil and grease)	5 ppm w/w max	Total sulphur (as S)	0.1 ppm v/v max
Phosphine	0.3 ppm v/v max	Taste and odour in water	No foreign taste or odour
Appearance in water	No colour or turbidity	Odour and appearance of solid CO_2	No foreign odour or appearance

It can also be used for optimal storage of fruit and vegetables in warehouses. The monitoring and control of the concentration as a component of fruit and vegetable storage ensures the optimal quality of the products.

It can be employed in Dry Ice production, since CO_2 dry ice is an excellent abrasive for industrial blasting. This enables sensitive surfaces, for example, to be gently cleaned. This minimally abrasive process is extremely environmentally friendly as no chemicals are used. CO_2 pellets are becoming increasingly important as a residue-free abrasive for a wide range of industrial cleaning processes.

For Fire Protection Systems, the benefits of using carbon dioxide is that water usage during extinguishing is avoided. Equipment and technology are not damaged. So, carbon dioxide is an important component of modern extinguishing systems and fire extinguishers.

9.4 Recovering CO_2 in the Foligno Plant

The biogas produced from the organic fraction of wastes coming from municipalities is an acceptable source, but it requires particular care in evaluation as a potential source of carbon dioxide for use in foods and beverages.

The upgrading process installed in the Foligno Plant produces 350 Nm^3/h of off gas, which is 99% CO_2. The operating hours of the plant are 8500 h/year on average, considering the period for maintenance. So, 2.975.000 Nm^3/year of off gas can be treated in the recovery part of the plant.

The 1% of biomethane contained in the off gas can be recovered, obtaining 3.5 Nm^3/h, which is, on a yearly basis, 29.750 Nm^3/year.

Table 22: Parameters for recovering bio-CH_4

Operating hours	8.500	h/year
Production	350	Nm^3/h
	630	t/h
	2.975.000	Nm^3/year
	5.355	t/year
CH_4 in off gas	1%	
Methane recovery from off gas	3,5	Nm^3/h

The more suitable technology that can be applied is the membrane technology. The other processes, based on solvent, can’t be applied since the CO_2 doesn’t come from the combustion of fuel.

The section of the plant for the recovery of the CO_2 is made up of a part of compression, a drying section and purification, a liquefaction section and a cryogenic tank for the storage of liquid CO_2 (24°C, 16 bar).

The CO_2 is compressed in a two-stage compressor and passes through the automatic molecular sieve dryer to remove completely humidity.

Then, it goes through the activated carbon purifier and through the dust filter to remove the impurities and the remaining powders. The gas thus purified is sent to the CO_2 liquefaction process; traces of non-condensable gases, still contained in CO_2, remain in the gaseous state when CO_2 becomes liquid. Air and non-condensable gases are used for the regeneration of the dryer, while pure liquid CO_2 is fed into the storage tank. CO_2 can be taken from the tank, vaporized and sent to the line of use.

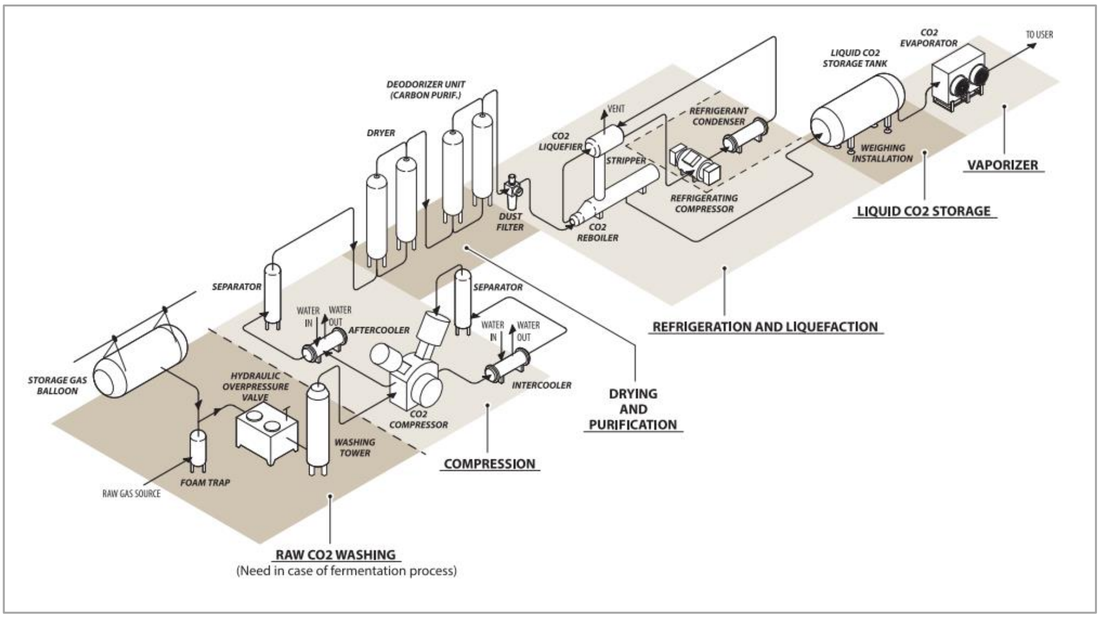


Figure 96: Plant flow diagram (TPI)

Figure 97: Pentair Evoluto+, membrane technology for recovering CO_2

Figure 98: TPI membrane technology

To estimate the feasibility of the introduction of the recovery plant, the OPEX and CAPEX have to be evaluated with respect to the incoming, deriving both from the recovery of the 1% of biomethane and from the selling of the CO_2.

Table 23: Estimation of the CAPEX and OPEX for the recovery

	Min	Max	
TOTAL CAPEX	**1.7**	**2.1**	**M€**
Specific consumption	0,35	0,55	kWh/Nm^3
Energy price		0,16	€/kWh
TOTAL ENERGY COSTS	**175.498**	**275.783**	**€/year**
Maintenance Add-On plant		40.000	€/year
Maintenance Analyzer		40.000	€/year
TOTAL MAINTENANCE COST		**80.000**	**€/year**
TOTAL OPEX	**255.498**	**355.783**	**€/year**

Table 24: Estimation of the incomes

	Min	Max	
CO_2 price	50	100	€/t
TOTAL SELLING CO_2	**282.000**	**564.000**	**€/year**
CIC for biomethane		0,65	€/Nm^3
TOTAL BIOMETHANE RECOVERY		**20.370**	**€/year**
TOTAL INCOMES	**302.370**	**584.370**	**€/year**

Considering an average value of the number above, the payback time for the technology for the recovering of the CO_2 has a payback time much higher than 8 years, which is the payback time for the plant itself. It returns that the investment isn't worth it for such values of CO_2 flowrate.

10. Conclusions

The biomethane production is getting more and more in the framework of energy production in Italy.

Although, the main obstacles to the spread of biomethane plants are of social matter. In the territories involved by a new project, an opposition movement is often formed involving committees, environmental associations, political parties and public administration. In some cases the contestation is not necessarily accompanied by the opposition to the technology process itself: the opponents in fact do not question the usefulness of the contested work but rather its location, not analysing in depth the reasons for a work and the benefits to long term.

Protests often mount because the subjects do not have the right information on the project and the technology used, which is why it is important that the public and private subjects engaged in the construction of a system immediately adopt a model of dialogue and involvement of the territory based on the listening to requests and on transparent communication.

So, to enhance Italy's exploitation of the potential of renewable gas, it is essential that everyone - citizens, businesses, institutions - have clear the environmental and economic advantages of closing the cycle of organic waste with the production of biomethane.

Regarding the process of biogas, compost and biomethane production itself, progress can be made, optimizing each step of the production. Especially, concerning the pre-treatment part which lead to a huge quantity of material to be disposed.

The Foligno plant is the first plant for biomethane production from OFMSW, built and managed by Asja Ambiente S.p.A., so it is the benchmark for the optimization of the processes. Real data, also included in this treatise, coming from the operation of the first year and a half of life of the plant, are an important unit of measure of the real behaviour of each machinery and of the biological processes involved in the production chain.

The possibility to recovery the CO_2 can close the circle of recovery the wastes, exploiting also the properties of the carbon dioxide in various fields. To do so, new technologies and processes are to be investigated, especially in case of dimension of the plant similar to the Foligno one, in order to make the investment economically worthy.

Considering incentives and social and environmental needs, renewable gas will be more and more produced, entering in the everyday life of the single users.

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